The Influence of Lighting Quality on Presence and Task Performance in Virtual Environments

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ABSTRACT

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The Influence of Lighting Quality on Presence and Task Performance in Virtual Environments

(under the direction of Frederick P. Brooks, Jr. and Mary C. Whitton)

This dissertation describes three experiments that were conducted to explore the influence of lighting in virtual environments.

The first experiment (Pit Experiment), involving 55 participants, took place in a stressful, virtual pit environment. The purpose of the experiment was to determine if the level of lighting quality and degree of texture resolution increased the participants' sense of presence as measured by physiological responses. Findings indicated that, as participants moved from a low-stress environment to an adjacent high-stress environment, there were significant increases in all physiological measurements. The experiment did not discriminate between conditions.

In the second experiment (Gallery Experiment), 63 participants experienced a non-stressful virtual art gallery. This experiment studied the influence of lighting quality, position, and intensity on movement and attention. Participants occupied spaces lit with higher intensities for longer periods of time and gazed longer at objects that were displayed under higher

lighting contrast conditions. This experiment successfully utilized a new technique, attention mapping, for measuring behavior in a three-dimensional virtual environment. Attention mapping provides an objective record of viewing times. Viewing times were used to examine and compare the relative importance of different components in the environment.

Experiment 3 (Knot Experiment) utilized 101 participants to investigate the influence of three lighting models (ambient, local, and global) on object recognition accuracy and speed. Participants looked at an object rendered with one lighting model and then searched for that object among distractor objects rendered with the same or different lighting model. Accuracy scores were significantly lower when there were larger differences in the lighting model between the search object and searched set of objects. Search objects rendered in global or ambient illumination took significantly longer to identify than those rendered in a local illumination model.

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Chapter 1

INTRODUCTION

1.1 Introduction

In the real world, rich colors, detailed surface textures, and complex lighting cues engage the human visual system, providing humans a context in which to operate. To provide context in the virtual world, computer scientists have attempted to allocate scarce computational resources to trigger the most important cues of the human visual system by modifying the rendering quality of the virtual environment (VE).

Rendering quality is defined as how indistinguishable a computer-generated image is compared to a photograph of the same scene (so-called *photorealism*) (Meyer et al., 1986). Graphics systems that create these images can be described by the set of parameters available to virtual reality (VR) researchers. These parameters include display resolution, color resolution, z-buffer resolution, geometric detail, texture detail, and lighting quality. A graphics system can be characterized by a vector of values for each of these parameters and can be compared to other graphics systems. This research will examine the lighting-quality component of rendering quality in a virtual environment. We define lighting quality in Section 1.4.

1.2 The Lighted Environment

Light is critical to the visual experience. Lighting exposes information about the environment and the objects within it. The interplay of light among objects creates a system of spatial cues, interpreted by the observer, which provides information about the objects' relative positions and orientations. As light interacts with surfaces, surface absorption and reflection occurs, establishing visual boundaries and providing information such as shading or darkness, color detail, surface texture, curvature, and continuity. These cues assist the observer in reasoning about and appraising the contents of the visual field (Veitch, 2001).

Light is a powerful "visual language," a medium that can be manipulated to influence user understanding of the environment. For example, Flynn (1973, 1979, 1992) has demonstrated that lighting influences a user's seating orientation, comprehension of room size and shape, and task performance. Lighting configurations also trigger certain behaviors. Public and private areas, for example, are lit differently to convey different intentions of spatial use and, thus, reinforce different sets of behaviors. Lighting patterns can alter the user's impression of meaning and importance. Yorks and Ginther (1987) showed that "lights affect our sense of priorities" while LaGiusa and Perney (1973) demonstrated that lighting configurations in educational settings can influence students' attentiveness to learning aids.

1.2.1 Light in the Virtual Environment

Light can be a crucial tool in creating compelling virtual environments. Researchers during the early stages of virtual reality struggled to create basic lighting in interactive computer-generated environments. As computers have grown in power, more complicated lighting configurations have become possible. In fact, VE designers today have a choice about the level and complexity of lighting they wish to calculate. Technological advancements such as faster computers, techniques for global illumination lighting simulation, light mapping, and programmable graphics chips have all contributed to the range of lighting options available in today's virtual environments.

With more options in lighting to explore, researchers have shown increased interest in investigating the role of lighting quality in virtual environments. Research has shown that lighting quality can influence task performance and object perception in virtual environments. For example, Hu et al. (2001) and Madison et al. (1999) focused on task performance under different lighting conditions and found that shadows and interreflections significantly improve object positioning consistency and object contact determination respectively. Christou (1994), investigating the influence of lighting on object perception, demonstrated that global (versus local) illumination significantly improved object shape estimations. Wanger (1992) studied the effect of shadow quality on the perception of spatial relationships and determined that sharp-edged shadows significantly improved object identification.

Figure 1.1. Virtual Research V8 HMD (left) and joystick (right). Both pieces of equipment are tracked with a 3rdTech HiBall optical tracking system.

This dissertation reports on three experiments carried out to study the influence of lighting quality in virtual environments on presence, behavior, and task performance respectively. All experiments were carried out with a head-mounted display (HMD) using a 3rdTech HiBall wide-area tracking system. The Pit Experiment (Experiment 1) and the Knot Experiment (Experiment 3) also made use of a tracked joystick to pick up or select objects in the VE (Figure 1.1).

1.3 Thesis Statement

This thesis investigates five hypotheses about lighting quality in virtual environments:

- *physiological responses and targeting accuracy will be heightened as lighting quality increases in stressful environments;*
- *attentiveness and movement towards lighted objects will increase as contrast is increased in low-stress environments;*
- *in low-stress environments, search accuracy in consistent lighting conditions will be significantly higher than in inconsistent lighting conditions;*
- *in low-stress environments, search times will improve with better lighting quality;*
- *global illumination will provide a significant improvement over local illumination on objective and subjective measures.*

1.4 Definitions

Lighting quality, in these experiments, is defined as the level of simulation fidelity a lighting model attains in approximation to the real world. In particular, this research will look at three different lighting models: an ambient illumination model, a local illumination model, and a global illumination model. These models were chosen because they differ considerably in the range of lighting effects that they can generate. Although all the terms described in the equations are functions of the wavelength of the light (λ), no wavelength-dependent features were used in the lighting models in this research. The exact nature of each lighting model can be defined in terms of its lighting equation.

The *ambient illumination model* used in this research is described in Foley et al. (1990) and can be represented by Equation 1.1.

$$I = I_a k_a \qquad \text{(Eq. 1.1)}$$

In Equation 1.1, the intensity of the illumination (I) on any surface is the product of the intensity of a constant ambient light (I_a) and the surface's ambient-reflection coefficient (k_a). This model represents the virtual world as being illuminated entirely by diffuse and non-directional light. The ambient lighting model described in Equation 1.1 is only a rough approximation of light transport and is not physically based. The ambient model displays objects with colors that are uniformly illuminated across their surfaces (Foley et al., 1990). It is the least sophisticated of the three lighting models.

The *local illumination model* considers objects to be lit with one or more point-light sources (Foley et al., 1990, p. 723). In contrast to the uniform surface brightness of the ambient lighting model, local illumination allows the object's surface brightness to vary depending on the angle of the incoming light and its distance from the surface. Specifically, the local illumination model is described by Equation 1.2.

$$I = I_a k_a + \sum_{i=0}^{n} I_{p_i} k_d \max\left(\overline{N} \bullet \overline{L_i}, 0\right) \qquad \text{(Eq. 1.2)}$$

The local illumination model includes the ambient model in its definition. The ambient term prevents the shading on the object from appearing too harsh and roughly approximates indirect illumination effects. In Equation 1.2, I_{p_i} is the i-th point light source's intensity. K_d is the surface's diffuse-reflection coefficient (between 0 and 1). $\overline{N}$ refers to the normal at a point on the surface, and $\overline{L_i}$ is a vector that points in the direction of the i-th light source. The $\overline{N} \bullet \overline{L_i}$ term is clamped to 0 to prevent illumination from light behind the surface. The contribution from each light source is summed to create the total diffuse illumination intensity value. If the intensity value, I, is too bright to be displayed with the graphics system, it is clamped to the highest value that can be displayed. The local illumination model used in this research is only an approximation of the physical phenomenon of diffuse lighting and is not directly related to energy measurements.

The *global illumination model* is the most technically sophisticated of the three models being investigated. Global illumination recreates nearly all of the lighting effects that can be seen in the real world. It is a superset of the local and ambient illumination models and creates images by distributing energy over all surfaces of all objects in the environment. It can handle point or area light sources and produces images which contain both direct and indirect illumination.

The principal equation describing the global illumination model is the rendering equation first proposed by Kajiya in 1986 and shown in Equation 1.3.

$$I(x,x') = g(x,x')\left[\varepsilon(x,x') + \int_S \rho(x,x',x'')I(x',x'')dx''\right] \qquad \text{(Eq. 1.3)}$$

As seen in Figure 1.2, Equation 1.3 describes the intensity, $I(x,x')$, of light leaving a point, x', on a surface going to another point, x, on a second surface as an attenuation factor *g* times the sum of two terms. $I(x,x')$ has units of ${}^{watt}/_{meter^2}$. The first term, ε, is a surface emittance term describing the intensity of the light emitted from x' to x in the scene. The second term, ρ, is

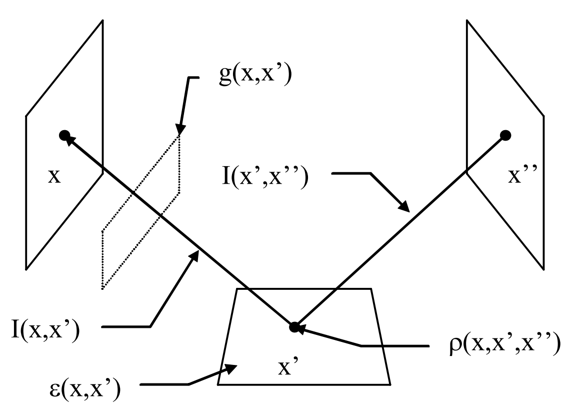


Figure 1.2: Three-Point Transport (Kajiya, 1986).

a surface scattering term that describes how much light energy is coming from other points in the scene, x'', bouncing off x' and into x. The $g(x,x')$ term is used to limit which surface points can contribute to the intensity value of point x by modeling surface occlusion. For the models in this research, the

Figure 1.3: Ambient, local, and global illumination models.

ρ term is limited to diffuse illumination, meaning that surfaces do not have a specular component. The lighting solutions created are limited to view-independent illumination effects and do not attempt to recreate visual phenomena such as atmospheric scattering, subsurface scattering, transparency, diffraction, polarization, fluorescence, and phosphorescence.

An example of the three lighting models is given in Figure 1.3 (adapted from Christou and Parker, 1995).

The lighting model is an important component of rendering quality and contributes to the effectiveness of a virtual environment (Hu et al., 2000; Madison et al., 1999). Effectiveness can be measured in several different ways. One of the means of determining the effectiveness of a virtual environment is by measuring the participant's sense of "presence" within that environment. Presence can be studied and measured from both subjective and objective perspectives. *Subjective presence* is the participant's reported sense of "being there" in the virtual environment (Heeter, 1992). *Objective presence* can be measured behaviorally and is defined as participants behaving and acting in a virtual environment in a manner consistent with human response to similar real situations (Meehan, 2001). In addition to presence measures, task performance can also be used to gauge the effectiveness of the virtual environment. *Task performance* in this research is defined as the ability of a participant to successfully complete an assigned task, such as searching for an object in a virtual environment. Subjective and objective presence measures, as well as task performance, can provide insight into how lighting quality can be used effectively in virtual environments.

1.5 Experimental Results

The first experiment (Pit Experiment), involving 55 participants, was conducted in a stressful virtual pit environment. The purpose of the experiment was to determine whether, under stressful conditions, the level of lighting quality and degree of texture resolution increased the participants' sense of presence as measured by physiological responses. Findings indicated that, as participants moved from a low-stress environment to an adjacent high-stress environment, there were significant increases in all physiological measurements. The experiment did not discriminate between conditions.

In the second experiment (Gallery Experiment), 63 participants experienced a non-stressful virtual art gallery. This experiment studied the influence of lighting quality, position, and intensity on movement and attention. Participants occupied spaces lit with higher intensities for longer periods of time and gazed longer at objects that were displayed under higher lighting contrast conditions.

Experiment 3 (Knot Experiment) utilized 101 participants to investigate the influence of three lighting models (ambient, local, and global) on object recognition accuracy and speed. Participants looked at an object rendered with one lighting model and then searched for that object among distractor objects rendered with the same or different lighting model. Accuracy scores were significantly lower when there were larger differences in the lighting model between the search object and searched set of objects. Search objects rendered in global or ambient illumination took significantly longer to identify than those rendered in a local illumination model.

1.6 Overview of the Thesis

This thesis describes three different experiments that were conducted to explore the influence of lighting in virtual environments. Chapter 2 provides background information and previous research results on virtual reality, presence, lighting, behavior, and task performance. Chapter 3 discusses the first experiment examining lighting quality and presence in a stressful environment. Chapter 4 examines the second experiment concerning the effect of lighting on behavior in a non-stressful virtual environment. Chapter 5 describes the third experiment on lighting model and task performance in a non-stressful virtual environment. Finally, chapter 6 summarizes the results of the three experiments and suggests future directions for investigating the influence of lighting in virtual environments.

Chapter 2

Background

2.1 Introduction

Humans have found ways of creating and using light purposefully since ancient times. Beginning with campfires and torches, humans sought to illuminate the night. Later, new sources, such as candles and oil lamps, allowed lighting to become an integral part of interior environments. With the advent of gas lights and electric lights, lighting became integrated into society as a system. Lighting systems allowed unprecedented control over lighting application in all types of environments.

2.2 The Study of Light in Natural Environments

People have studied light from a wide range of perspectives. Isaac Newton in the 1600s studied the components of light from a scientific perspective (Tipler, 1991). He discovered that light was composed of a spectrum of energies and laid the foundation for our current understanding of *geometric optics* (describing light propagation in terms of rays). Light plays an important part in artistic creation. By studying light in the natural world, Leonardo da Vinci (1452-1519) introduced and employed the concept of chiaroscuro, which models and defines forms with the modulation of light and shade to give objects a more natural appearance (Arasse, 1998). Claude Monet (1840-1926) became obsessed with light and used it to great effect sometimes painting the same scene up to 40 times (Rouen Cathedral) under different lighting conditions (Levine, 1994). In the field of psychology, James Gibson (1904-1979) discussed light as the raw input to the visual system and investigated the informative nature of spatial variations in light. His theory of "ecological optics" introduced innovative ideas about how organisms process visual stimuli. Gibson maintained that an organism’s perceptual system is shaped by its interaction with the environment (Gibson, 1979). In the field of illumination engineering, John Flynn (1930-1980) conducted a series of influential studies on interior lighting and human response. His groundbreaking work elevated lighting from a functional medium to an expressive medium in interior environments (Flynn, 1992). He studied lighting from many different facets including its influence on behavior, mood, and task performance. Flynn's research resulted in a number of lighting recommendations which became standard for the profession by virtue of their incorporation into the lighting guidelines of the Illuminating Engineering Society of North America.

2.3 The Study of Light in Virtual Environments

Advances in computers, displays, and sensors have enabled the creation of environments that can be perceived but do not have a physical embodiment. These are known as *virtual environments*. Virtual environments, just as physical environments, use lighting to communicate information about the composition and contents of the scene. However, unlike real environments, the quality of light simulated in the virtual environment is controlled entirely artificially and is dependent on computational algorithms to determine the character of the light produced.

2.3.1 Computer Graphics

Computer graphics uses a variety of techniques to create images on output display devices such as computer monitors or head-mounted displays. Every image is composed of individually colored picture elements called *pixels*. To form an image, each pixel must be evaluated with respect to the surfaces represented by that pixel in order to derive a single color value. A displayed pixel's color value may be calculated using one point or by combining colors calculated at multiple nearby points. Using more evaluation points (*sampling points*), rough edges between surfaces can be smoothed out and approximated more faithfully giving a less "jagged" or stair-stepped appearance to the edges of objects. The use of multiple sample points to determine the color of a single pixel is called *anti-aliasing*. Anti-aliasing incurs additional computational costs to determine which surfaces a pixel represents and in what proportion.

To generate the colors for each sample (and ultimately each pixel), a lighting model must be calculated for the surfaces represented by each pixel. There are two components to a lighting model. One component is concerned with how the light is distributed in the scene, while the second component is concerned with how surfaces are shaded. Once the lighting model is processed and all of the pixels displayed, the environment and its contents can be subjected to viewer appraisal.

2.3.1.1 Light Distribution in Computer Graphics

The most common method used in producing computer generated images is referred to as *scan conversion* (Rogers, 1998). In scan conversion algorithms, surfaces are represented by polygonal elements, most frequently triangles. These triangles are projected onto the display in rows called raster scan lines. The triangles are typically sorted to remove completely hidden surfaces from further processing (Sutherland, 1974). Pixel intensity values are then calculated by interpolating surface properties across raster scan lines, such as the surface's normal vector, and calculating the surface shading model. Because of the simplicity of this method of image generation, specialized hardware can be created to produce images at interactive rates. However, this method of lighting only allows local surface and lighting information to be calculated. Light is not distributed in the scene, it is calculated for each surface independently.

As scan conversion research was progressing, Whitted (1980) introduced ray tracing into computer graphics. Ray tracing takes an alternate approach to creating a computer-generated image. Ray tracing simulates the bouncing of rays of light around an environment and produces far more realistic images than those created by scan conversion. Ray tracing simulates the reflection, refraction, scattering, and absorption of light bouncing between surfaces and captures both the direct and indirect aspects of lighting (called global illumination). Unfortunately, this realism comes at great computational cost.

Another global illumination algorithm, radiosity, was invented by Goral et al. in 1984 to avoid the computational burden of ray tracing while still producing useful global lighting simulations. Radiosity limits light interaction to only diffuse surfaces, making the global illumination of the environment computationally tractable. Throughout the 1980s and 1990s, improvements were made to radiosity and ray-tracing algorithms to increase their realism and speed. In 1996, Jensen introduced an algorithm that extended ray tracing with additional data structures to create a new form of lighting simulation called photon mapping. Photon mapping can simulate a wider range of lighting phenomena than radiosity but with a lower computational cost than ray tracing.

Ray tracing, radiosity, and photon mapping are complex algorithms that require dedicated hardware to run interactively on most computers. While such hardware implementations have been attempted by graphics researchers, interactive global illumination systems are not currently practical.

2.3.1.2 Surface Shading in Computer Graphics

Computer graphics researchers have worked over several decades to create different computational models of light to improve the visual quality and realism of graphics images. Early models of lighting created a single color for each visible surface facet. This so-called *flat shading* was introduced by Bouknight in 1970. Bouknight's model was quickly improved by Gouraud (1971) to include linear (and higher-order) interpolation of lighting values across the surface to be shaded. Gouraud's linear interpolation resulted in much smoother shading of curved surfaces. Phong (1975) incorporated an additional exponential term into the diffuse shading model to incorporate specular components into surface lighting. However, Phong's model produced surfaces that were too shiny and gave computer graphics surfaces a notably artificial, "plastic" appearance. An example of flat shading, Gouraud shading, and Phong shading can be seen in Figure 2.1. In 1982, Cook and Torrance proposed another lighting model. Their work was derived from models of light interaction with metals previously investigated by Torrance and Sparrow in 1967. The Cook-Torrance model solved the artificial shininess of computer graphics surfaces and introduced a more realistic, physically-plausible surface appearance.

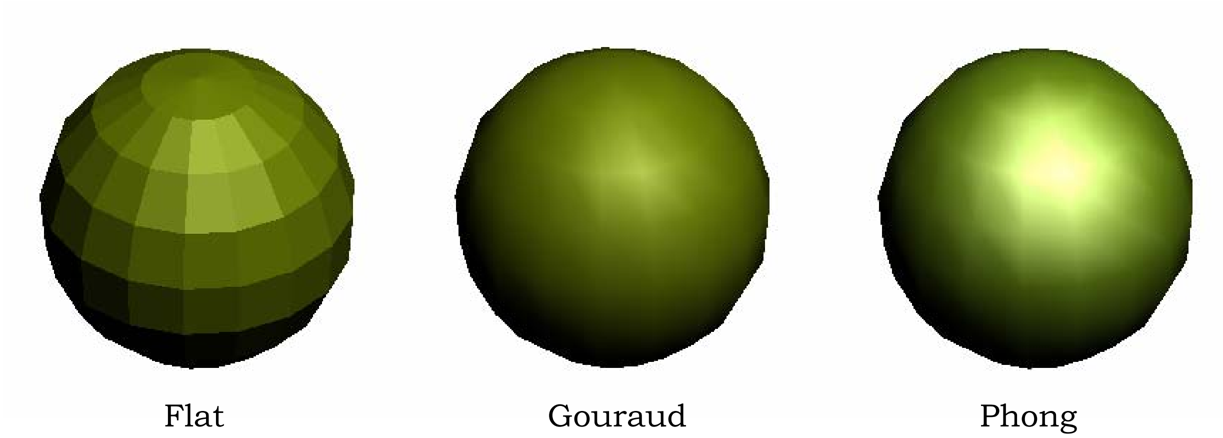


Figure 2.1: Flat, Gouraud, and Phong-shaded spheres.

Other researchers, going beyond Cook-Torrance, began investigating specific surface phenomena such as those seen in hair (Kajiya and Kay, 1989), cloth (Yasuda et al., 1992), clouds (Harris, 2001), and skin (Hanrahan, 1993). Surface shading models were also developed by directly measuring surfaces and mathematically capturing their appearance for later reconstruction in a computer generated environment (LaFortune et al., 1997).

In this dissertation, when lighting values are calculated across a surface element using the graphics hardware, Gouraud's surface shading method is used.

2.3.2 New Directions in Lighting Research

The conditions under which a given computer graphics lighting model is useful remain an open research question. Information from other disciplines that study light in the real environment can serve to guide the study of lighting in virtual environments.

In this thesis, we seek to understand lighting as it applies to virtual environments by pursuing three different lines of investigation, namely understanding lighting's role in presence, behavior, and task performance. As discussed at the end of Section 1.4, each line of investigation contributes a different perspective on the study of lighting and how lighting can affect users of virtual environments.

2.4 Presence

Presence in virtual environments, its definition and measurement, has been an active area of investigation in virtual reality research.

2.4.1 Definitions of Presence

Steuer (1992) makes a distinction between presence in the real environment and in the virtual environment. Steuer defines presence as "the sense of being in an environment," applying this term only to natural environments. He defines telepresence as "the experience of presence in an environment by means of a communication medium," applying this term to virtual environments. Steuer's concept of telepresence is synonymous with the term "presence" as used in today's virtual reality literature. Steuer further defines telepresence in terms of vividness and interactivity which refers to the richness of sensory experience and the ability to modify the virtual environment respectively.

Heeter (1992), in her paper "Being There: The Subjective Experience of Presence," states that presence "derives from the feeling like you exist within but as a separate entity from a virtual world that also exists." Heeter divided presence into three categories: subjective personal presence, social presence, and environmental presence. *Subjective personal presence* is a measure of the reasons why one feels as though one is part of an environment. *Social presence* is the extent to which one feels that other beings exist in the same virtual world. *Environmental presence* is how much the environment recognizes one's existence and reacts to one's actions.

Slater et al. (1996) use two concepts in their discussion of virtual environments, immersion, and presence. *Immersion* is a "quantifiable description of a technology" such as the display resolution, tracking accuracy, color depth, etc. They describe *presence* as "a state of consciousness, the (psychological) sense of being in the virtual environment, and corresponding modes of behavior."

Meehan (2001) studied physiological reactions to stressful virtual environments and defined presence as "perceiving stimuli as one would perceive stimuli from the corresponding real environment." Meehan's definition of presence is the one adopted for the research in this thesis.

2.4.2 Measurements of Presence

Virtual reality researchers use both subjective and objective measures to evaluate presence. Subjective presence measures usually take the form of post-experience questionnaires. Objective presence measures include physiological readings and behavioral responses.

2.4.2.1 Subjective Measurements

Witmer and Singer (1998) designed a presence questionnaire consisting of 32 questions concerning different constructs thought to be related to presence in virtual environments. The question responses are on a 1 to 7 scale and are numerically summed to arrive at a total presence score.

Lessiter et al. (2001) introduced the ITC-Sense of Presence Inventory consisting of 44 questions scored on a five-point scale. The questions relate to four aspects of the participant's experience: sense of physical space, engagement, ecological validity, and negative effects. *Ecological validity* refers to the "tendency to perceive the mediated environment as lifelike and real." Although Lessiter et al. report that the questionnaire is reliable and valid, it has not been widely adopted in the presence community.

Usoh et al. (1999) used their combined understanding of presence and experimental experience to formulate the University of College London (UCL)

Presence Questionnaire. This questionnaire explores “the sense of being in the VE, the extent to which the VE becomes the dominant reality, and the extent to which the VE is remembered as a ‘place’” (Usoh et al., 2000). Several researchers of interactive virtual environments have used this questionnaire (Insko, 2001; Mania, 2001; Meehan, 2001), and it will be used in this dissertation to evaluate the participant's subjective sense of presence.

2.4.2.2 Objective Measurements

Finding objective measures of presence that can be applied to different virtual environments has been an aim of VR researchers for over a decade.

Eberhart and Kizakevich (1993) were the first to use physiological reactions to study responses to virtual environments. They measured core body temperature, skin temperature, skin resistance, and heart rate while a participant took part in a navigation task and a walking task. Eberhart and Kizakevich reported anecdotally that high-speed navigation resulted in higher blood pressure readings and that lag times in visual display “seem to be correlated with alpha and beta frequencies in brain activity.”

Pugnetti and colleagues (1995, 1996) studied electroencephalograms (EEG) and evoked-potentials (EP) in an immersive virtual environment. Evoked-potentials refer to characteristic sequences of waves in an EEG corresponding to specific neurological activity. Participants were asked to perform a well-known neuropsychological test, the Wisconsin-Card Sorting

Test. Physiological measurements in the virtual environment showed results similar to those when the test was performed in a real environment.

Yamaguchi (1999) studied fatigue induced by a virtual environment experience by monitoring core temperature, heart rate, blood pressure, and urinary catecholamine release after participants were exposed to stressful and non-stressful scenarios. He found that the stressful scenario was not significantly different in the measured parameters than the non-stressful scenario.

Jang et al. (2002) studied normal physiological responses to two virtual environments, a flying environment and a driving environment. Yang measured heart rate, skin resistance, and skin temperature. He found that heart rate increased significantly when participants were exposed to the driving virtual environment. However, the other measures failed to reach significance but showed some statistical trends. Jang et al. concluded that "skin resistance and heart rate can be used as objective measures in monitoring the reaction of non-phobic participants to virtual environments."

Meehan (2001) evaluated changes in heart rate, skin temperature, and galvanic skin response as a means of establishing objective measures of presence in a stressful virtual environment. The environment consisted of a training room connected to a room that contained a stress-inducing virtual pit. Meehan, in collaboration with Insko (2001), applied these physiological measures to different environmental configurations such as the inclusion of static haptic cues as well as changes in frame rate. Meehan found that exposure to the pit environment resulted in significant increases in heart rate and skin conductance and a significant decrease in skin temperature. In his experiments, Meehan concluded that changes in heart rate met his requirement for a reliable, valid, multi-level sensitive, and objective correlate of presence in stressful virtual environments.

In this dissertation, heart rate, skin temperature, and galvanic skin response were used as objective presence measures in a stress-inducing pit environment.

2.4.3 Rendering Quality and Presence

2.4.3.1 Theoretical Assertions

Rendering quality is mentioned in many theoretical discussions of presence with the belief that increased rendering quality should increase a participant's sense of presence.

Steuer (1992) includes the concept of *vividness* in his description of presence. Vividness “means the representational richness of a mediated environment as defined by its formal features, that is, the way in which an environment presents information to the senses.” Steuer expects vividness to yield increased presence. Heeter (1992) also includes rendering quality as an important component of presence. She states that "In immersion VR, a sense of personal presence is based in part on simulating real world perceptions."

Held and Durlach (1992) advocate the concept of using increased quantity and quality of sensory feedback in telepresence situations to aid in task performance and sense of being in another environment.

Sheridan (1992), in his "Musings on Telepresence and Virtual Presence," states that one of the three principal determinants of the sense of presence is the "extent of sensory information" available to the user.

Ellis (1996), commenting on issues brought up in Sheridan's work, agrees with the concept that utilizing pictorial cues in the graphical elements of a simulation can help induce a sense of presence. He further states that the “distinctiveness” of a virtual environment from a real environment could be a technique used to measure presence. Ellis refers to Schloerb’s method of analyzing responses of participants to virtual and real environments and then determining the agreement between the responses to both environments to measure presence (Schloerb, 1995).

Lombard and Ditton (1997) take a cross-media approach to the study of presence and break the concept of presence into several categories, one of which is rendering quality. They state that "images which are more photorealistic ... are likely to provoke a greater sense of presence as well."

Witmer and Singer (1998) in their description of their presence questionnaire address the concept of rendering quality and state that "presence should increase as a function of VE scene realism (as governed by scene context, texture, resolution, light sources, field of view (FOV), dimensionality, etc.)." They further state that "the more consistent the information conveyed by a VE is with that learned through real-world experience, the more presence should be experienced in a VE."

2.4.3.2 Studies on Rendering Quality and Presence in Virtual Environments

Slater et al. (1995a) were some of the earliest researchers to investigate rendering quality in an immersive virtual environment. In one particular experiment, they investigated the influence of dynamic shadows and sound on presence and task performance. The study used eight participants and was composed of two parts. One part consisted of a participant choosing a spear from behind a screen and then guiding this spear via a 3D mouse toward a target. The other part of the study used a pointing task involving a virtual radio. Before participants began the trial, Slater et al. had them write an essay and scored it to determine their dominant sensory input method (visual, auditory, or kinesthetic). Participants were exposed to the virtual environment under different rendering conditions. In particular, the number of lights casting shadows in the environment was an independent variable. Slater et al. recorded which spears participants chose (they were to choose the spear closest to the wall by using shadow cues) and how close their virtual spears came to reaching a target on an adjacent wall. After this task, subjects were asked to point toward the source of a sound coming from a real radio located in a different position from the radio depicted in the virtual environment. The angle between the virtual radio and the participant's pointing direction was recorded. After the trial was over, the participant answered a presence questionnaire.

Slater et al. found that shadows did not influence the choice of spear and that shadows did not significantly improve a participant's targeting accuracy. However, subjects were significantly better at stopping the spear before it hit the target when shadows were rendered. Presence was significantly enhanced by shadows for visually dominant participants. Participants pointed toward the virtual radio significantly more often than the real radio when shadows were present.

Dinh (1999) conducted a study to investigate the effects of tactile, olfactory, auditory, and visual sensory cues on the participant's sense of presence and memory in a virtual environment. Three-hundred twenty-two participants were recruited for the study. Two different levels of visual quality (high and low) were explored. The high-visual-quality condition used local lighting sources and applied high resolution texture maps to objects. The low-visual-quality condition used only ambient illumination and reduced the texture maps to one-fourth of their original resolution. Although having more sensory inputs increased presence and memory scores, visual quality did not significantly affect the perceived sense of presence or object location recall.

It is important to note that, in Dinh's study, although the other inputs (tactile, olfactory, or auditory) were either present or absent, rendering quality was always present but was either increased or decreased based on the current experimental condition. Additionally, Dinh states that both visual conditions used in the study were "at the low end of the visual quality spectrum" and "represent minor changes" in the appearance of the environment.

Welch et al. (1996) conducted two studies to examine the influence of pictorial realism, interactivity, and lag on the sense of presence on a driving task. Forty participants were presented with a series of driving environments that each differed in one of two of the characteristics examined. In the first experiment, pictorial realism and interactivity were compared. In the second experiment, pictorial realism and lag were compared. Participants were told to drive as quickly and smoothly as they could through one lap on a virtual road. The high realism condition consisted of a blue sky, hilly road surface and surround, green background, red farm houses, oncoming cars, and guard posts. The low pictorial realism condition consisted of a black sky, flat road surface and surround, black background, no peripheral objects, and no oncoming cars. After driving in an environment, participants were asked to indicate numerically whether the environment they just saw produced a greater or lesser sense of presence than the previous environment.

In both experiments, high pictorial realism significantly increased participants' presence scores. However, in a post-experiment interview, participants indicated that realism played a lesser role than interactivity or latency. Welch et al. suggest that their changes in the environmental presentation could be described as environmental "complexity" rather than pictorial realism. Welch et al. further state that "an unconfounded examination of [pictorial realism] will require keeping complexity constant while varying the degree to which the graphic representation is similar to the 'real world'."

Mania (2001) examined the link between lighting impressions and the sense of presence in real and virtual environments under different viewing conditions in an experiment using 105 participants. Participants viewed either a real environment or a photorealistic computer graphics simulation of the real environment. Five viewing conditions were explored in the experiment. Three conditions involved viewing the simulated environment either using a stereo HMD with head-tracking, a mono HMD with head-tracking, or a mono HMD with a mouse interface to control the viewpoint. The other two conditions used a set of goggles to view either the real-world environment or the simulated environment displayed on a monitor navigated using a mouse. The goggles were a custom-made shell constructed to replicate the field of view that one would see through the head-mounted display used in the experiment. Three minutes of viewing time was allowed after which participants were given a lighting questionnaire and a presence questionnaire. The subjective responses to the lighting questionnaire did not reveal any significant differences across conditions which, given the large number of participants involved, suggests that lighting impressions were viewed similarly in the real and virtual environments. There was also a significant positive correlation between the sense of presence and subjective impressions of lighting for the HMD monocular viewing condition.

2.5 Behavior

Behavioral responses to lighting in virtual reality has had limited study. The University of North Carolina's large-area tracker presents an invaluable opportunity to explore the link between lighting quality and behavior in virtual environments. Although the study of user’s responses to lighting in virtual environments is still in its early stages, much can be learned from other disciplines that have investigated human behavioral responses to lighted environments in the real world.

2.5.1 Studies of Lighting in Illumination Engineering

One of the earliest and most innovative researchers on illumination engineering was John Flynn, who during the 1970s conducted studies on subjective responses to lighting as well as lighting's influence on overt behavior.

At the 1973 Illuminating Engineering Society (IES) Conference in Philadelphia, John Flynn presented his studies on the effect of environmental lighting on user impressions and behavior. He realized that "light can be discussed as a vehicle that facilitates the selective process [of viewing] and alters the information content of the visual field." Ninety-six subjects took part in a study at a General Electric lighting research facility. The participants were divided into 12 groups of 8 and exposed to different lighting conditions in a conference room. Six different lighting arrangements were presented to each group. Participants were required to fill out a Lighting Impression Questionnaire. The questionnaire utilized Osgood-type ratings scales consisting of 34 pairs of opposing words such as "cold" versus "warm" or "bright" versus "dim." After data were collected from the participants, the responses were evaluated with factor analysis to identify groups of terms that correlated with specific lighting configurations. Flynn used rating scales in studying lighting and found that different lighting configurations induced common impressions among the users.

A second study involved 46 subjects who rated differences in a series of lighting configurations on a simple scale of 0 to 10 where 0 represented “no change” and 10 represented a “very large change.” By altering lighting parameters (bright/dim, peripheral/overhead, uniform/non-uniform) between conditions and using a multidimensional scaling procedure, Flynn was able to identify which lighting changes were associated with specific impressions.

Finally, Flynn collected observational data in a separate restaurant-type setting from uninstructed participants. He found that changes in lighting did not influence seat selection but did influence the seating orientation of restaurant patrons. Most participants oriented themselves towards the lighted area of the room.

Taylor and Sucov (1974) collected data on the movement of people toward lights. One hundred eleven people participated in the study which required them to enter a doorway through a curtain and read a printed message in front of them. After reading the message, the participant chose to turn left or right along a two-foot wide by eight-foot long passageway to enter the main experiment room. Taylor and Sucov adjusted the lighting brightness ratio between the two sides and studied its effect on people's choice (left or right). The illumination on the control side of the passageway was held constant while the opposite side was illuminated at a ratio of 1, 3, 10, 30, or 100 times as bright as the control side. The control side could be either the left or right side of the passageway. The direction the participant chose was recorded as a function of the illumination ratio. After completing a lighting preference questionnaire, the participant had a choice of exiting through the same passageway which was now lit in a different ratio. Their choice (left or right) was again recorded.

Taylor and Sucov found that 70 percent of people entered through the brighter side and 58 percent left through the brighter side. The higher the illumination ratio, the higher the percentage of subjects that entered via the brighter side. All subjects entered the brighter side at an illumination ratio of 1:100. When leaving, however, participants tended toward the brighter side from ratios of 1:1 to 1:10 but were less likely to leave towards the brighter side as the ratio increased to 1:100. Taylor and Sucov state that this result might reflect the participant's preference to leave via a familiar path rather than the brighter one.

Yorks and Ginther (1987) conducted three studies about wall lighting placement and the behavior of people in a work environment. Their first experiment involved the participant sitting at a desk in the center of a room with different wall lighting configurations. The participant filled out two questionnaires concerning his impression of the room under the current lighting condition. The second experiment consisted of a room with three desks, three chairs, and a plant. The desks were arranged in a row and the participant was asked to sit at one of the desks as he entered the room. Seating choice was recorded under different wall lighting configurations. The third experiment used the same procedure as the second experiment but without lighting variation. This experiment was used as a control to compare against the second experiment.

Yorks and Ginther found that people prefer wall lighting in front of them (similar to Flynn's finding that people orient themselves toward lighted areas). By lighting different walls in the room, different impressions of the space were reported (such as "authoritative" for rear wall lighting). For the seating experiment, illuminating the front wall caused people to choose a seat closer to the front of the room. Without wall lighting, people chose a seat near the back of the room. As Yorks and Ginther state in their discussion, "one of the greatest implications [of this study] is the confirmation that light can influence overt behavior."

For this dissertation, Flynn's Lighting Impression Questionnaire was used. It has been shown to have discrimination power in evaluating impressions of lighting in real environments (Flynn, 1973) and is the only lighting questionnaire that has been used in previous VR lighting experiments (Mania, 2001).

2.6 Task Performance

Lighting and task performance has been studied in the disciplines of illumination engineering, psychology, and virtual reality. The quantitative measures available to evaluate task performance make it a prime candidate for experimentation. Research on the relationship between virtual reality and lighting has borrowed extensively from the psychological literature because of the mature methodology and history of previous results.

2.6.1 Illumination Engineering, Lighting, and Task Performance

Much attention has been given to the purposeful design of lighting systems to accommodate people and the tasks they must perform in a given environment. The study of work environments (office, school, retail, and industry) has given rise to the adoption of standard illumination guidelines for different types of tasks. For example, complicated assembly work requires five times more illumination than packaging and labeling; transcribing requires five to ten times the illumination as word processing. (Kaufman, 1987)

The purpose of lighting in a task-oriented environment is to increase the potential for high visual performance. The best visual acuity occurs when the brightness difference between the central task and the background is between 1:1 and 4:1, with the task area being brighter than the background. Proper lighting has been shown to increase worker performance and reduce visual fatigue (Flynn, 1992).

2.6.2 Psychology, Lighting, and Task Performance

Liter (1997) explored naming-time latencies in relation to common objects, artifacts, and four-legged animals shown as shaded images or in silhouette. The objects were computer-modeled, 3D data files from Viewpoint Data Labs and were shaded with Gouraud shading or were completely black in silhouette. Twelve participants were instructed to name the objects seen on a computer monitor as quickly and accurately as possible with the first name that came to mind. Overall, silhouette naming times were significantly slower and less accurate than their shaded counterparts. In particular, when silhouettes did not allow recovery of unique object features, silhouette naming times were significantly longer yet.

Tarr (1998) studied the influence of lighting direction and shadow type on 3-D object recognition. He conducted three experiments in which novel objects, *greebles*, were constructed so that they had similar features and were displayed on a computer monitor. In Experiments 1 and 2, participants had to determine if two greebles were identical under different lighting conditions. Experiment 3 consisted of a naming time experiment. Participants were asked to identify greebles shown from two different viewpoints as well as under different illumination conditions.

Tarr found that when two greebles were displayed with different illumination directions naming times were significantly longer. When shadows were present, changes in lighting direction caused increases in response time and lower accuracy. When the colors (all grayscale) were inverted on the images and shadows were drawn as white instead of black, changes in illumination direction resulted in much larger increases in response time and lower accuracy. Without shadows, overall recognition performance was lower than with either black or white shadows. In the third experiment, changes in lighting direction influenced response time and accuracy in the same ways in both viewing directions. Tarr contends that this indicates that shadows are processed in the brain as part of the object rather than as part of the visual image on the retina.

Castiello (2001a) used 20 participants to investigate naming times for objects lighted from two different directions with either congruent or incongruent cast shadows. Naming times were longer for objects that had cast shadows that differed from the shape of the lighted object or were inconsistent with the light direction. Participants were slower to name objects when cast shadows were absent.

Another experiment by Castiello (2001b) used similar lighting and shadow conditions as in the previous study. However, control conditions were added to include objects without shadows and objects drawn in silhouette with congruent shadows. Castiello reported that objects that were drawn with congruent lighting and shadows were named faster than those with incongruent lighting and shadows. However, objects drawn in silhouette with a congruent shadow took the longest time to name.

Collier and Scharff (2000) studied the influence of lighting direction and changes in perspective on detecting target stimuli in computer-generated drawings of cubes with a varying number of distractor elements (also cubes). The target cube was lit from one direction, all the distractors from another single direction. Thirty-two participants were asked to detect the target stimuli as quickly and accurately as they could in a series of trials. Collier and Scharff found that top/bottom lighting directions were processed faster than left/right lighting directions.

2.6.3 Virtual Reality, Lighting, and Task Performance

There is considerable overlap in the types of studies performed in the VR lighting community and those in psychology. VR studies, however, employ a greater variation in the type of displays used, explore a larger variety of rendering conditions, and use trackers or sensors to allow participants to perform more complex tasks than those reported in the psychology literature.

Christou (1994, 1995) implemented his own radiosity system to generate stimuli for studies on the effects of local and global illumination in perceptions of three-dimensional space and surface properties. Christou found that indirect illumination provided by a global illumination system increased accuracy in a shape perception task and contributed to the appearance of object "solidity." He was also able to show that indirect illumination allows for successful disambiguation of geometric form in situations where local illumination does not. In addition, Christou found that indirect illumination allows participants to make more accurate distinctions between changes in surface reflectance than were possible using a local illumination model.

Madison (1999) explored the use of shadows and interreflections in providing cues to object contact. In her study, an image of a block potentially touching a surface was presented with or without shadows and with or without lighting interreflections. Further conditions included the use of multiple shadows and different colors (red/white) for interreflection and shadow. Madison found that interreflections between surfaces were equally as strong as shadows in conveying contact information to participants. However, using both shadows and interreflections resulted in the highest accuracy during the trials. Incorrectly colored shadows and interreflections resulted in lower accuracy than correctly colored shadows and interreflections but were considerably more accurate than having no shadows or interreflections at all.

Hu et al. (2002) performed two studies examining the cues of shadows and interreflections on task performance in both monocular and stereo-viewed virtual environments. In the first study, six participants were required to use a haptic interface device to lower a virtual block onto a plane. Each participant performed hundreds of trials. Shadows were found to improve the performance of the participants. In a second study, participants were required to report the distance between a virtual block and a virtual table under different viewing and rendering conditions. Hu found that shadows and interreflections resulted in a significant improvement in a distance estimation task.

Willemsen and Gooch (2002) describe the results of a directed walking task conducted in either a real environment or virtual renditions of that real environment. Their study used 12 participants who examined a target some distance away on the floor and then, with vision blocked, walked as close to the target as they could. Subjects performed the task in either a real, image-based (photographic panorama), or "traditional" virtual environment (a textured, polygonal model of the environment).

The authors found a small difference in the accuracy of distance judgments between the polygonal virtual environment and the image-based depiction of the environment in favor of the image-based depiction. A significant underestimation of distance, however, occurred when subjects wore a headmount in a virtual environment as versus walking freely in the real environment. Willemsen and Gooch concluded that the rendering quality was not as significant as the display device in producing underestimations of distance.

2.7 Discussion

This chapter has surveyed the study of light in natural and virtual environments. We have focused on the relevant contributions of virtual reality, illumination engineering, and psychology to the study of lighting and its effects on presence, behavior, and task performance in real and virtual environments. The experiments described in this dissertation incorporate the concepts presented in this chapter with the intention of broadening our knowledge of the effects of lighting in virtual environments.

Chapter 3

Experiment 1: The Pit Experiment

3.1 Introduction

The purpose of the Pit Experiment was to explore a small subset of the visual cues available in a virtual environment and investigate their impact on the participant's sense of presence and his ability to perform certain tasks in the VE. In particular, this study examined the effect of visual cues provided by texture resolution and lighting quality on presence, task performance, depth estimation, and memory. Although there are a wide variety of display technologies available to present visual information to a user, this study focused on VEs that make use of a head-mounted display which is tracked over a large area.

3.2 Background

Presence in this study was defined as "perceiving stimuli as one would perceive stimuli from the corresponding real environment" (Meehan, 2001).

Michael Meehan showed that, for certain environments, physiological reactions correlate with the user's sense of presence (Meehan, 2000; Meehan, 2001). To study presence, Meehan used a VE which consisted of two rooms separated by a door: a Training Room and a Pit Room. The Training Room contained regular living room furniture, tables on either side of the room, a painting, and a window with curtains. The window showed an outside view and the curtains moved as if in a gentle breeze. The Pit Room was furnished as well but contained a six-meter drop surrounded by a two-foot-wide ledge. That pit environment was used in this experiment (Figure 3.1).

Figure 3.1: The virtual environment used in the Pit Experiment.

Meehan used the differences between the participants' baseline physiological readings, captured during their time in the Training Room, and their physiological reactions to seeing the pit (a stress reaction) as the basis for his presence measurement. He was able to alter the environment in several different ways in order to investigate how certain changes affected participants' responses. If there were no physiological changes when viewing the pit, Meehan surmised that the participants were not convinced at all that they were high above the floor or in possible danger. Therefore, he argued, they were not "present" in the environment since they did not react to it. On the other hand, if there was a significant increase in heart rate upon seeing the pit, Meehan concluded that the scenario the participants were experiencing was compelling.

The original idea for the Pit Room came from a UK virtual environment researcher, Mel Slater, who derived the idea from the visual cliff experiments of Eleanor Gibson in 1960 (Gibson, 1960; Slater, 1995b). The pit environment offers several different parameters that can be altered. As discussed in Chapter 2, Meehan chose to measure the reaction of participants: 1) under repeated exposures, 2) with or without a real 1.5 inch wooden ledge on the floor surrounding the pit, and 3) drawing the environment at different frame rates. Using physiological measurements in conjunction with presence questionnaires, he was able to show significant differences in the users' reactions under some of the conditions.

Another component of the Pit Experiment involved the use of a spatial task of dropping objects onto targets on the Pit Room floor. Hu (2001) investigated the cues for imminent object contact in an environment with realistic shadows and reflections. The ability of the user to judge spatial relationships was enhanced with more sophisticated (and more accurate) lighting scenarios. Slater (1995a) found that shadow cues did not significantly improve targeting accuracy but did improve target contact determination. There is little relevant research that has been published about the use of virtual environments for a dropping task such as the one proposed here. We anticipated that a visually rich environment would help participants more accurately judge their position in the VE and hit the target. On the other hand, we understood that a more realistic pit environment (where the task was performed) could induce more stress on the users which might hinder their ability to hit the target.

Depth estimation was also examined in the Pit Experiment. Kline and Witmer (1996) showed that the use of texture detail enhanced the ability of a person to judge distances for areas up to six feet away. Jaeger (1998) performed studies on texture cues and distance estimation in virtual environments. He found that even simple texture cues improved the participant's ability to estimate distances. Considerable information on shadow and texture perception also exists in the psychology literature which supports the use of multiple cues to help participants correctly judge spatial relationships such as relative depth (Hoffman, 1998; Gregory, 1997).

The final aspect of the study built on the Pit Room's potential to induce stress. Research has shown that a person's ability to recall information is degraded when subjected to stress (Myers, 1998; Revelle & Loftus, 1990; Williams, 1994). This experiment utilized that fact by testing the participant's ability to recall objects that furnish the Training Room and the Pit Room. This complements the spatial task by testing a cognitive activity.

3.3 Conditions

This experiment extended the research of Meehan by using physiological measurements while the participants were shown the VE in different rendering styles in the head-mounted display. Except for the conditions manipulated, the virtual environment in this user study is the same as Meehan's original scene with the physical ledge.

Figure 3.2: The Pit Room rendered with low-quality lighting and low resolution textures**.**

Figure 3.3: The Pit Room rendered with high-quality lighting and high resolution textures.

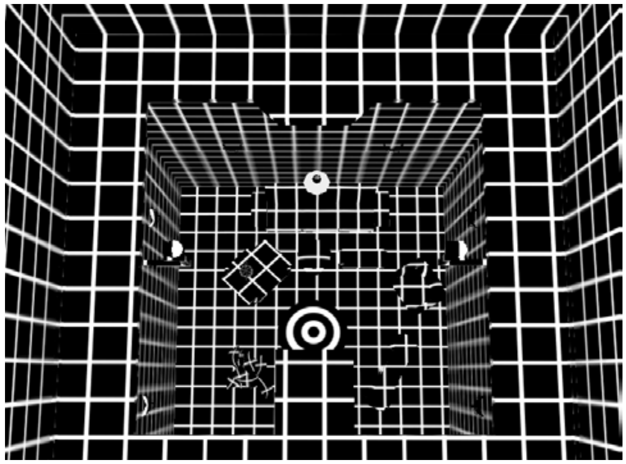


Figure 3.4: The Pit Room rendered with a one-square-foot, black and white grid texture.

Condition	Description
1	Low-Quality Lighting, Low Texture Resolution
2	Low-Quality Lighting, High Texture Resolution
3	High-Quality Lighting, Low Texture Resolution
4	High-Quality Lighting, High Texture Resolution
5	Grid

Table 3.1: Description of the five different rendering conditions.

The environment was drawn with one of five rendering conditions (Figures 3.2-3.4 and Table 3.1), and the rendering to which each participant was exposed was selected according to a balanced Latin Square design. The environment was rendered with either high or low texture resolution and either high or low lighting quality. In the fifth drawing method, the environment was rendered with a one-square-foot grid texture in black and white applied to all objects. Low-quality lighting is defined as the base textures for the various objects in the room without any lighting computations applied. Rooms were equally bright with no shadows or variations in illumination (ambient illumination). High-quality lighting was computed with a commercial radiosity package. High-quality textures were usually 1024x1024 pixels for large objects such as the Training Room walls and 512x512 pixels for objects such as the table tops. The lower resolution textures were 1/8th the size of the higher resolution textures (e.g., 128x128 pixels for the walls).

Conditions 1 through 4 demonstrate progressive increases in rendering quality which capture more of the visual effects and detail that would be seen in the real world. Condition 5, the grid condition, has the lowest rendering quality of all the conditions.

3.4 Hypotheses

Measured differences in physiological reactions, targeting accuracy, memory performance, simulator sickness scores, and presence questionnaire scores were recorded for each participant.

The hypotheses that were tested in this experiment were:

1) *increased rendering quality results in higher reported presence and physiological response*,
2) *increases in lighting quality are more significant than increases in texture resolution*,
3) *hitting targets on the bottom of the Pit Room shows lower accuracy with lower rendering quality*,
4) *object recall is worse in the Pit Room than in the Training Room for all conditions*, and
5) *the reported depth of the Pit Room is more accurate with increased rendering quality*.

3.5 Method

3.5.1 Participants

This study used 55 participants (25 M, 30 F) recruited from a University of North Carolina, Chapel Hill psychology class. The age range was between 18 and 23 years with a mean age of 19.18 years. Participants were required to have stereo vision, normal or corrected 20/20 vision, no prior experience with virtual reality, no precluding medical conditions, and no significant phobia of heights. Participants were also required to be right-handed so they could use the virtual hand required for task performance. Students were given one hour of class credit for taking part in the study and did not receive monetary remuneration.

3.5.2 Materials

3.5.2.1 Apparatus

This experiment used a Virtual Research V8 head-mounted display. The V8 has a resolution of 640x480 color pixels for each eye and has a 60° diagonal total field of view. A 3rdTech HiBall optical tracking system reported the position and orientation of the participant's head and hand during the experiment. The participant's "hand" in the virtual environment was controlled using a tracked joystick with a trigger. The participant pressed the trigger to pick up an object and released the trigger to drop an object. The virtual environment model contained approximately 30,000 polygons and utilized 70 megabytes of texture memory. The low texture resolution conditions used $1/8^{th}$ the amount of texture memory as the high texture resolution conditions. Drawing was done using an ATI Radeon 8500 with dual monitor outputs (ATI, 2002). Lighting computations applied to the VE were done using the commercial radiosity calculation package, Lightscape, and took 20 hours to distribute 99% of the light on a 700 MHz PC (Autodesk, 2001).

A mock-up of the tables and walls were constructed out of Reddiform Styrofoam blocks so that participants could touch real objects while in the virtual environment. In the Pit Room, there was also a 1.5 inch wooden plank aligned with the virtual ledge so that users could put their foot out and sense

Figure 3.5: A picture of the laboratory space with a participant (originally from Usoh et al., 1999).

a drop off in height. Figure 3.5, reproduced from Usoh et al. (1999), shows the laboratory configuration.

Physiological measurements were taken with a ProComp+ device by Thought Technology, Inc. worn on a backpack (Thought Technology, Ltd., 2001). Heart rate and skin conductance sensors were used for the experiment.

3.5.2.2 Questionnaires

After signing a consent form, the participant completed a number of questionnaires before and after his exposure to the virtual environment. The questionnaires included a Participant Health Questionnaire, the Height Anxiety Questionnaire, the Height Avoidance Questionnaire, the Virtual Environment Questionnaire, the Simulator Sickness Questionnaire, and the Guilford-Zimmerman Aptitude Survey Part 5 – Spatial Orientation. These questionnaires are reproduced in Appendix D.

Since this study intended to extend results established by Meehan's research, it had to use the same measures he did. These include the Height Anxiety, Height Avoidance, Simulator Sickness, Virtual Environment, and Participant Health Questionnaires. The validity of the questionnaires has been established by previous researchers in psychological studies and virtual reality experiments (Cohen, 1977; Kennedy et al., 1993; Slater and Steed, 2000).

The Participant Health Questionnaire is a two-question, general health measure. It determines if the participant is well enough to proceed with the experiment. If the subject reports a lack of well-being, he is excused from the rest of the experiment.

The Height Anxiety and Height Avoidance Questionnaires are a general assessment of the anxiety that may be induced by the Pit Room in the VE. Each questionnaire consists of 20 questions that require a response on an anxiety scale of either 0 to 2 or 0 to 6 (Cohen, 1977).

The Virtual Environment Questionnaire was originally developed by Slater and has been used in previous studies by Usoh (1999) and Arthur

(1999). It assesses a person's subjective sense of presence while interacting with a virtual environment. The questionnaire consists of twenty questions requiring a response on a scale from 1 to 7. It also requests general comments. This questionnaire was modified for this study by adding two questions. One asks the participant to recall objects in the Training Room and Pit Room. The other asks the participant to estimate the pit depth.

Sometimes participants feel nauseous while navigating in a virtual environment. The Kennedy-Lane Simulator Sickness Questionnaire assesses general discomfort experienced during the experiment. It consists of 17 multiple-choice questions, with a supplementary sheet containing definitions for some of the terms used in the questionnaire (Kennedy et al., 1993). The Simulator Sickness Questionnaire was administered before and after the exposure to the virtual environment.

The Guilford-Zimmerman Aptitude Survey Part 5 – Spatial Orientation was administered before exposure to the virtual environment to gauge the participant's spatial ability. It consists of 59 questions and has a ten minute time limit. Each question shows two images from the bow of a boat on a lake with the horizon in the distance. The participant is asked to choose the direction of motion of the boat from a list of options (Guilford and Zimmerman, 1948).

At the close of the session, the participant took part in an oral interview that asked open-ended questions about his experience in the VE.

3.6 Procedure

Before exposure to the environment and after signing a consent form, the participant's interpupilary distance was measured. The participant then completed the following questionnaires: a Participant Health Questionnaire, the Kennedy-Lane Simulator Sickness Questionnaire, the Cohen Height Anxiety Questionnaire, the Cohen Height Avoidance Questionnaire, and the Guilford-Zimmerman Aptitude Survey Part 5 – Spatial Orientation.

After completing the questionnaires, the participant was led into another room and shown the VR equipment. The VR application that the participant would experience was started in one of the five conditions described in Table 3.1. The participant was fitted with an HMD and physiological sensors and stood still for one minute "while the equipment was calibrated." During that time, a physiological baseline was taken. The participant then listened to a set of pre-recorded instructions in the Training Room. He was instructed to look around the Training Room, pick up a ball with his virtual hand, and drop the ball on a target in the corner of the room. After dropping the ball in the Training Room, he picked up another ball, and the door to the Pit Room opened. The participant carried the ball into the Pit Room and looked for a target at the bottom of the pit. After the participant dropped the first ball into the pit, he then picked up two other balls situated near the ledge of the pit and dropped them onto the same target at the bottom of the pit. Heart rate and skin conductance continued to be recorded while the participant was in the Pit Room.

After completing the task, the participant returned to the Training Room and waited for one minute. During that time, the participant’s heart rate and skin conductance were again recorded.

Once the measurements were taken, the participant filled out two more questionnaires. The Kennedy-Lane Simulator Sickness Questionnaire and the Slater, Usoh, Steed Presence Questionnaire (Slater et al., 1994; Usoh, 1999). Finally, an oral interview was conducted to obtain further comments on the environment and the participant’s experience. The participant received one hour of experimental class credit for an Introduction to Psychology class. A more detailed outline of the experimental procedure is given in Appendix B.

3.7 Results

The following data were analyzed: changes in the participant's heart rate and skin conductance, targeting accuracy, reported accuracy of pit depth, object recall in the VE, and questionnaire scores.

Physiological Measures. Perhaps the most important variable in the experiment was the change in the participant’s heart rate from the Training Room to the Pit Room under different rendering conditions. Meehan found that the change in heart rate was the most reliable and sensitive measure of presence in all of his experiments (Meehan, 2001). In this experiment, heart-

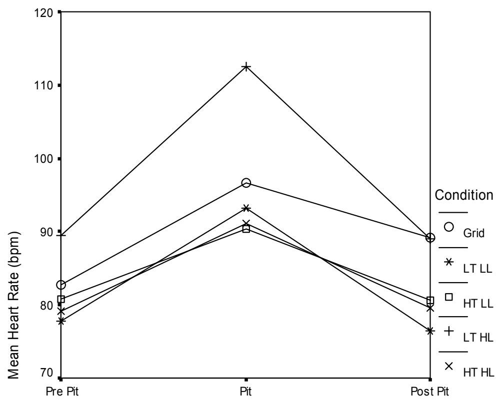


Figure 3.6: Heart rate data before, during, and after exposure to the Pit Room.

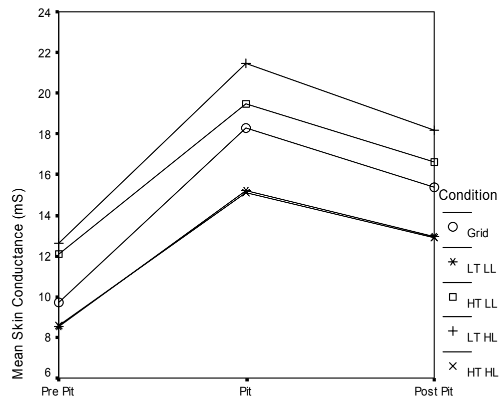


Figure 3.7: Skin conductance data before, during, and after exposure to the Pit Room.

rate data were obtained from 42 of the 55 participants (18 M, 24 F). Equipment failure prevented the collection of heart-rate data from 13 participants.

Overall, there was a significant increase ($p < 0.001$) in heart rate from the Training Room to the Pit Room for both men and women under *all* conditions. The average participant's heart rate increased by 14.7 beats per minute (bpm) from 81.8 to 96.5 (Figure 3.6).

Women showed about twice the amount of heart rate increase as men (18.3 bpm vs. 10.2 bpm); but this difference was not statistically significant ($p < 0.063$). There was no significant difference in heart rate between men and women before exposure to the pit (80 bpm vs. 83 bpm respectively).

When heart rate increases for the five rendering conditions were compared (either directly or as percent increases), no significant differences were found.

In terms of *absolute* heart rate in the Pit Room, there were some significant findings. Men's and women's heart rates were significantly different (90.2 bpm vs. 101.3 bpm with $p < 0.007$). The low texture resolution, high-quality lighting condition (condition 3) was significantly different ($p < 0.002$) from the other conditions and had the highest mean Pit-Room heart rate of 112.55 bpm. Grouping the conditions by lighting quality and texture resolution also produced significant differences. High-quality lighting had a significantly higher Pit-Room heart rate than low-quality lighting ($p < 0.046$). Texture resolution had the opposite effect. High quality texture resolution yielded a lower Pit-Room heart rate than low texture resolution ($p < 0.012$).

Skin conductance data for 53 participants (24M, 29F) tended to follow the heart rate data. Skin conductance showed a significant increase from the Training Room to the Pit Room ($p < 0.001$) as seen in Figure 3.7. However, the measure was not able to show differences by rendering condition or gender. In terms of values for skin conductance in the Pit Room, there was a trend ($p < 0.072$), such that men had a higher skin conductance score than women.

Task Performance. Spatial task performance was evaluated by having participants drop balls onto bull's-eye targets in both the Training Room and the Pit Room. A practice session was conducted in the Training Room to allow participants to become familiar with how the equipment worked in picking up and dropping a ball. After the practice session, participants picked up a ball in the Training Room and proceeded to the Pit Room where they dropped the ball on a target on the Pit Room floor, 6 meters below. Once in the Pit Room, they then located, picked up, and dropped two other balls onto the Pit Room target. They then returned to the Training Room and physiological measurements were again taken.

The accuracy of the ball dropping in the Pit Room was based on the distance the ball landed from the center of the target. If a ball landed in the center of the target, the participant scored zero. If the ball landed 0.3 meters from the center of the target, the score was 0.3 and so on. The scores for the three ball drops were summed to calculate a final accuracy score. Overall, men scored significantly higher than women ($p < 0.026$). Of the 25 men who participated, two were highly inaccurate (>95% from the mean) in two out of three drops. Of the 30 females who participated, four dropped all three balls off target (>95% from the mean) and 10 dropped at least one ball off target. Also, there was significant correlation between the accuracy of each successive ball drop. For example, the error in the score for the first ball significantly correlated ($p < 0.001$, r=0.48) with the error for the second ball. The error in the second ball correlated significantly ($p < 0.001$, r=0.57) with the error in the last ball. In other words, participants showed high internal consistency in their performances (accurate or inaccurate). There was a significant correlation between the absolute heart rate in the Pit Room and the participant's error in dropping the first ball for both genders ($p < 0.018$, r=0.364). The higher the heart rate, the less accurate the participant was in dropping the first ball. The rendering conditions did not significantly affect targeting accuracy ($p < 0.453$).

Depth Estimation. Participants were asked to estimate the depth of the pit in feet after their exposure to the Pit Room. The average estimated depth was significantly different from the true depth. The average estimate was 15.66 feet versus the true depth of 19.68 feet ($p < 0.001$). The perception of depth did not vary significantly between men and women or among rendering conditions.

Memory. Participants were asked to recall objects seen in the Training Room and in the Pit Room. Overall, participants remembered 46% of the 10 scored objects in the Training Room, while they remembered only 26% of the 8 scored objects in the Pit Room ($p < 0.001$). There was no significant difference between men and women or between rendering conditions. However, there was a significant ($p < 0.026$) difference between the total number of objects remembered in the grid condition versus all other conditions taken as a group. Participants remembered less in the grid condition than in the other conditions. Participants, on average, recalled more objects in higher texture resolution conditions; but this increase was not significant ($p < 0.391$).

Questionnaires. Simulator Sickness Questionnaire scores were generally higher after exposure to the virtual environment, but the increase was not significant. Men showed a slight decrease in sickness, 0.6 points, while women showed an increase of 8.1 points ($p < 0.067$). There were no significant differences by rendering condition. The average Simulator Sickness score after exposure to the virtual environment was 17 (out of a possible score of 235).

Height Anxiety and Height Avoidance Questionnaires showed no significant differences between men and women or by rendering condition. The test scores did not correlate significantly with the increase in heart rate or skin conductance.

The Guilford-Zimmerman Spatial Orientation Test showed no significant correlation to the ball-dropping scores according to rendering condition or with lighting and texture grouped together. Men performed significantly better on the Spatial Orientation Test than women ($p < 0.047$). The test score also correlated significantly with the error in dropping the first and second balls in the Pit Room ($p < 0.05$, r=-0.27; $p < 0.03$, r=-0.31 respectively).

The Virtual Environment Questionnaire, which tests presence, showed no significant difference by rendering condition, gender or when lighting and texture were grouped together. Participants were also asked to write comments about the positive and negative aspects of the VE experience. Regarding the negative aspects, 39% mentioned equipment cables and 35% mentioned extraneous sounds in the lab. In terms of positive aspects of the VE, 37% mentioned being able to touch objects, 22% mentioned being able to look out of the virtual window in the Training Room, 15% mentioned the movement of the virtual curtains next to the window, and 11% mentioned the lighting of the environment.

Many participants commented in the oral debriefing that the window and seeing a picture of a world outside the room were positive features of the environment. In addition, the movement of the curtains on the window was another element that participants mentioned specifically when discussing their experience. Participants often commented on the startling effect of the pit.

3.8 Discussion

A surprising result was that all conditions, including the grid condition, produced similar increases in physiological response implying that presence was experienced in all conditions even in the minimalist rendering of the environment. This result is contrary to many theories of presence, which suggest that a higher level of rendering quality should induce a higher state of presence (Lombard and Ditton, 1997; Sheridan, 1996; Steuer, 1992; Zeltzer, 1992).

Spatial task performance, as measured by the accuracy of dropping three balls onto a target in the Pit Room, did not vary by rendering condition but did vary by gender. Significant differences in spatial ability were found between male and female participants. Females also tended to score lower on the Guilford-Zimmerman Spatial Orientation Test. In view of the fact that females had a larger increase in heart rate and Simulator Sickness scores, one could hypothesize that anxiety and ocular discomfort could have been factors affecting task performance. Both men and women significantly underestimated the depth of the pit.

Object recall showed a significant difference between the Pit and Training Rooms under all conditions, with recollection being greater in the low-stress Training Room than in the high-stress Pit Room. Participants in the grid condition recalled a significantly lower *total* number of objects compared to participants in all other conditions combined.

Heart rates did increase between the Training Room and the Pit Room under all conditions. *Absolute* heart rate in the Pit Room varied significantly among conditions with the low texture resolution, high-quality lighting condition producing the highest Pit Room heart rate. Based on the *increase* in heart rate, it would appear that the Pit Room generated a response in the participants that overshadowed the influence of the rendering conditions of the virtual environment. Very minimal visual cues, as demonstrated in the grid environment, were capable of arousing strong physical and emotional reactions.

The results of this study suggest that lighting and texture differences were masked by the sense of personal danger experienced by participants in the experimental environment. Once the participant observed the proper cues to perceive a drop in distance, the sense of personal danger took over his perception of the environment. In the grid condition, the kinetic depth effect was enhanced by the high contrast texture and may be the essential cue for providing the sense of depth to the participants. In the post-exposure oral interview, nearly 60% of the participants described a sense of fear engendered by the Pit Room.

Chapter 4

Experiment 2: The Gallery Experiment

4.1 Introduction

The purpose of the Gallery Experiment was to investigate the effect of lighting quality, lighting position, and lighting intensity on user behavior and presence in a non-stressful virtual environment. In particular, this experiment investigated whether manipulating the lighting configuration on objects in a virtual environment could influence participant behavior, altering patterns of attention, movement, and reported sense of presence. The participant's response to the environment was measured by behavioral metrics and questionnaires. As in the Pit Experiment, this study used a head-mounted display which was tracked over a large area.

The Gallery Experiment utilized a non-stressful, art gallery environment in which specific objects were highlighted in different areas of the gallery. The time participants spent looking at the highlighted objects was recorded and analyzed using attention maps. The length of time the participant occupied specific areas of the gallery was also examined.

4.2 Background

Studies have shown that human behavior and attentiveness in a real environment can be affected by different lighting configurations. For example, Taylor and Sucov (1974) found that when subjects are given a choice, brighter paths are chosen more often when entering rooms. Flynn (1973) found that seat selection in a restaurant setting changed in accordance with changes in the lighting configuration. Participants consistently oriented themselves to face the lighted areas (walls, stairways) of the room. Inspired by Flynn's "light cue theory," Yorks and Ginthner (1987) found that wall lighting can influence seat selection as well as room impression. In particular, participants preferred to sit with a lighted wall directly in front of them. Yorks and Ginthner offered evidence that lighting configurations "appear to affect user attention, direction of focus, movement, retention of visual detail, and social interaction." In their paper, "Brightness Patterns Influence Attention Spans" (1973), LaGiusa and Perney demonstrated that attention acquisition and attention duration increased for fifth-grade students when learning aids were highlighted with track lighting. Students who were exposed to the experimental classroom lighting also performed better on a memory recall exercise. Philips Lighting Company's Retail Lighting Application Guide (1991) recommends lighting as a tool for attracting people and holding their attention. Philips further advocates the use of lighting to help establish circulation patterns and create visual interest in product displays. Taylor, Sucov, and Shaffer (1973) investigated display lighting preferences and found that increases in lighting intensity served to increase the attraction of attention.

4.2.1 Attention and Presence

Witmer and Singer (1998) propose the use of attention as a basis for the theoretical development of a presence metric. They describe attention as a "necessary condition" to achieve presence. Witmer and Singer argue that "as users focus more attention on the VE stimuli [as opposed to the real world], they become more involved in the VE experience, which leads to an increased sense of presence in the VE." Attending to a consistent set of stimuli in the virtual environment further reinforces the sense of being part of the VE while simultaneously discounting the effect of the real world. Witmer and Singer theorize that there is an attentional threshold where increased allocation of attentional resources toward the virtual environment begins to increase the sense of presence.

Darken (1999) postulated that presence can be measured more effectively if broken down into measurable components. He explored the use of attention and spatial comprehension as possible metrics for presence. Darken had 70 subjects perform a divided-attention task and measured their level of engagement between the real and virtual worlds by means of a presence questionnaire as well as by a quiz based on the content they observed during their trials. He concluded that "our results clearly support the use of attention as at least a partial measure of presence."

4.2.2 Lighting and Presence

Mania (2001) conducted a study involving 105 participants which examined lighting impressions and the sense of presence in five different tracking and display conditions. The same environment was viewed in all displays and was either real or simulated using a global illumination system. The participant filled out a lighting impression questionnaire and the UCL/SUS presence questionnaire at the end of the trial. Mania found that the lighting impression questionnaire scores recorded for the real and simulated environments were not significantly different. The presence questionnaire scores were also not significantly different among viewing conditions. However, in the head-tracked, monocular, head-mounted display condition, she found that there was a significant negative correlation between lighting scores and presence scores.

4.2.3 Lighting Experiment

The Gallery Experiment studied the participant's reported sense of presence using questionnaires and behavioral aspects of attention using viewing time toward specific lighted elements in the virtual environment. We postulate that since real-world lighting has been shown to increase a participant's attention toward areas of an environment, and since attention has been linked to presence in a VE, virtual lighting should enhance the participants' sense of presence by selectively focusing their attention on objects within the virtual environment.

4.3 Attention Mapping

In the Pit Experiment, the influence of lighting quality in a *stressful* pit environment was studied. We decided, in this experiment, to examine the influence of lighting configurations in a *non-stressful* art gallery environment. Due to the neutrality of the gallery environment, we anticipated that the physiological measurements of the participants would not fluctuate significantly and, therefore, developed another objective method of measuring participant response to the VE.

This study used a novel form of behavioral measurement called *attention mapping*. An attention map is a record of the accumulated times a participant spends looking at various parts of the virtual environment (in three dimensions) during his exposure. An attention map is derived from readings taken from the tracker on the user's head during his immersion in the virtual environment. In this study, attention mapping assumes that eyes are oriented so that they are predominantly looking at the center of the view field in the HMD.

4.3.1 Attention Mapping Background

Previous work in psychology on mapping attention has focused on controlling the stimuli or measuring eye movements in response to stimuli. Schyns et al. (2002) examined facial recognition by displaying partial facial images to participants. They then recorded how successful participants were at categorizing the faces according to different criteria (such as labeling faces male or female). By superimposing the areas exposed, weighted by the success rate of categorization, Schyns et al. were able to produce a map of probabilities that indicated what portions of the face were most likely associated with specific categorization tasks.

Wooding (2002) described an experiment where an eye tracker was left running in the National Gallery of London as part of a millennium exhibition. Eye tracking information was recorded over three months for 5,638 participants who viewed digitized images of paintings in a room at the gallery. To analyze the data, Wooding placed a Gaussian blob (with a fixed height) at each fixation point on an image. He created a height map by accumulating thousands of these fixations. The height maps were then used to discuss the areas of interest and total viewing coverage in different paintings used in the study.

Although Schyns's and Wooding's methods are useful for capturing information about two-dimensional images, the attention mapping used in this study allows for the collection of data as a person walks freely about a three-dimensional environment.

In the virtual reality literature, Dijkstra and Duchowski discuss methods of collecting three-dimensional viewing information from users as they experience an environment.

Dijkstra et al. (1998) discuss the potential of using eye-tracking equipment in making design decisions in virtual environments. Specifically, Dijkstra et al. considered applying eye tracking and virtual reality to streamline the architectural design process. Although they outlined a system using a projector, eye-tracker, and three-dimensional mouse, they did not implement a functional system.

Duchowski et al. (2002) presented an eye-tracking system integrated into a Virtual Research V8 HMD. They describe the difficulties in using the eye-tracking system and coordinating eye-tracking data with head-tracking data (e.g., detecting fixations and calibrating the eye tracker within the HMD). Duchowski et al. applied their system to the task of visual inspection of cargo containers. After the data were collected, they were able to determine if participants viewed the proper inspection points.

Dijkstra et al. and Duchowski et al. did not, for their purposes, need to measure relative viewing times as is done in attention mapping.

4.3.2 Construction of an Attention Map

Attention mapping is similar in concept to a painting system with the user's gaze acting as the brush. Attention mapping permits unrestrained viewing while accumulating observation times.

Figure 4.1: VE from user's point of view (left) and the attention-mapped environment (right). Brighter grays indicate longer viewing times.

Once the user is fitted with an HMD, head-movement data are collected as the user walks about the virtual environment. These data include head position and orientation along with a time-stamp. The time-stamp records the precise moment that the position and orientation data were gathered in a log file.

To analyze the data, the log file is replayed producing a series of images that coincide with the user's original viewing path. Each pixel of each image is analyzed to discover what particular surface elements of the visible objects are in view at any particular moment. By analyzing all the pixels, accumulated viewing times are collected for each object over the participant's entire trial and stored in separate data arrays. Figure 4.1 shows the original environment and the attention-mapped environment.

A more complete explanation of attention mapping is given in Appendix A.

4.4 Conditions

The virtual environment used in this experiment was a gallery setting composed of two rooms (a Training Room and a Gallery Room) separated by a door (Figure 4.2).

Figure 4.2: Top-down and perspective views of the gallery environment. In the top-down view, the Training Room is on the left; and the Gallery Room is on the right.

In both the Training Room and the Gallery Room, paintings and assorted vases set on pedestals were displayed. The paintings were similar in theme (floral) and character without being identical. Likewise, the vases were compatible, being similar in shape and texture. In the Training Room, a painting and vase on opposite sides of the room were highlighted at a 2:1 (low) contrast ratio. In this study, low-contrast-ratio means that the object is highlighted with twice as much light as the ambient illumination in the environment. The lighting configuration in the Training Room remained the same throughout all conditions of the experiment.

One of five different lighting conditions was presented in the Gallery Room for each trial. There were five trials in total for each participant. In the Gallery Room, a painting and a vase on opposite sides of the room were highlighted at 2:1 (low) or 7:1 (high) contrast ratios. The Gallery Room was also presented under uniform lighting with no highlights on any of the objects.

To summarize, each of the participants experienced all of the five gallery conditions listed below:

1) low-contrast ratio, painting on left and vase on right highlighted (low-contrast PLVR);
2) low-contrast ratio, painting on right and vase on left highlighted (low-contrast PRVL);
3) high-contrast ratio, painting on left and vase on right highlighted (high-contrast PLVR);
4) high-contrast ratio, painting on right and vase on left highlighted (high-contrast PRVL); and
5) uniform lighting (no objects highlighted).

Each participant experienced the five conditions in a series of five trials according to a balanced Latin square order. In addition, there were two different levels of lighting quality explored in this experiment as a between-subjects factor. The environment was lit with either the global illumination model or the local illumination model for all the trials of a participant.

4.5 Hypotheses

This study investigated whether manipulating the lighting configuration on objects in a virtual environment can influence participant behavior by altering patterns of attention, movement, sense of presence, and subjective impressions of lighting.

The hypotheses that were tested in this experiment were:

1) *Increasing the lighting emphasis on objects in a virtual environment will increase the participant's attentiveness toward those objects as confirmed by patterns of attention and movement;* and
2) *Higher contrast lighting configurations of the environment will evoke a higher lighting impression score and a stronger sense of presence as measured by questionnaires and observed behaviors corresponding to the real world.*

4.6 Method

4.6.1 Participants

This study involved 63 college-aged students (33 M, 30 F) recruited from a University of North Carolina, Chapel Hill psychology class and from the Computer Science Department. Participants were required to have stereo vision, normal or corrected to normal 20/20 vision, no precluding medical conditions, and no prior experience with virtual reality. Participants were given one hour of class credit or $10 for taking part in the study.

4.6.2 Materials

4.6.2.1 Apparatus

As in the Pit Experiment, this study used a Virtual Research V8 head-mounted display and a 3rdTech HiBall optical tracking system to report the user's head position and orientation during the experiment. The virtual environment consisted of 19,412 polygons with 29 megabytes of textures. The frame rate was held constant at 60 frames per second. Drawing was done using an nVidia Ti4600 video card with dual monitor outputs on a 1.8Ghz Dell Precision Workstation (nVidia, 2002). Global illumination computations applied to the VE were done using 3D Studio Max and took 10 hours per condition on a 2.8 Ghz PC.

Lighting values for the locally illuminated version of the virtual environment were generated using six independent observers. Each observer adjusted local illumination lighting values to match the globally illuminated version of the virtual environment. The application allowed the observer to adjust two values in both the Training Room and Gallery Room. The first value was a multiplier for the lights, and the second value was an ambient light setting. Using a multiplier instead of setting each light independently preserved the ratio of the lights while allowing changes in overall brightness. The application displayed the globally illuminated version of the environment in one window and the locally illuminated version of the environment in another. Observers adjusted parameters until the globally and locally illuminated versions of the environment corresponded with each other. The light values from all the observers were consistent, and the final values were calculated by averaging the settings from all the observers.

In addition to adjusting light values within the application, the light output from the head-mounted display also needed to be calibrated between the locally and globally illuminated versions of the virtual environment. HMD output calibration was done using a Lutron LX-200 light meter. Light meter readings from inside the head-mounted display were taken at five different places in the gallery environment. The brightness of the HMD was then adjusted in the locally illuminated version of the gallery to minimize the difference in HMD output readings between the two environments.

Figure 4.3: A student examining a virtual piece of art in the Gallery Room.

A styrofoam mockup of the table in the Training Room and of the dividers and walls in the virtual environment was constructed out of Reddiform styrofoam blocks (Figure 4.3). This prevented participants from seeing the rest of the graphics laboratory. Once the trial began, it also prevented participants from walking through the virtual walls defining the Training Room and Gallery Room. The styrofoam walls reduced incidental sounds from the graphics laboratory and prevented extraneous light sources from distracting users in the head-mounted display.

4.6.2.2 Questionnaires

The participant completed a Participant Health Questionnaire, Demographics Questionnaire, and Simulator Sickness Questionnaire before the first trial. Questionnaires that were administered after each successive trial included the: Simulator Sickness Questionnaire, Virtual Environment Questionnaire, Positive and Negative Affect Scales (PANAS) Questionnaire, and Lighting Impression Questionnaire. The questionnaires were administered on a computer via a web-based interface.

The Participant Health Questionnaire, Simulator Sickness Questionnaire and Virtual Environment Questionnaire were the same as the ones used in the Pit Experiment. See Chapter 3 for a description of these questionnaires and Appendix D for the complete texts of all the questionnaires.

A five-question Demographics Questionnaire was administered to gather information about the participant's age, gender, class year, computer use, computer gaming experience, and physical activity level.

The PANAS Questionnaire was developed by Watson et al. (1988) to help study the structure of affect. The PANAS is composed of two, 10-item mood scales that consist of positive and negative terms (for example, "enthusiastic" or "afraid"). The scales have been used in numerous studies in psychology and have been found to be highly internally consistent and reliable. The questionnaire was used in this study to investigate variations by condition or trial number as well as correlations with other questionnaires, particularly the Virtual Environment Questionnaire.

The Lighting Impression Questionnaire was originally developed by Flynn (1973). The questionnaire uses an Osgood-type semantic differential rating scale on fifteen pairs of words (for example, "warm" ... "cold"). The participant chooses between the pairs of words by selecting a number on a scale from 1 to 7. The numerical choice on the scale for that pair of words indicates which word more closely fits the participant's impression of the environment and how strongly. The questionnaire has been found to be useful in gauging subjective impressions of lighting in real environments and has been used in a virtual reality study as well (Mania, 2001).

4.7 Procedure

Upon arriving, the participant was seated at a desk in a room outside the graphics laboratory. After signing the consent form, the participant filled out two questionnaires via a web-based interface. A two-question, Participant Health Questionnaire was used to determine if the participant was well enough to complete the rest of the study or was under the influence of any medications. The Simulator Sickness Questionnaire was used to obtain a baseline value for sickness before experiencing the virtual environment. In addition, his interpupilary distance was measured with an Essilor digital corneal reflection pupilometer. This measurement enabled customization of the stereo settings for each participant.

After filling out the questionnaires, the participant was led into the graphics laboratory, which contained a styrofoam mockup representing the walls, dividers, and table in the virtual environment. The participant was then shown the VR equipment and the HMD was placed on his head, eliminating all views of the real world. A door-sized, cardboard divider between the Training Room and Gallery Room, which had concealed the real-world Gallery Room, was removed. Directions played through headphones on the HMD instructed the participant to walk around the Training Room. This familiarized the participant with moving while wearing the equipment. Additionally, he was instructed to direct his gaze toward objects using head movements instead of only ocular movements. After this training period, a virtual door opened from the Training Room into the Gallery Room. The participant had been previously told in the recorded instructions that he would have two minutes to explore the Gallery Room. After the two minutes were up, the participant heard instructions to return to the Training Room. The cardboard door was replaced between the Gallery Room and the Training Room before the HMD was taken off.

The participant was led back to the room outside the graphics lab and filled out a Simulator Sickness Questionnaire, a Virtual Environment Questionnaire, a PANAS Questionnaire, and a Lighting Impression Questionnaire. The PANAS Questionnaire was used to determine the participant's state of mind after experiencing the virtual environment (such as excited or threatened). After the questionnaires were completed, the participant returned to the graphics lab to experience the next lighting condition. Each time the participant would practice in the Training Room and then walk into the Gallery Room. Each participant experienced each condition one time for a total of five trials.

4.8 Results

The following data were analyzed: changes in attention and movement based on light position, intensity, and quality; questionnaire scores for Simulator Sickness, Presence, Lighting Impressions, and Affect; questionnaire score correlations; and gender differences in response to the questionnaires.

4.8.1 Attention Results

For the attention data, the objects that were highlighted in the Gallery Experiment were analyzed individually and in pairs. In the gallery

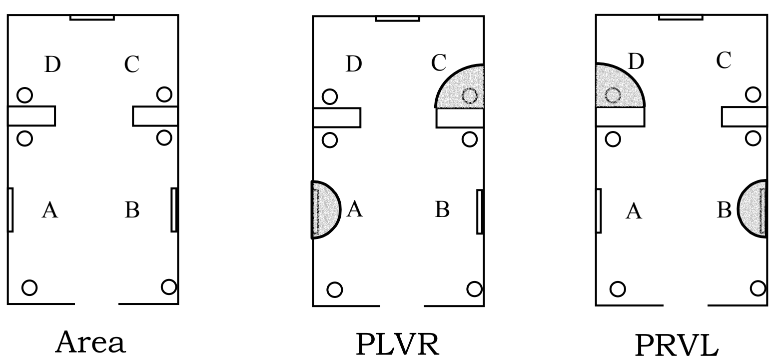


Figure 4.4: The three lighting positions (area; painting on the left, vase on the right (PLVR); painting on the right, vase on the left (PRVL)). Highlighted objects are in grey.

environment, paintings and vases were distributed throughout, on both the right and left sides. In the 2:1 and in the 7:1 lighting ratio conditions, two objects were highlighted in the gallery, a painting and a vase. In this experiment, when a painting on the left was highlighted, a vase on the right was highlighted in the same manner. Likewise, when a painting on the right was highlighted, a vase on the left was highlighted in the same manner. The participants' responses to these four objects (2 paintings and 2 vases) were analyzed individually and in pairs. Pairs of objects included the left and right paintings in the front of the gallery (A and B in Figure 4.4), the left and right vases in the rear of the gallery (C and D in Figure 4.4), and painting and vase pairs (A,C and B,D in Figure 4.4).

For both locally and globally illuminated virtual environments, attention varied with the contrast ratio of the lighting configuration. Where differences in viewing time were significant, the lighted object was always viewed for a longer period of time. Higher illumination ratios resulted in larger differences in viewing time.

Individual Objects. Viewing times for all four objects, individually, varied significantly by condition ($p < 0.001$ for each object). For example, the left painting viewing time was significantly higher under 7:1 ratio lighting than under area lighting which had a 1:1 contrast ratio ($p < 0.001$). A 7:1 ratio produced significant increases in viewing times for each object, regardless of position, compared to its viewing time under the area lighting condition ($p < 0.005$). A 2:1 contrast ratio, however, was insufficient to cause significant changes in viewing time for any of the individual objects compared to the area lighting condition. There were no significant differences in viewing time for individual objects based on the trial number.

Pairs of Objects. Pairs of objects were analyzed using a paired-samples t-test. If two objects differ significantly in viewing time, the difference will be significantly greater or less than zero. Three paired variables were examined: the viewing times for the left and right painting (A and B in Figure 4.4), the viewing times for the left and right vase (D and C in Figure 4.4), and viewing times for the left painting and right vase versus the right painting and left vase (A,C vs. B,D). In all tests that showed significant differences, the lighting altered the difference in viewing time in favor of the lighted object. In area lighting which had a 1:1 contrast ratio, no significant differences were seen in the pairs. At a 2:1 contrast ratio, 4 of 6 paired-samples t-tests showed significant differences in viewing time with an average increase of 5.6 seconds (a 28% increase). At a 7:1 contrast ratio, all pairs of variables showed differences in viewing time with significant increases for lighted objects of 11.6 seconds (a 73% increase).

Absolute Values. We examined the absolute value of the differences in viewing times between pairs of objects, namely, paintings (|A-B|), vases (|C-D|), and diagonals (|(A+C)-(B+D)|). Each pair was examined with respect to increasing contrast ratios. Table 4.1 summarizes the differences in viewing times.

<table>
<tr><td></td><td></td><td colspan="3">Contrast Ratio</td></tr>
<tr><td></td><td></td><td>1:1</td><td>2:1</td><td>7:1</td></tr>
<tr><td rowspan="3">Pairs of Objects</td><td>Paintings |A-B|</td><td>7.8 s</td><td>9.1 s</td><td>13.8 s</td></tr>
<tr><td>Vases |C-D|</td><td>5.0 s</td><td>6.6 s</td><td>8.1 s</td></tr>
<tr><td>Diagonals |(A+C)-(B+D)|</td><td>9.2 s</td><td>12.4 s</td><td>19.6 s</td></tr>
</table>

Table 4.1: Absolute values of viewing time differences for pairs of objects.

Paintings, vases, and diagonals showed difference trends that failed to reach significance when comparing the 1:1 to 2:1 ratio ($p < 0.69$, 0.38, and 0.35 respectively). However, the paintings, vases, and diagonals showed significant differences when comparing the 1:1 ratio to the 7:1 ratio ($p < 0.001$, $p < 0.04$, and $p < 0.001$ respectively). The paintings and diagonals also showed significant differences when comparing the 2:1 and 7:1 ratios ($p < 0.001$ for each ratio). Plots for differences in viewing times based on contrast ratio are given in Figure 4.5.

Local vs. Global. Comparing local to global illumination based on lighting contrast or position did not reveal any significant differences. Global illumination induced only a 5.9% increase in viewing time differences between the highlighted pairs of objects examined in this analysis (A,C vs. B,D) ($p < 0.63$).

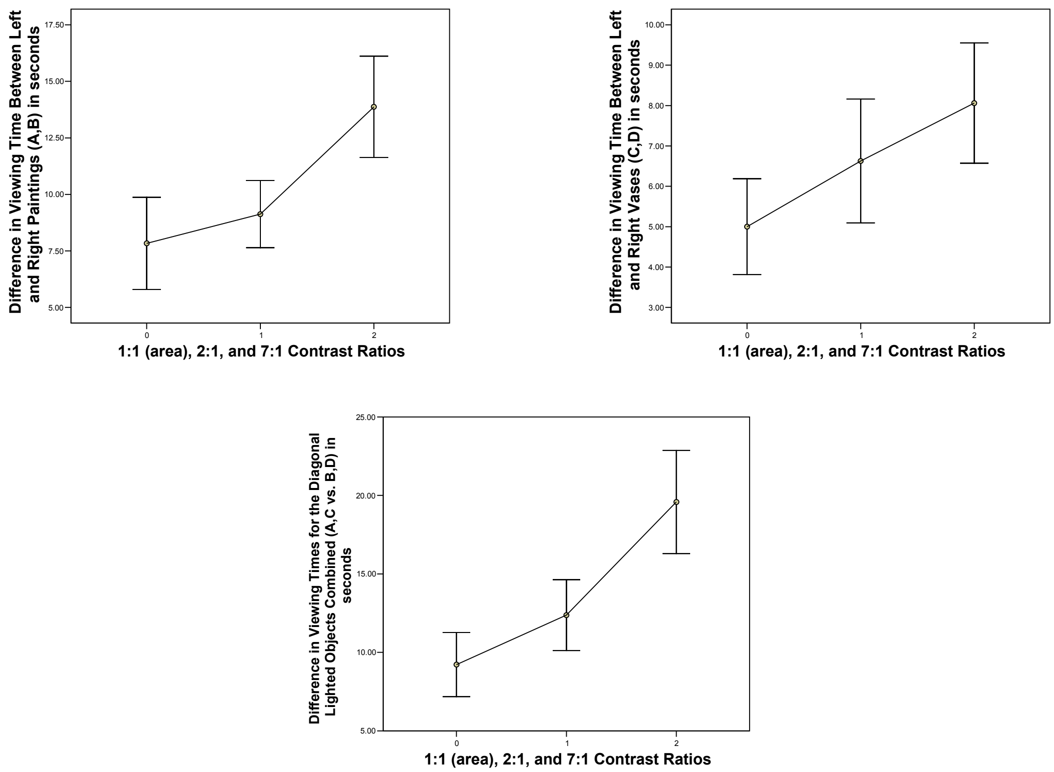


Figure 4.5: Plots for differences in viewing time between pairs of objects based on lighting contrast ratio.

One-Minute Analysis. To determine if trends in viewing time could be detected earlier, we analyzed only the first 60 seconds of the attention data. The data revealed results similar to the full attention data set but, overall, fewer tests reached significance. As in the full attention data set, individual objects showed significant differences based on condition and contrast ratio but not by trial number. For pairs of objects using a paired-samples t-test, 2 of 6 tests showed significance at a 2:1 ratio, whereas all six tests showed significance at a 7:1 ratio. None of the absolute values of differences of object pairs showed significance with increased contrast ratio for one minute, but all of them showed differences at two minutes. In summary, the one-minute analysis exposed viewing trends that were more fully developed after a two-minute exposure.

4.8.2 Movement Results

Movement in the virtual environment was analyzed by dividing the gallery into four quadrants as seen in Figure 4.6. The time spent in each quadrant during each trial was computed. The time data for the quadrants were analyzed for individual quadrants and for quadrants in pairs (1,2; 3,4; 1,3; 2,4).

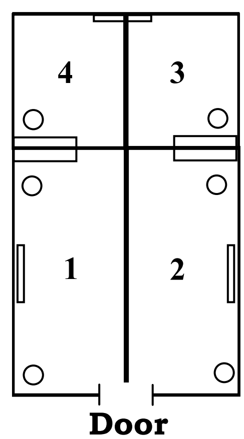


Figure 4.6: The quadrants used in analyzing movement in the Gallery Room.

Quadrants that contained highlighted objects were occupied for longer periods of time. Occupancy time for the front of the gallery (1,2) was always longer than for the rear (3,4). Higher illumination ratios resulted in more significant differences in occupancy times between pairs of quadrants. Global illumination did not differ significantly from local illumination in the 2:1 or 7:1 lighting ratios.

Individual Quadrants. In all cases where there was a significant increase in occupancy time, the quadrant contained a highlighted object. In all cases where there was a significant decrease in occupancy time, the quadrant did not contain a highlighted object. When the global and local illumination data were combined, ANOVAs for each of the four quadrants showed significant differences by condition. This means that the time a participant spent in a particular quadrant varied significantly between one or more of the different lighting conditions. The p-values for quadrants one through four are $p < 0.007$, $p < 0.004$, $p < 0.001$, and $p < 0.001$ respectively.

Pairs of Quadrants. The quadrants were organized into four groups: (1 vs. 2), (3 vs. 4), (1,2 vs. 3,4), and (1,3 vs. 2,4). The groups were then analyzed using a paired-samples t-test to determine if the difference in time spent in grouped quadrants was significantly greater or less than zero. Overall, the grouped quadrants in the front of the gallery (1,2) were occupied significantly longer than the grouped quadrants in back of the gallery (3,4) with $p < 0.001$. There are two factors that could have contributed to this difference: 1) participants entered the gallery from the front and 2) the front quadrants of the gallery were proportionally larger and contained more objects than the back of the gallery. At a 2:1 contrast ratio, 50% of the groups showed significant differences in time spent in them. At a 7:1 ratio, 88% of the groups showed a significant difference in the time spent in them. When there was a significant difference in time spent between groups of quadrants, quadrants that contained highlighted objects were always occupied for longer periods of time. The data are summarized in Table 4.2.

	1 vs. 2			3 vs. 4			1,2 vs. 3,4			1,3 vs. 2,4		
	P-value	Quad.	Extra Time (sec)	P-value	Quad.	Extra Time (sec)	P-value	Quad.	Extra Time (sec)	P-value	Quad.	Extra Time (sec)
Area (1)	0.32	1	3.55	0.35	3	1.74	**0.001**	**1,2**	**52**	0.2	1,3	5.28
PLVR 2:1 (2)	0.13	1	4.86	0.91	3	0.28	**0.001**	**1,2**	**39.9**	0.16	1,3	5.14
PLVR 7:1 (3)	**0.01**	**1**	**10.53**	**0.001**	**3**	**10.96**	**0.001**	**1,2**	**42.68**	**0.001**	**1,3**	**21.49**
PRVL 2:1 (4)	**0.03**	**2**	**8.45**	0.1	4	3.78	**0.001**	**1,2**	**47.03**	**0.01**	**2,4**	**12.23**
PRVL 7:1 (5)	0.27	2	4.13	**0.003**	**4**	**5.89**	**0.001**	**1,2**	**48.11**	**0.03**	**2,4**	**10.02**

Table 4.2: The amount of extra time spent in quadrants when grouped as pairs. Significant differences in occupancy time are in bold.

Local vs. Global. When comparing local illumination to global illumination, no significant differences were found in quadrant occupancy time except in the 1:1 contrast ratio condition. For the 1:1 contrast ratio condition, participants spent a significantly longer amount of time (3.4 seconds) in quadrant 4 in the local illumination condition than in the global illumination condition ($p < 0.04$). One possible explanation for the extra time could be due to the participant's turning around and deciding where to move next. When the environment was lit with either the 2:1 or 7:1 lighting configuration, there were no significant differences in time spent in each quadrant between the locally and globally illuminated versions of the environment. Global illumination induced a 7.7% increase in differences between the quadrants containing highlighted objects examined in this analysis (1,3 vs. 2,4). However, this difference did not prove to be significant ($p < 0.49$).

One-Minute Analysis. To understand fully how movement was influenced by lighting, we analyzed the first 60 seconds of the movement data. Overall, participants spent more time in the front quadrants of the gallery (1,2) than in the back quadrants of the gallery (3,4) in all conditions. Using the same groupings of quadrants as in the two minute movement data set, 37% of the groupings showed significant differences in the time spent in them at a 2:1 contrast ratio, while 63% of the grouping showed significant differences at the 7:1 contrast ratio. Again, all the differences demonstrated an increase in occupancy times for quadrants which contained highlighted items.

4.8.3 Questionnaire Results

There were four questionnaires administered after each trial of the experiment.

Simulator Sickness Scores. Combining the questionnaires from the local and global illumination conditions, the Simulator Sickness Questionnaire showed a significant increase from the pre-trial scores to the sickness questionnaire scores calculated after each trial (Figure 4.7). The

Simulator Sickness Questionnaire is composed of an overall score and three subscores (nausea, ocular discomfort, and disorientation). When the trial scores were compared to the pre-trial scores, they showed significant increases for the nausea, ocular discomfort, disorientation, and total sickness scores ($p < 0.001$ for all scores) with an average score increase of 152%.

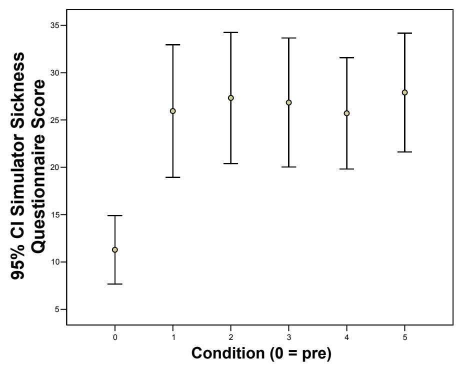


Figure 4.7: The total simulator sickness score by condition. Condition 0 is a pre-trial score.

Sickness scores also varied by trial and showed a trend toward higher sickness scores for later trials. Ocular discomfort showed significant increases from the first trial to the third, forth, and fifth trial. The total sickness score increased significantly from the first trial to the fourth and fifth trial. The highest average score was 35.1 for the fifth trial. However, this score is low, much below the maximum possible score of 235. No subjects were distressed enough to comment during the experiment.

There were no significant changes in sickness scores related to light position or contrast ratio. Sickness scores did not show any significant differences when the gallery was lit with local or global illumination.

Presence Scores. The SUS Presence Questionnaire was administered after each trial (five times in total). The Presence Questionnaire is composed of three subscores (Reported Presence, Behavioral Presence, and Ease of

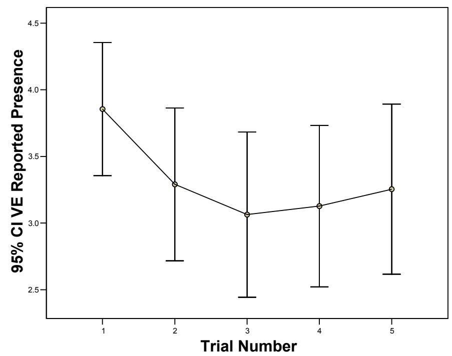


Figure 4.8: Reported Presence scores by trial number.

Locomotion). None of the Presence Questionnaire subscores varied significantly by condition or trial number. However, there was a trend in the presence data indicating that the participants were reporting lower presence scores for later trials (Figure 4.8).

The Ease of Locomotion score was significantly higher for the local illumination conditions as versus the global illumination conditions as a whole ($p < 0.04$). Further analysis showed that the significant differences in the Ease of Locomotion score occurred in the 1:1 contrast ratio condition but not in the 2:1 or 7:1 contrast ratio conditions.

Lighting Impression. The Lighting Impression Questionnaire varied significantly by condition. Participants reported significantly higher lighting impression scores for the 7:1 contrast ratio conditions (conditions 3 and 5) as versus the 2:1 (conditions 2 and 4) or 1:1 contrast ratio condition as seen in Figure 4.9.

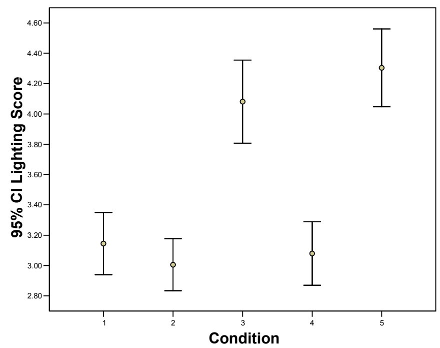


Figure 4.9: Lighting Impression Scores by condition. The high contrast conditions (3 and 5) had significantly higher scores than the low contrast conditions.

Of the available descriptive terms for lighting provided by the questionnaire, participants described the environment as significantly more "confined," "tense," "dim," "subduing," "non-uniform," "gloomy," "small," "dislike," "complex," "cold," "unpleasant," and "uncomfortable" for the 7:1 contrast ratio condition as versus the 2:1 or 1:1 conditions ($p < 0.001$ for all terms). The lighting questionnaire scores did not vary significantly between the global and local illumination conditions.

The Lighting Impression Questionnaire scores did vary significantly by trial (Figure 4.10). The first trial lighting scores were significantly lower (use of more positive descriptive terms) than the scores for the third or fourth trial. This may be due to the fact that the participant had not seen the other lighting conditions and therefore did not have a basis for comparison as in later trials.

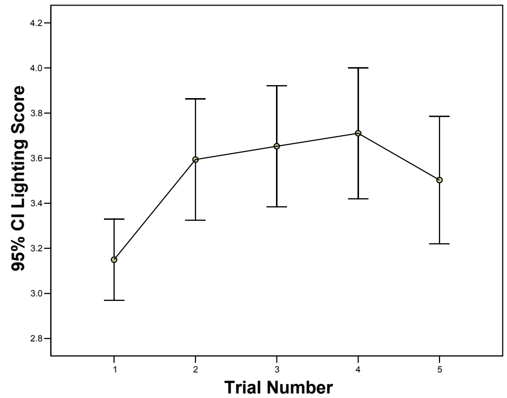


Figure 4.10: Lighting scores by trial.

PANAS Questionnaire. The PANAS questionnaire was administered after each of the five trials. The PANAS is composed of two scores, Positive Affect and Negative Affect. The Positive and Negative Affects scores did not vary significantly by condition. However, as seen in Figure 4.11, the Positive Affect Score did vary significantly by trial number ($p < 0.001$). Later trials had a significantly lower Positive Affect Score meaning that lower scores were given to positive terms towards the end of the experiment. The Negative Affect Score did not vary significantly by trial number, but had a similar downward trend.

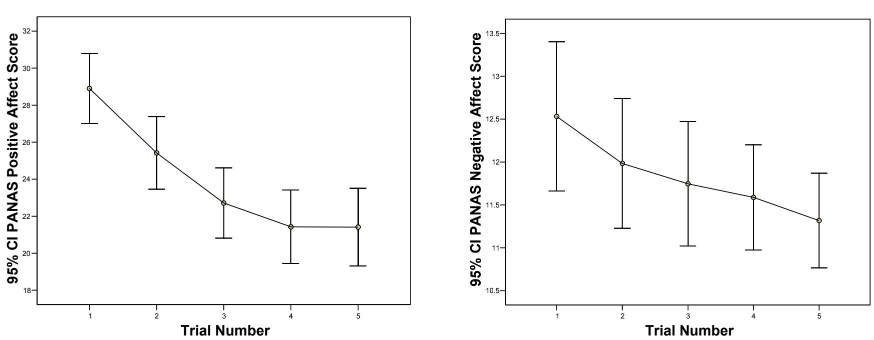


Figure 4.11: Positive and Negative Affect Scores for the PANAS Questionnaire by trial. Note that the y-axis range is different for the Positive and Negative Affect Scores.

Further analysis of the PANAS Questionnaire was performed by taking the sum and difference between the Positive and Negative Affect Scores (Figure 4.12). Participants showed significantly higher differences in the scores (significantly more positive state of mind) during early trials as compared to later trials ($p < 0.001$). Total emotional response went down with later trials.

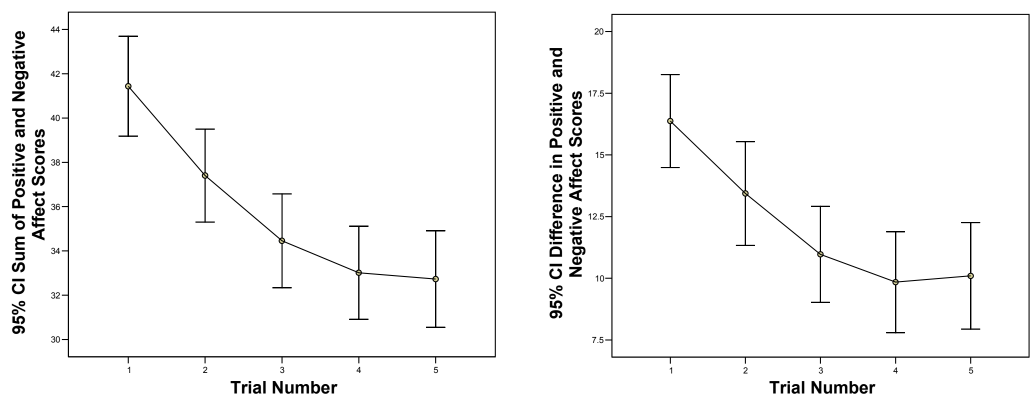


Figure 4.12: The sum and difference between the Positive and Negative Affect Scores by trial. Note that the y-axis range is different for the Positive and Negative Affect Scores.

PANAS scores did not vary significantly between local and global illumination conditions.

4.8.3.1 Questionnaire Correlations

Correlations between all the questionnaire scores were examined. Higher presence scores (Reported Presence and Behavioral Presence) showed significantly positive correlations with Positive Affect Scores and the difference between Positive and Negative Affect Scores (seen in Figure 4.13). Higher presence scores showed significantly negative correlations with the Negative Affect Score, Nausea Score, Ocular Discomfort Score, Total Sickness Score, and Lighting Impression Score. The Ease of Locomotion Score had the same correlations as the Reported Presence and Behavioral Presence scores, with the exception of the Lighting Impression Score.

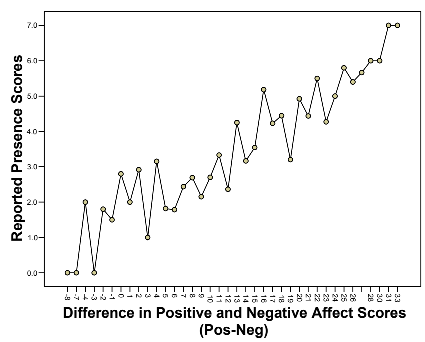


Figure 4.13: The difference between the Positive and Negative Affect Scores plotted against Reported Presence Scores ($p < 0.001$, $r = 0.52$).

The Lighting Impression Questionnaire had significant negative correlations with Reported Presence Scores, Behavioral Presence Scores, and Positive Affect Scores. As participants more heavily weighted terms such as “dislike” and “unpleasant” in the Lighting Impression Questionnaire, their Reported Presence, Behavioral Presence, and use of positive affect terms decreased. The Lighting Impression Questionnaire had significant positive correlations with the Ocular Discomfort, Nausea, Disorientation, and Total Sickness Scores. It is important to note that higher lighting scores indicate generally more negative impressions of the lighting in the environment.

4.8.3.2 Gender Results

Gender differences were found for the Simulator Sickness Questionnaire, Presence Questionnaire, PANAS Questionnaire, and Demographics Questionnaire. Women reported significantly higher sickness values for Ocular Discomfort ($p < 0.01$). Men reported significantly higher presence scores for Reported Presence, Behavioral Presence, and Ease of Locomotion ($p < 0.001$ for all cases) as seen in Figure 4.14.

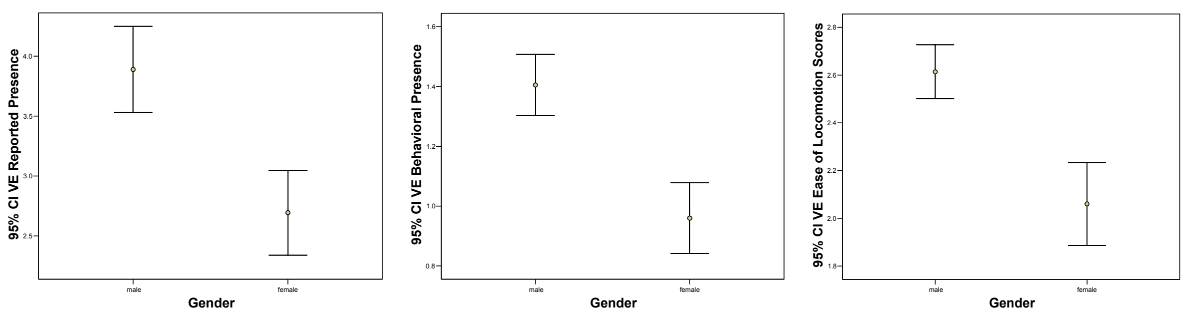


Figure 4.14: Reported Presence, Behavioral Presence, and Ease of Locomotion Scores by Gender.

The PANAS Questionnaire also showed significant difference in Positive Affect Scores. Men had a significantly higher Positive Affect Score compared to women ($p < 0.02$). Further analysis using the sum and difference of the Positive and Negative Affect Scores also showed gender differences. Men had a significantly higher combined affect score than women ($p < 0.05$) and had a higher differential between positive and negative scores ($p < 0.01$).

In the Demographics Questionnaire, men reported significantly more computer or video game playing than women ($p < 0.001$).

4.9 Discussion

This experiment successfully utilized a new technique, attention mapping, for measuring behavior in a three-dimensional virtual environment. Attention mapping provides an objective record of viewing times which can be used to examine and compare different components of the environment.

By examining the data from the attention maps, tracker readings, and questionnaires, this experiment showed that, in a non-stressful environment, variations in lighting can influence attention, movement, and impressions of lighting. While a 2:1 contrast ratio resulted in some significant difference in these measures, a 7:1 ratio more dependably produced larger differences in attention, movement, and lighting impression. Attention increased toward highlighted objects, participants stayed in areas of the environment that contained highlighted objects for longer periods of time, and higher lighting impression scores were reported in higher contrast ratio conditions. Local illumination resulted in similar changes in behavior and impression as global illumination. Additionally, women had higher sickness scores, lower presence scores, and lower positive affect scores than men.

Chapter 5

Experiment 3: The Knot Experiment

5.1 Introduction

The purpose of the Knot Experiment was to investigate the influence of lighting models on task performance and memory. In particular, this study examined the effects of ambient, local, and global illumination on a participant's ability to either correctly identify a target object among distractor objects on a table or determine that the target object was not on the table at all. To avoid previous-learning effects with familiar objects, the target objects and distractor objects were distinct, knot-like geometric shapes. At the conclusion of the experiment, participants were shown specific objects and asked if they had searched for those objects during the experiment.

5.2 Background

A detailed discussion of lighting effects on task performance in illumination engineering, psychology, and virtual reality literature was presented in Chapter 2. What follows is an overview of the salient points as they relate to the Knot Experiment.

5.2.1 Illumination Engineering

One of the key concerns in illumination engineering is determining adequate light levels for a given task. From the 1930s to the current day, lighting guidelines have been developed to promote the use of proper illumination levels. Engineering research studies indicate that correct lighting levels are a significant factor in successful task completion (Kaufmann, 1987; Rea and Ouellette, 1988; CIE, 1972).

5.2.2 Psychology

A number of psychology studies indicate that the presence of shadows can have a significant positive effect on object naming, disambiguating spatial relationships, and determining the location of objects (Liter, 1997; Tarr, 1998; Castiello, 2001; Collier, 2000). Also, silhouetted objects are named less quickly than those objects with internal shading (Liter, 1997; Hayward, 1998). Braje et al. (1999) found that the presence or absence of shadows did not significantly alter the recognition times for natural objects (fruits and vegetables).

5.2.3 Psychological Experiments in Virtual Environments

Christou (1994) found that indirect illumination was important in estimating shape dimensions and in creating impressions of object solidity. Madison (1999) found that indirect illumination (such as that from a global illumination system) was an important factor in determining object contact in virtual environments. Hu et al. (2002) also found that shadow cues improved the consistency of participants in an object-contact task.

Thompson et al. (1998) discuss the utility of shadows and light interreflections in clarifying the spatial relationships between objects in VEs. In VR applications that lack haptic feedback or sound, the visual indications of near-contact or proximity are needed even more than in the real world. Indirect lighting, used alone, was found to improve accuracy as much as shadows alone in determining object contact. Thompson et al. report that shadow quality is less important in tasks such as estimating height than in more precise tasks such as determining contact. However, the presence of any shadows or interreflections significantly enhances spatial task performance. Thompson et al. conclude that "even virtual reality systems where realism is not the primary goal might well benefit from at least approximating indirect lighting, particularly since in such cases simple techniques are likely to be sufficient for conveying an adequate sense of spatial organization."

Wanger (1992) performed three experiments on shadow sharpness and shape. He found that the existence of shadows greatly increased the accuracy of size and position estimations of objects and was “a powerful cue for indicating an object's three dimensional shape.” However, the sharpness of the shadow did not influence size and position estimations. Wanger found that soft-edged shadows significantly degraded performance on a shape-matching task (for example, discriminating between a cup shape and a capsule shape based on shadow shape). He found that "soft shadows [versus hard shadows] can be detrimental to determining an object's shape in the absence of other cues."

In contrast with Wanger’s work, this experiment concentrates on the lighting model used, as opposed to point versus area light sources creating sharp or soft shadows.

5.3 Conditions

The Knot Experiment examined the influence of the lighting model on task performance in a visual search task. In this study, participants learned object characteristics in one lighting model condition and then searched for that object under another lighting model condition. Three lighting models were explored in this study: ambient, local, and global illumination.

The virtual environment consisted of a single room which contained an empty table above which hung an empty picture frame. The participant pressed a trigger on a joystick to start the trial. An image of a search object (rendered with ambient, local, or global illumination) appeared in the picture frame. After the participant studied the search object for 10 seconds, the image of the search object vanished. A group of 15 objects then appeared on the table rendered in one of three lighting models (ambient, local, or global). After that, the participant tried to locate the search object on the table (Figure 5.1). A total of nine different combinations of lighting were explored in this study. Each participant experienced only one of the nine lighting conditions during his trials. The conditions are listed in Table 5.1.

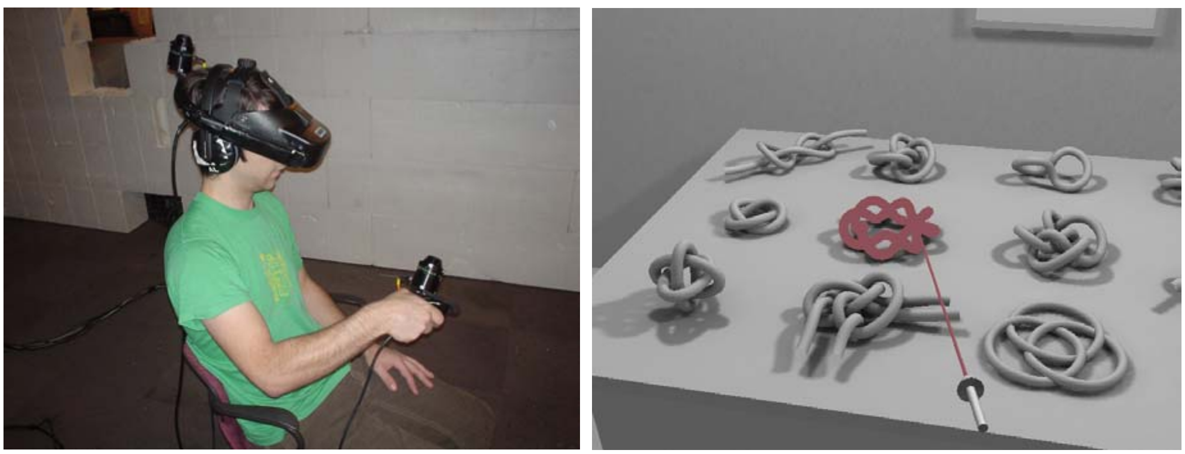


Figure 5.1: An image of a user wearing the equipment (left) and selecting an object during a trial (right).

	Search Object / Table Objects	Search Object Lighting Model (SOLM)		
		Global (G_s)	Local (L_s)	Ambient (A_s)
Table Object Lighting Model (TOLM)	Global (G_t)	1 G_s/G_t	2 L_s/G_t	3 A_s/G_t
	Local (L_t)	4 G_s/L_t	5 L_s/L_t	6 A_s/L_t
	Ambient (A_t)	7 G_s/A_t	8 L_s/A_t	9 A_s/A_t

Table 5.1: The conditions tested in the Knot Experiment.

In the Knot Experiment, conditions used either consistent or inconsistent lighting. In *consistent lighting* (conditions G/G, L/L, A/A), the search object and table objects were rendered in the same lighting model. For example, rendering both the search object and table objects in a local illumination model would be a consistent lighting condition. In *inconsistent lighting* (L/G, A/G, G/L, A/L, G/A, L/A), the search object and the table objects were rendered in different lighting models. For example, rendering the search object in ambient illumination and the table objects in global illumination would be an inconsistent lighting condition (denoted as A/G).

5.4 Hypotheses

By analyzing search time, search accuracy, and memory accuracy under the various lighting models, we can determine if there are significant differences in performance across lighting conditions.

We hypothesize that:

1) *participants will be more accurate when searching for an object in consistent lighting conditions than in inconsistent lighting conditions*;
2) *studying and then searching for an object in inconsistent lighting conditions will result in longer search times than studying and then searching in consistent lighting conditions*;

3) *within the consistent lighting conditions, local and global illumination conditions will result in faster search times than in the ambient illumination condition*;

4) *global illumination will result in higher accuracy scores and faster search times than local illumination;* and

5) *memory scores will be higher for global and local search object lighting conditions than for the ambient search object lighting condition.*

5.5 Method

5.5.1 Participants

This study used 101 participants (33 M, 68 F) recruited from a University of North Carolina, Chapel Hill psychology class and one participant from the Computer Science Department. The age range was between 18 and 28 with a mean age of 19. Participants were required to have stereo vision, normal or corrected-to-normal 20/20 vision, no prior experience with virtual reality, and no precluding medical conditions. Since timing data were gathered, participants were required to be right-handed, so as to more consistently maneuver the hand-held pointing device used in the experiment. Students were given a half hour of class experiment credit for taking part in the study and did not receive monetary remuneration.

5.5.2 Materials

5.5.2.1 Apparatus

As in the Pit and Gallery Experiments, this study used a Virtual Research V8 head-mounted display and a 3rdTech HiBall optical tracking system to report the user's head and hand poses during the experiment. The participant used a tracked joystick with a trigger to control a pointer to select objects. Participants signaled the beginning of a trial, the discovery of the search object, and the selection of the object by pressing the trigger on the joystick. Image generation was done using an nVidia Ti4600 video card with dual monitor outputs using a 1.8 GHz Dell Precision Workstation (nVidia, 2002).

Since global illumination cannot yet be done in real-time, scenes were pre-computed for display during the experiment. Lighting computations and texture coordinate calculations applied to objects in the VE were done using 3D Studio Max v5.1 and took a total of four hours per condition on a 2.8 GHz PC (Discreet, 2003). An additional two hours was needed to arrange the objects in the VE and prepare the environment for display after lighting was computed.

The participant sat in a chair with arm rests and held the joystick in his right hand. Tracker readings from the participant's head and hand were recorded during the trials. In addition, the time it took for each participant to signal that he had found the search object and the time it took the participant to point at the found object were also recorded. A memory questionnaire was administered after the trials were completed.

5.5.2.2 Object Generation

In a study of lighting direction and shadow color on reaction times, Tarr et al. (1998) created a set of novel stimulus objects called *greebles*. Greebles were generated based on guidelines of desirable properties established by Tarr et al. In this experiment, we also follow Tarr et al.'s methodology of establishing a set of desirable properties for stimulus objects and then generating classes of objects based on those properties.

Objects in the Knot Experiment were generated using a program called KnotPlot (Scharein, 1998). KnotPlot allows the user to select various parameters related to mathematical knots, yielding a three-dimensional model of the knot that can be exported to a modeling program for scaling and positioning on the table. In addition, KnotPlot contains an extensive catalog of knots that can be selected, modified, and exported.

The class of knots was chosen as search objects in order to avoid the use of previous knowledge that would speed recognition of familiar objects. The participant had to rely on the lighting cues presented in the search object for creation of a mental representation of the object. The objects in the study had several properties critical for lighting. First, the objects overlapped themselves, which produced intrinsic shadows in the global illumination conditions. Second, their complicated shapes each produced a unique cast shadow pattern on the table. Third, the objects were given a uniform gray color to avoid the use of color in aiding recognition. Fourth, the objects' surfaces were rendered with a uniform albedo to avoid confusion between lighting and material properties.

5.5.2.3 Questionnaires

After signing a consent form, the participant completed two questionnaires. The Participant Health Questionnaire gauged whether the participant was well enough to continue with the experiment. A Demographics Questionnaire was used to collect information about the participant: gender, class year, computer use, computer and video game playing, and level of physical activity.

After the participant had finished his trials, he filled out a Memory Questionnaire. The Memory Questionnaire consisted of ten questions. Each question had a picture of an object rendered in the same lighting condition as the search objects used during the experiment. Half the objects shown were search objects in the previous trials. The other half of the objects shown were distractor objects that were seen on the table. The order of the questions was randomized for each participant. The participant designated whether he had searched for the particular objects shown and how confident he was in his choices.

All the questionnaires for the Knot Experiment are reproduced in Appendix D.

5.6 Calibration

A calibration process was necessary to minimize the differences among the global, local, and ambient illumination versions of the virtual environment. Global illumination was calculated using finalRender Stage-0 v1.2 and 3D Studio Max v5.1 (Cebas, 2002). For the global illumination version, the lighting was created by two 0.6 by 0.6 meter area lights set to 40% white. They were positioned 1.2 meters apart from each other and 1 meter directly above the table. The materials were set without any specular properties and had the same diffuse reflection coefficient, $\rho=0.59$. The local illumination version used the same lighting and material settings as the global illumination version. The local illumination version was rendered using 3D Studio Max's built-in local illumination model applied to the objects. The ambient illumination version of the model was derived from averaging the pixel values in multiple objects in the local illumination version of the environment. The average grayscale value (gray level 122 of 256) was then used as a constant material color for the objects. For each lighting model, the surface lighting values computed were stored in textures applied to each object. An example of an object in all three lighting conditions can be seen in Figure 5.2 with further examples in Appendix E.

Figure 5.2: A knot drawn in ambient, local, and global illumination.

External calibration was done using a Lutron light meter. Six light readings were taken in the HMD for the global illumination version of the environment while an empty table was in view. To calibrate the local illumination version of the environment, the same view was set up, and six light-meter readings were taken and averaged. The brightness of the HMD was adjusted to match the global illumination light-meter readings. To calibrate the ambient illumination version of the environment, six light-meter readings were taken and averaged. The brightness of the HMD for the ambient version of the virtual environment was then adjusted to match the global illumination light-meter readings.

5.7 Procedure

Upon arriving, the participant was seated at a desk outside the graphics laboratory. After signing the consent form, the participant filled out the

Participant Health and Demographics Questionnaires. Interpupilary distance was then measured with an Essilor digital corneal reflection pupilometer. After that, the participant was instructed in the experimental procedure.

The participant was accompanied to the graphics laboratory where he was seated in the middle of the tracker space. The HMD and the joystick equipment was shown and explained. After the HMD was placed on the participant's head and the joystick placed in his right hand, the participant heard instructions through earphones on the HMD (see Appendix B). The instructions informed the participant of the procedure for the experiment and told the participant to press the trigger on the joystick to begin his trials.

An arrow was used to represent the participant's right hand in the environment. The arrow was used in the experiment to select either different objects on the table or to select a button off to the side that indicated that the object was not on the table at all (see Figure 5.1).

The participant first went through 8 practice trials to familiarize himself with the mechanics of signaling either that he had found the search object or that the search object was not on the table. The user signaled this decision event by pressing the trigger on the joystick. After the decision was made, a beam emanated from the pointer to allow the participant to select the object he had chosen or the “Object Not on Table” button. The “laser-beam” interface was used to minimize the amount of movement necessary for the participant to indicate his choices. Once the final selection was made, objects on the table disappeared; and a new trial was initiated.

The tables used in the 8 practice trials held 5 to 12 objects. The search table difficulty was gradually increased to help the participant acclimate himself to the experiment. Fifteen objects, however, were presented on each table used in the main experiment. Once the participant began the study, the experiment progressed from the practice phase to the main set of trials without a break. The participant conducted 18 trials with the full set of table objects. Trials were presented according to a balanced Latin square design, 9 trials with the search object present on the table and 9 with it absent.

Once the participant had finished all 26 trials, he filled out the Memory Questionnaire.

5.8 Results

We analyzed the data with respect to accuracy of object selection, search time, and questionnaire responses. The accuracy and search times were grouped according to: whether the lighting was consistent or inconsistent, search object lighting model (SOLM), and table object lighting model (TOLM). Consistent and inconsistent lighting was defined in Section 5.3. Table 5.1 depicts the grid of lighting model conditions.

5.8.1 Accuracy

Overall, the Knot Experiment showed that consistent lighting resulted in higher accuracy than inconsistent lighting. As the lighting became more inconsistent between the search object and the table objects, inaccuracies increased. The search object lighting model had a more noticeable influence on search accuracy than the table object lighting model. A summary of the accuracy scores by condition is given in Table 5.2.

		Search Object Lighting Model (SOLM)					
		Global (G_i)		Local (L_i)		Ambient (A_i)	
Table Object Lighting Model (TOLM)	Global (G_t)	(1)	80.3%	(2)	74.4%	(3)	48.6%
	Local (L_t)	(4)	73.9%	(5)	77.3%	(6)	62.5%
	Ambient (A_t)	(7)	54.5%	(8)	66.2%	(9)	70.3%

Table 5.2: Accuracy scores for the different conditions in the Knot Experiment. (n) = condition number.

Significance testing for accuracy was computed using an Arcsin Transform to account for the changes in the variance of participants' scores (Hogg and Craig, 1978).

Consistent vs. Inconsistent. When the accuracy scores of the consistent lighting conditions (conditions G/G, L/L, and A/A) were compared to the accuracy scores of the inconsistent lighting conditions (conditions L/G, A/G, G/L, A/L, G/A, L/A), participants scored significantly higher in the conditions with consistent lighting, 76% vs. 63% ($p < 0.001$). Condition G/G had the highest accuracy scores of any of the nine conditions at 80% accuracy.

Conditions G/G, L/L, and A/A, where lighting was consistent, had accuracy scores of 80%, 77%, and 70% respectively (Figure 5.3). However, this downward trend in accuracy did not approach significance ($p < 0.13$). Conditions G/G and L/L (global and local illumination) grouped together were close to being significantly more accurate than ambient illumination (79% vs. 70%, $p < 0.051$).

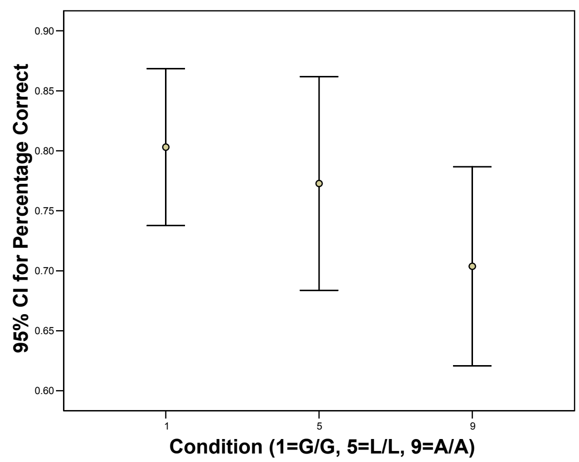


Figure 5.3: Accuracy scores for global, local, and ambient consistent lighting conditions.

Comparing global and local illumination against each other showed no significant difference in accuracy ($p < 0.58$). There was a 69% overlap in the 95% confidence intervals between the global and local illumination accuracy scores. However, the t-test used to compare the scores showed a low power value (power=0.08, β=0.92). Thus, our ability to determine if local and global illumination are the same in their ability to achieve high accuracy is limited. If they are indeed not the same, 270 participants would be needed per condition to reach significance.

Search Object. When the conditions were grouped by SOLM (G/G,G/L,G/A vs. L/G,L/G,L/A vs. A/G,A/L,A/A), the conditions in which the search object was presented in global illumination or local illumination each resulted in significantly higher accuracy scores than those conditions where the search object was rendered with ambient illumination ($p < 0.003$ for ambient vs. local illumination and $p < 0.04$ for ambient vs. global illumination). The accuracy scores for the global illumination and local illumination SOLM conditions did not differ significantly when compared to each other ($p < 0.69$). Participants identified 69% of the objects correctly when the search object was presented in global illumination, 72% correctly in local illumination, and 61% correctly for ambient illumination.

Table Objects. When the conditions were grouped by TOLM (G/G,L/G,A/G vs. G/L,L/L,A/L vs. G/A,L/A,A/A), no significant differences in search accuracy were observed.

Diagonals. Another set of analyses was conducted by grouping the conditions by diagonals. In the first group (conditions G/G, L/L, and A/A), the SOLM and TOLM were the same. In the second group (conditions G/L, L/A, L/G, A/L), the search object and table objects differed by one lighting-model level (for example, a global SOLM with a local TOLM). In the third group (conditions G/A and A/G), the search object and table objects differed by two lighting-model levels (either global SOLM and ambient TOLM, or ambient

SOLM and global TOLM). The first group had the highest accuracy score, 76%. The second group had an accuracy score of 69%. The third group had an accuracy score of 52%. The first group had a significantly higher accuracy score than the second group ($p < 0.04$). The second group had a significantly higher accuracy score than the third group ($p < 0.001$). A plot of the accuracy scores for the three groups is given in Figure 5.4.

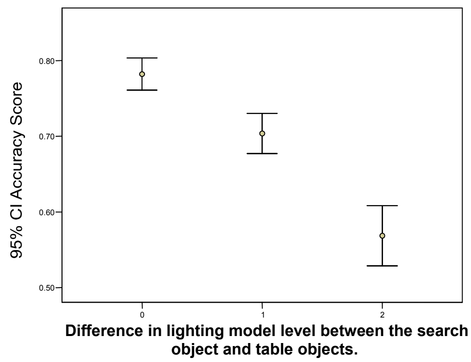


Figure 5.4: The accuracy scores for the diagonal conditions. (0=conditions G/G, L/L, A/A; 1=conditions L/G, G/L, A/L, L/A; and 2=conditions A/G, G/A).

Most Accurate and Inaccurate Object. The most accurately identified object and most inaccurately identified object were also examined. The most accurate object did not vary in identification accuracy when grouped by TOLM or SOLM. The most inaccurate object did differ significantly in its identification accuracy when grouped by SOLM. The identification accuracy for this search object rendered in ambient illumination was significantly lower than the local or global illumination versions ($p < 0.02$ in both cases). The most inaccurate object was correctly identified 25% of the time in ambient illumination, 52% in local illumination, and 53% in global illumination). The most accurate and most inaccurate search objects are shown in Figure 5.5.

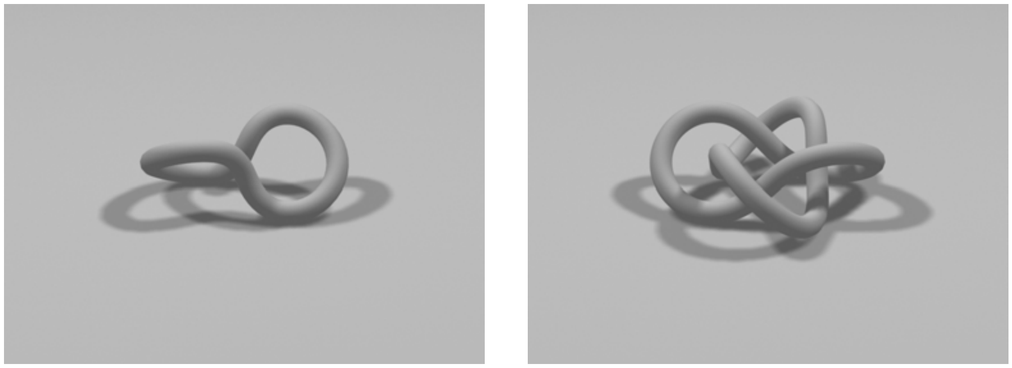


Figure 5.5: The most accurately identified search object (left) and most inaccurately identified search object (right) shown in global illumination.

5.8.2 Time

Search time was analyzed separately for trials when the participant chose the correct object and for trials when the participant chose the incorrect object.

5.8.2.1 Trials - Correct Object Chosen

For trials where the correct object was chosen, there were several significant search time differences among the nine conditions. When grouped by TOLM (conditions G/G, L/G, A/G vs. G/L, L/L, A/L vs. G/A, L/A, A/A), conditions with globally illuminated table objects had significantly longer search times than either local or ambient illumination conditions. When grouping by SOLM (conditions G/G, G/L, G/A vs. L/G, L/L, L/A vs. A/G, A/L, A/A), the locally illuminated search objects had significantly faster search times than either the ambient or global illumination versions of the search object. The longest search times occurred when the search object was rendered in ambient illumination and the table objects were presented in global illumination. Summaries for the search times for correct searches by condition are given in Table 5.3.

		Search Object Lighting Model (SOLM)			
		Global (G_i)	Local (L_i)	Ambient (A_i)	TOLM Avg.
Table Object Lighting Model (TOLM)	Global (G_t)	(1) 7.8 s	(2) 6.7 s	(3) 8.5 s	7.6 s
	Local (L_t)	(4) 6.5 s	(5) 5.6 s	(6) 7.5 s	6.5 s
	Ambient (A_t)	(7) 6.9 s	(8) 6.0 s	(9) 7.1 s	6.7 s
	SOLM Avg.	7.1 s	6.1 s	7.6 s	

Table 5.3: Search times for correct searches in the Knot Experiment by condition. (n) = condition number.

Table Objects. When the conditions were grouped by TOLM, there were significant differences in the search times ($p < 0.001$). When the table objects were presented in global illumination (conditions G/G, L/G, A/G), the average search time was 7.6 seconds. In local illumination (conditions G/L, L/L, A/L), the average search time was 6.5 seconds. In ambient illumination (conditions G/A, L/A, A/A), the average search time was 6.7 seconds. The globally illuminated table objects had significantly longer search times than either the local or ambient illuminated table objects ($p < 0.001$ and $p < 0.004$ respectively). Local and ambient were not significantly different from each other ($p < 0.8$).

Search Object. When grouped by SOLM, search objects rendered in local illumination had significantly lower search times than search objects rendered in either ambient or global illumination. Conditions in which the search object was locally illuminated (conditions L/G, L/L, L/A) had an average search time of 6.1 seconds. Conditions in which the search object was globally illuminated (conditions G/G, G/L, G/A) had an average search time of 7.1 seconds. Ambiently illuminated search objects (conditions A/G, A/L, A/A) had an average search time of 7.6 seconds. The locally illuminated conditions had significantly faster times than either of the ambient or global illumination groups ($p < 0.001$ in both cases). Ambient and global were not significantly different from each other ($p < 0.23$).

Consistent vs. Inconsistent. There were no significant differences in search times when the conditions were grouped according to consistent (conditions G/G, L/L, A/A) or inconsistent (conditions L/G, A/G, G/L, A/L, G/A, L/A) lighting between the search object and table objects ($p < 0.63$). Surprisingly, if the SOLM level was greater than the TOLM (conditions G/L, G/A, L/A), search times were significantly faster than if the SOLM level was the same or lower than the TOLM ($p < 0.001$ and $p < 0.004$ respectively).

Search times were significantly longer when the lighting between the search object and table objects differed by two lighting model levels (conditions A/G, G/A) than when the lighting model differed by one level (conditions L/G, G/L, A/L, L/A) or no levels (conditions G/G, L/L, A/A). Conditions A/G and G/A had an average search time of 7.7 seconds. Conditions L/G, G/L, A/L, L/A had an average search time of 6.7 seconds. Conditions G/G, L/L, and A/A had an average search time of 6.8 seconds. The groups with lighting that differed by two levels had significantly longer search times than the groups with a one level difference or no level difference ($p < 0.006$ and $p < 0.03$ respectively).

5.8.2.2 Trials - Incorrect Object Chosen

Search time data were also analyzed for trials in which the participant chose an incorrect object. Overall, participants took significantly longer to find the search object if they chose incorrectly (8.1 seconds for incorrect searches versus 6.9 seconds for correct searches, $p < 0.001$). A summary of the search times for incorrect searches is given in Table 5.4.

		Search Object Lighting Model (SOLM)		
		Global (G_i)	Local (L_i)	Ambient (A_i)
Table Object Lighting Model (TOLM)	Global (G_t)	(1) 10.2 s	(2) 8.3 s	(3) 9.2 s
	Local (L_t)	(4) 7.5 s	(5) 7.3 s	(6) 8.4 s
	Ambient (A_t)	(7) 6.7 s	(8) 7.4 s	(9) 8.1 s

Table 5.4: Search times for incorrect objects in the Knot Experiment by condition. (n) = condition number.

5.8.2.3 Trials – "Object Not on Table" Button Chosen

Correctly choosing the "Object Not on Table" button took an average of 8.16 seconds while incorrectly choosing the button took 8.5 seconds. However, this difference was not significant at the $p < 0.05$ level ($p < 0.36$). The timing data for determining (correctly or incorrectly) that the search object was not on the table is shown in Tables 5.5 and 5.6. Correctly choosing the object on the table was significantly faster than correctly choosing the "Object Not on Table" button (5.41 sec. vs. 8.16 sec., $p < 0.001$).

		Search Object Lighting Model (SOLM)		
		Global (G_i)	Local (L_i)	Ambient (A_i)
Table Object Lighting Model (TOLM)	Global (G_t)	(1) 9.2 s	(2) 8.0 s	(3) 10.1 s
	Local (L_t)	(4) 7.7 s	(5) 6.6 s	(6) 9.0 s
	Ambient (A_t)	(7) 8.2 s	(8) 7.2 s	(9) 8.2 s

Table 5.5: Time to *correctly* determine if the search object is not on the table in the Knot Experiment by condition. (n) = condition number.

		Search Object Lighting Model (SOLM)		
		Global (G_i)	Local (L_i)	Ambient (A_i)
Table Object Lighting Model (TOLM)	Global (G_t)	(1) 11.8 s	(2) 8.1 s	(3) 9.3 s
	Local (L_t)	(4) 8.4 s	(5) 7.7 s	(6) 8.8 s
	Ambient (A_t)	(7) 7.4 s	(8) 7.2 s	(9) 8.3 s

Table 5.6: Time to *incorrectly* conclude that the search object was not on the table in the Knot Experiment by condition. (n) = condition number.

5.8.3 Memory Questionnaire

A Memory Questionnaire was administered after the participant had completed all experimental trials. The Memory Questionnaire showed that, on average, participants correctly remembered 78% of the 18 objects presented to them as search objects. The Memory Questionnaire did not show any significant differences by table object lighting condition or search object lighting condition.

5.8.4 Correlations

Several correlations were computed using the data from the Demographics Questionnaire. Increased computer use, computer game or video game playing, or time spent exercising corresponded to significantly lower times in locating the search object if the participant chose the correct object ($p < 0.03$, r=-0.05; $p < 0.001$, r=-0.16; and $p < 0.001$, r=-0.09 respectively). There was a significant negative correlation between computer or video game playing and the time to find the search object if the participant chose an incorrect object ($p < 0.001$, r=-0.23). More active game players chose the wrong object more quickly. There was a trend toward positive correlation between time spent exercising and accuracy ($p < 0.08$; r=0.04). There was also a positive correlation between computer use and computer gaming and reported confidence scores in the Memory Questionnaire. Increased computer use or game playing correlated with higher confidence in the Memory Questionnaire questions ($p < 0.01$; r=0.25 and $p < 0.03$; r=0.22 respectively) but not higher accuracy ($p < 0.54$ and $p < 0.62$ respectively). Figure 5.5 shows computer use, game playing, and exercise plotted against search times.

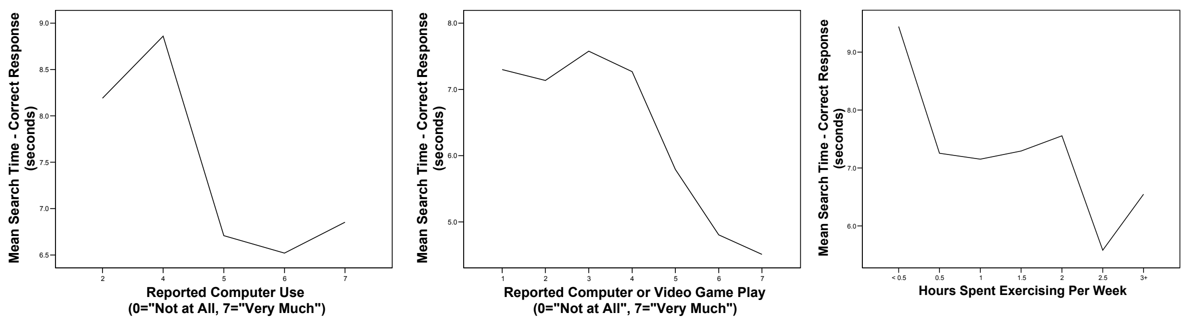


Figure 5.6: Search times plotted against reported computer use, game playing, and time spent exercising ($p < 0.03$, r =-0.07; $p < 0.001$, r = -0.17; $p < 0.001$, r = -0.11 respectively).

5.8.5 Gender

For the Knot Experiment, search accuracy did not vary by gender, but there were differences in search times and questionnaire responses.

Men and women did not differ significantly in their search accuracy (69% vs. 66% respectively, $p < 0.29$). In trials where the participant chose the correct object, men's search times were significantly faster than women's (5.9 seconds vs. 7.4 seconds respectively, $p < 0.001$). In trials where the participant chose the incorrect object, men's search times were also faster than women's (7.0 seconds vs. 8.6 seconds respectively, $p < 0.001$).

Men reported higher confidence in their memory questionnaire answers as opposed to women (3.98 vs. 3.77 respectively, $p < 0.02$), but men did not score significantly better on the memory questionnaire than women (80% vs. 77% respectively, $p < 0.32$).

Finally, men reported significantly more computer gaming or video gaming than women ($p < 0.001$). This may account for the speed differences.

5.9 Discussion

The purpose of this experiment was to examine the influence of different combinations of lighting models on performance in a search task. Search time, object selection accuracy, and object identification from memory were analyzed.

Surprisingly, the search times for both globally illuminated search objects and table objects were significantly longer than the locally illuminated versions. Originally, we thought that the more detail provided to the participant by global illumination, the faster the search time would become. However, it is possible that the extra detail generated by global illumination required more features to be compared when searching for a match.

Another unexpected result was that, when the search object and table objects were drawn in the same lighting model (consistent), there was no significant difference among the accuracy scores for global, local, or ambient illumination. However, global illumination did have the highest overall accuracy. In conditions with consistent lighting, the participants attained significantly higher accuracy scores than when the lighting was inconsistent. The accuracy scores became significantly lower when there was a greater difference between the search-object lighting model and table-objects lighting model. The data support the notion that lighting consistency is more important than the specific lighting model when identifying complex, unfamiliar objects. The participants seemed to acclimate themselves to whatever rendering condition was presented.

Computer use, video or computer game playing, and exercise all correlated with lower search times. Familiarity with searching for objects in computer games could have assisted the participants when applying these searching skills in an unfamiliar computer-generated environment. It is unclear why exercise would decrease object selection times. However, one could speculate that participants who exercise may be more alert and more competitive than participants who do not work out at all.

There were several gender differences observed. In particular, men found objects significantly faster than women whether they chose the correct or incorrect object. While men were also significantly more confident in their answers to the memory questionnaire than women, men were not significantly better at remembering the objects. Men also reported a significantly higher amount of video game playing than women.

Chapter 6

Conclusions and Future Directions

6.1 Introduction

Light and shade are complementary phenomena. The interplay of light and shade provides a wide range of informational cues to the human visual system and assists the observer in reasoning about the contents of the visual field. These cues create visual boundaries, reveal surface properties, and help prioritize the elements within the environment. Light and shade can also elicit a range of human responses such as modifying behavior and altering the subjective impression of a space (Yorks & Ginther, 1987; Flynn, 1977; Veitch, 2001; Christou, 1994).

In this dissertation, we investigated five hypotheses about lighting quality in virtual environments:

H1: *physiological responses and targeting accuracy will be heightened as lighting quality increases in stressful environments*;

H2: *attentiveness and movement towards lighted objects will increase as contrast is increased in low-stress environments*;

H3: *in low-stress environments, search accuracy in consistent lighting conditions will be significantly higher than in inconsistent lighting conditions;*

H4: *in low-stress environments, search times will improve with better lighting quality;* and

H5: *global illumination will provide a significant improvement over local illumination on objective and subjective measures.*

The results of the experiments that tested these hypotheses are discussed in the next three sections. A summary of the conditions and measures in each experiment is presented in Table 6.1.

Experiment	**Lighting Conditions**	**Questionnaires**	**Other Measures**
Pit Experiment	Global, Ambient, Grid	Participant Health, Simulator Sickness, Height Anxiety, Height Avoidance, Guilford-Zimmerman Spatial Orientation Test, Virtual Environment	Heart Rate, Skin Conductance, Ball Dropping Accuracy, Oral Interview
Gallery Experiment	Global, Local	Participant Health, Simulator Sickness, Virtual Environment, PANAS, Lighting Impression	Viewing Times, Quadrant Occupancy Times
Knot Experiment	Global, Local, Ambient	Participant Health, Memory	Selection Accuracy, Search Speed, Selection Speed

Table 6.1: A summary of the conditions and measures used in the three experiments.

6.2 The Pit Experiment

In the Pit Experiment, we examined the impact of visual cues provided by texture resolution and lighting quality on presence, task performance, depth estimation, and memory in a stressful virtual environment. Two levels of lighting quality and two levels of texture resolution were explored. In addition, a separate condition utilized a black and white grid texture applied to all objects. Physiological measurements were recorded during the experiment as an objective measure of presence. Participants also performed a ball-dropping task to determine if rendering quality influenced their ability to hit a target.

Contrary to hypothesis **H1**, similar increases in physiological response occurred in all conditions. This was an unexpected result, implying that participants experienced about the same degree of presence in all conditions, even when surface illumination was reduced to a simple grid pattern. Spatial task performance, as measured by the accuracy of dropping three balls onto a target, was not significantly different by condition. Object recall was significantly lower in the grid condition as versus all other conditions.

We originally anticipated that higher levels of rendering quality would result in greater increases in heart rate. However, the results of this study seem to suggest that, in a stressful environment, even minimal lighting and texture cues provide enough information to the user to elicit an increased sense of presence as measured by physiological response.

6.3 The Gallery Experiment

The purpose of the Gallery Experiment was to investigate the effect of lighting quality, lighting position, and lighting intensity on user behavior and presence in a non-stressful virtual environment. Data were collected and analyzed from tracker readings, questionnaires, and attention maps.

Attention mapping is a new tool we developed for visualizing behavior in a three-dimensional environment. In the Gallery Experiment, attention mapping was used as a method of recording participants' viewing times for objects during their exposures to the virtual environment. By quantifying viewing behavior, attention maps provide a basis for comparing viewing behavior in any virtual environment. Attention maps are constructed by playing back the participant's log file and analyzing the resulting images pixel by pixel to determine how long a particular surface element was viewed.

In support of hypothesis **H2**, the Gallery Experiment showed that, in a low-stress virtual environment, variations in lighting can influence attention, movement, and impressions of lighting. A higher contrast ratio resulted in increased attention toward highlighted objects, increased occupancy times in areas of the environment that contained highlighted objects, and higher lighting impression scores (use of more negative descriptors). In contrast to hypothesis **H5**, lighting with the local illumination model resulted in similar changes in behavior and impression as with the global illumination model. Women had significantly elevated simulator sickness scores, lower presence scores, and lower positive affect scores than men. However, the sickness scores for all participants were still well below the maximum score possible.

6.4 The Knot Experiment

The Knot Experiment examined the influence of different combinations of lighting models on a search task. Object selection search time, accuracy, and questionnaire scores were analyzed.

Longer search times for search objects rendered in global and ambient illumination, as opposed to local illumination, was an unexpected result. This is in conflict with hypothesis **H4**. One possible explanation for these longer search times is that the global illumination search objects provided more features to match. On the other hand, the ambient illumination conditions might not have provided the participant with enough features for comparison. Local illumination conditions (which display the search object with surface shading but without cast shadows) may have provided the necessary information to discover the search object on the table without ambiguity or excess information.

Analysis of the accuracy scores revealed additional interesting results. In support of hypothesis **H3**, accuracy scores for conditions where the lighting was consistent were significantly higher than when the lighting was inconsistent. Accuracy scores were significantly lower when the differences in lighting models between the search object and table objects were greater. Search objects rendered in global or ambient illumination took significantly longer to identify than those in local illumination. Participants who reported more computer use, played more video or computer games, and exercised more hours per week searched faster. Men also had faster search times and reported more confidence in their memory questionnaire responses than women but did not have significantly higher search accuracy or memory scores. Men reported significantly more video game playing than women.

6.5 Discussion

The results of all three experiments have important implications for designing virtual environments. The Pit Experiment showed that stressful environments may not need to be designed with the same degree of detail as non-stressful ones. Participants have shown that they can be engaged in the environment even with low rendering quality. When the stressor becomes the focal point of the experience, it overrides other aspects of the environment making them secondary. As demonstrated with attention mapping, the Gallery Experiment showed that lighting in virtual environments can effectively influence viewing direction, viewing duration, and movement. Virtual environment designers can use lighting as a persuasive tool when constructing virtual environments, tailoring the lighting to selectively guide interaction with the environment. The Knot Experiment showed that virtual environments would not necessarily have to be rendered in the highest lighting quality as long as the lighting was consistent. Depending on the task, the rendering could be designed to provide an experimentally derived set of cues to enhance performance.

When studying virtual environments, designers will find it worthwhile to adopt a multidisciplinary approach. This would include investigating the results and methodology used in real world research for a variety of disciplines. For the design and analysis of the three experiments in this dissertation, we utilized information from virtual reality as well as illumination engineering, architecture, and psychology. Studying other disciplines can provide important suggestions for developing a framework for similar experiments in a virtual setting.

6.6 Future Directions

6.6.1 Attention Mapping

In the Gallery Experiment, attention mapping was used to derive participant viewing times for individual objects. Attention mapping could also have many other applications where passive behavioral recording is desirable. By capturing typical user viewing behavior, we can generate semantic information about the environment such as participant preferences for a particular object or area of an environment.

In virtual environment walkthroughs, attention mapping can provide information about which objects in the environment are more likely to be examined by a typical viewer. This information could then be used to provide hints to the rendering software resulting in more intelligent loading and unloading of objects in the environment. For example, the attention maps in the Gallery Experiment showed that participants spent very little time looking at the ceiling or the door behind them. These objects could be represented using a simplified model to decrease loading times and increase rendering speed.

For security applications, attention mapping could provide information about which areas in a room or building typically receive less scrutiny, thereby identifying areas of potential vulnerability. Attention mapping can also have commercial applications by indicating which displays, products, or mock-ups attract the most interest.

If we included viewing direction along with duration for each surface element, we could develop an *attentional "BRDF."* In computer graphics, a BRDF is a bi-directional reflectance distribution function which describes how energy is reflected off a surface from a given angle. An attentional BRDF is similar in concept but would use an observer's viewing time as the "energy" being distributed onto objects in the environment. An attentional BRDF would describe how long a typical person spent looking at a surface element from a particular angle. This would enable even more specific rendering optimizations. For example, when rendering a room with two entrances, the application could lower the detail of different objects based on which entrance the user chose, simplifying different sets of objects that were less likely to be observed from a specific direction.

6.6.2 Lighting Impression, Affect, and Presence

The Lighting Impression Questionnaire used in the Gallery Experiment included descriptive terms ("relaxing/tense," "comfortable/uncomfortable," "pleasant/unpleasant") which provided insight into the subjective response of the participant to lighting in the virtual environment. Different lighting conditions evoked significantly different responses. The Lighting Impression scores showed a significant negative correlation with the Positive Affect scores (from the PANAS Questionnaire) and the Reported Presence scores. The Positive Affect scores also had a significant positive correlation with Reported Presence.

The PANAS Questionnaire may be useful in gauging the participant's state of mind in other virtual environments as well. It seems to capture more subtle moods such as frustration, fatigue, and novelty that the Virtual Environment questionnaire does not address. These mood factors could contribute to the degree to which participants accept the virtual environment. The PANAS questionnaire may be most useful if given before exposure to the virtual environment and then in conjunction with the Virtual Environment Questionnaire afterwards, since it would provide information about the participant's pre-exposure disposition. The PANAS Questionnaire could also offer insight into differences in gender reactions to virtual environments. For example, men reported significantly higher scores on the PANAS questionnaire than women which may be related to the extent men play video games and are familiar with interacting with virtual environments as a positive activity.

The experimental data analysis suggests that there is a link between lighting contrast, lighting impression, affect, and presence that could be examined more fully. It would appear that there is a threshold in lighting contrast beyond which the subjective sense of presence is reduced. When used together, the Lighting Impression, PANAS, and Virtual Environment questionnaires provide a more comprehensive understanding of the participant's reaction to a virtual environment.

Appendix A: Attention Mapping

As defined in Chapter 4, an *attention map* is a record of the accumulated times a participant spends looking at various surfaces of a three-dimensional virtual environment during his exposure.

At the beginning of a VR session, the user is fitted with a head-mounted display which is connected to a tracking system. As the user explores the virtual environment, head position and orientation readings are recorded in a log file along with a time-stamp.

Then, new texture coordinates, texture maps, and floating-point arrays containing accumulating viewing times are generated for the all the surfaces in the environment. As shown in Figure A.1, new texture coordinates are computed to prevent texture reuse and to create a one-to-one correspondence between the texture applied to the object and the surface of the object. Each object, therefore, has a single texture map associated with it, and objects are unwrapped so that the entire geometry of the object can be represented in one texture map.

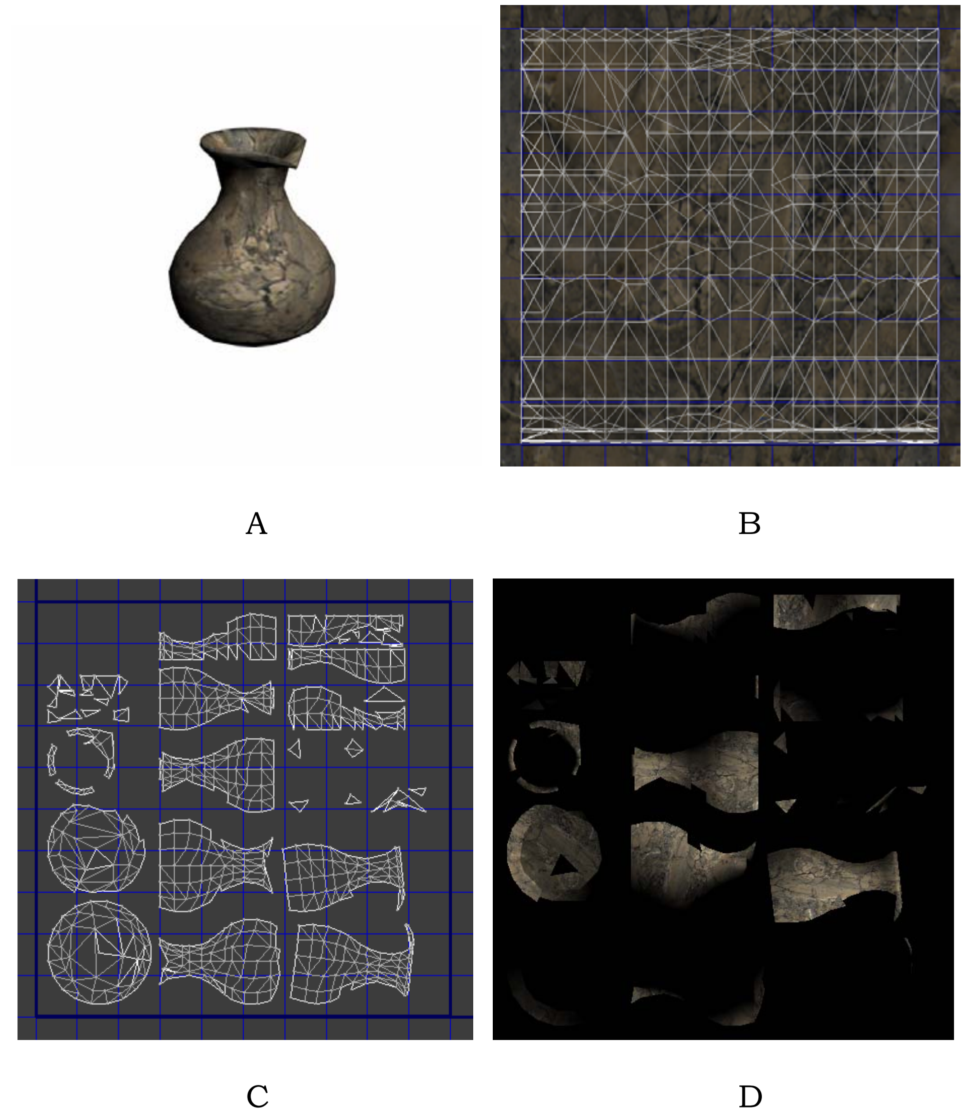


Figure A.1: A) The original object with a texture map, B) the object's original texture coordinates with several areas of texture reuse, C) the object's remapped texture coordinates (now 1:1 correspondence between texture and surface), and D) the pre-illuminated texture corresponding to the new texture coordinates.

Each color channel of the texture maps stores information about the surface of the object to which it is applied. The red component contains the object ID. The green and blue components include the texture coordinates (u,v) for that particular texel in the texture. The object ID combined with the (u,v) information will allow us to update the proper surface elements when viewed by the replayed log file. For example, a texture might have a texel value of (10, 120, 240) which would indicate that the texel at (120,240) of object 10 should be updated. Since each texture channel is composed of 8 bits, this method can only support 256 objects, and textures of 256x256 texels in size. With more sophisticated texture representations, such as floating-point texture formats, more objects can be textured with higher resolution. Each object also has associated with it a 256x256 floating-point array. This array accumulates the viewing time in seconds for each texel.

Once the new texture coordinates and texture maps are applied to the objects, the log file is replayed to reconstruct the movements of the user in the environment. The camera is placed in the same position and orientation as the tracker reading being processed. The resulting image (Figure A.2) is then read back, and each pixel of the image is processed in turn. Since the texels of the visible objects are drawn on the screen, reading back the frame-buffer values tells us what objects and what portions of the visible surfaces on those objects are in view at any given moment.

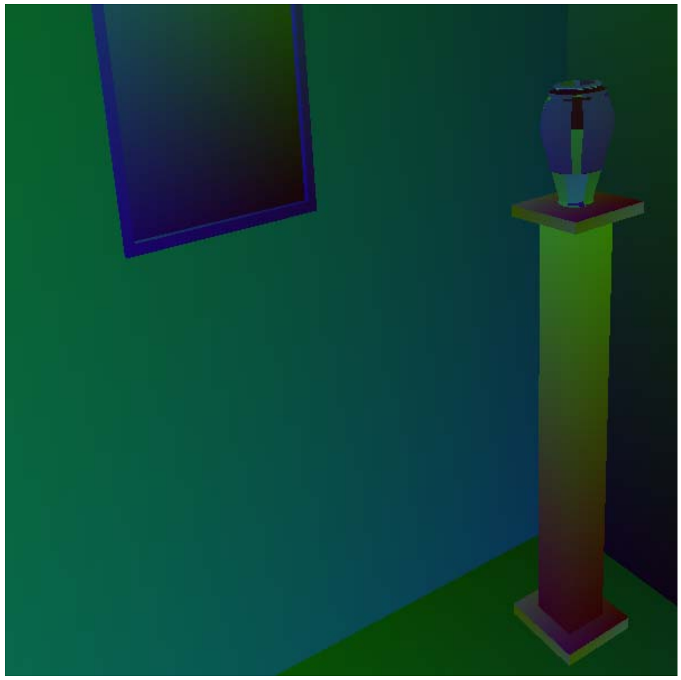


Figure A.2: A frame from a log file with object ID and surface information encoded into texture color channels.

We then update the floating-point arrays for these texels with the difference between the time stamp for the current tracker reading and the previous tracker reading. Thus viewing times are accumulated for each piece of each surface for each object in the environment.

Accumulated viewing times are used to calculate new texture maps. The maps are normalized so that the longest viewing time on a surface element appears completely white, and shorter viewing times are successively grayer as seen in Figure A.3. The environment can then be redisplayed with the new texture maps to show what areas had the highest concentration of viewing time. In the Gallery Experiment, attention mapping was used to derive viewing times for specific objects in order to compare their viewing times under different lighting conditions.

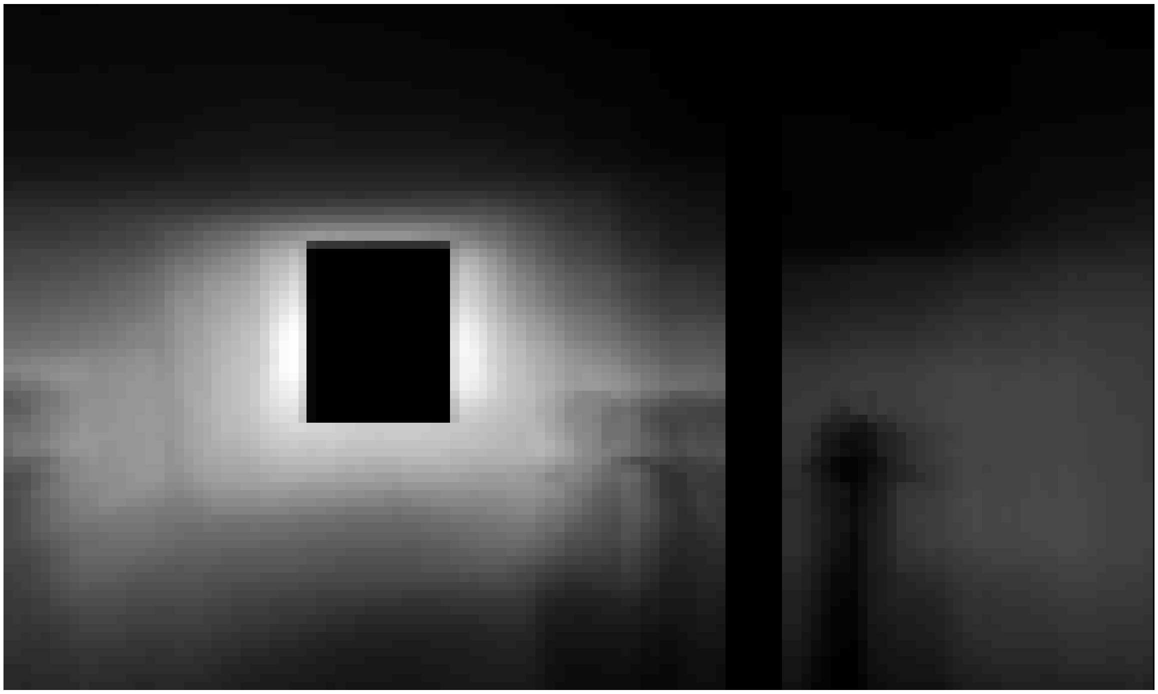


Figure A.3: An image of a wall with attention mapping.

In Figure A.3, the black rectangle is part of the wall obscured by a painting. Outlines for three vases and pedestals can also be seen with different silhouettes, blurred by the fact that the objects obscured different parts of the wall as the viewers regarded them from different viewpoints.

Appendix B: Experimental Procedures

B.1 The Pit Experiment Procedure

An outline of the procedure for the Pit Experiment is given below. The questionnaires are explained in Appendix D.

1. When the participant comes to the graphics laboratory he/she will:
   a. Fill out and sign the Consent Form (which will be copied and returned)
   b. Fill out the Participant Health Questionnaire
   c. Fill out the Simulator Sickness Questionnaire
   d. Fill out the Height Anxiety Questionnaire
   e. Fill out the Height Avoidance Questionnaire
   f. Fill out the Guilford-Zimmerman Aptitude Survey Part 5 - Spatial Orientation

2. The participant's interpupilary distance is measured.

3. Participant attaches physiological sensors to himself.

4. The researcher helps him put on the head-mounted display. The participant will then see a VE rendered in one of five possible conditions (chosen randomly):
   a. low-quality lighting and low-resolution textures
   b. low-quality lighting and high-resolution textures
   c. high-quality lighting and low-resolution textures
   d. high-quality lighting and high-resolution textures
   e. grid

5. Instructions for the participant are played from a pre-recorded CD (see Appendix C.1)

6. Pre-task physiological base line is taken in the Training Room for one minute.

7. Participant becomes familiar with the equipment and practices dropping one ball on a target in the Training Room.

8. The door to the Pit Room is opened and the task of picking up balls and dropping them on a target is performed in the Pit Room.

9. Participants return to the Training Room and a post-task physiological base line is taken for one minute.

10. The participant removes the physiological equipment and head-mounted display and then:
    a. Fills out the Simulator Sickness Questionnaire
    b. Fills out a Virtual Environment Questionnaire
    c. Participates in an Oral Interview

The participant receives one hour of experimental class credit.
The conditions were randomized according to a balanced Latin square design.

B.2 The Gallery Experiment Procedure

An outline of the procedure for the Gallery Experiment is given below. The questionnaires are explained in Appendix D.

1. When the participant comes to the graphics laboratory he will:
    a. Fill out and sign the Consent Form (which will be copied and returned)
    b. Fill out a Participant Health Questionnaire
    c. Fill out a Simulator Sickness Questionnaire
    d. Have his interpupilary distance measured

2. The participant is fitted with VR equipment (head-mounted display) and the Gallery Room will be lit with:

    1. low contrast lighting on a painting on the left and a vase on the right (low contrast plvr)
    2. low contrast lighting on a painting on the right and a vase on the left (low contrast prvl)
    3. high contrast lighting on a painting on the left and a vase on the right (high contrast plvr)
    4. high contrast lighting on a painting on the right and a vase on left (high contrast prvl)
    5. uniform lighting (no objects highlighted)

3. The participant hears instructions from headphones in the head-mounted display (see Appendix C.2) and is given two minutes to explore the Gallery Room.

4. The participant will then:
    a. Fill out a Simulator Sickness Questionnaire
    b. Fill out a Presence Questionnaire
    c. Fill out a PANAS Questionnaire
    d. Fill out a Lighting Impression Questionnaire

The participant repeats steps 2, 3, and 4 five times (once for each condition).

The participant receives either experimental class credit or $10 upon the completion of the experiment. The condition for each session is elected according to a balanced Latin square design.

B.3 The Knot Experiment Procedure

An outline of the procedure for the Knot Experiment is given below. The questionnaires are explained in Appendix D.

1) When the participant comes to the graphics laboratory he will:
   a. Fill out and sign the consent form (which will be copied and returned)
   b. Fill out a Demographics Questionnaire
   c. Fill out a Participant Health Questionnaire
   d. Have his interpupilary distance measured

2) The participant is fitted with VR equipment and will experience one of the following nine lighting quality conditions:

   1) global illumination search object / global illumination table objects
   2) global illumination search object / local illumination table objects
   3) global illumination search object / ambient illumination table objects
   4) local illumination search object / global illumination table objects
   5) local illumination search object / local illumination table objects
   6) local illumination search object / ambient illumination table objects
   7) ambient illumination search object / global illumination table objects
   8) ambient illumination search object / local illumination table objects
   9) ambient illumination search object / ambient illumination table objects

3) The participant hears instructions from headphones in the head-mounted display (see Appendix C.3) about how to search for objects on the tables.

4) The participant performs the search task in the same lighting combination for 26 trials.

5) The participant will then:
   a. Fill out a Memory Questionnaire

The participant receives a half hour of experimental class credit.
Trials were presented according to a balanced Latin Square design.

Appendix C: Experimental Directions

C.1 The Pit Experiment Directions

Directions were played from a CD while the participant was in the Training Room for the experiment. There were two versions of the directions, one for the case in which there were textures on the objects and one for the grid condition. This was necessary because the grid did not have the same easily identifiable landmarks that were in the other conditions.

Non-Grid Condition Directions

We will now give you a brief tour of the environment and let you get accustomed to the equipment.

Please look all around the room you are in. <Pause 10 seconds> Also notice that you have a virtual right hand. The virtual hand will follow the movements of your real hand. Please move your right hand in front of you so that you can *see* how it moves. <Pause 5 seconds>

Please locate the painting on the wall. Walk over and take a good look at the painting. <Pause 10 seconds> Now turn to your right, walk over to the counter, and look out the window. <Pause 10 seconds> Note that you can feel the counter in front of you <Pause 4 seconds>

To your right, in the center of the room there is a pedestal with a ball on it. Please turn and walk to the pedestal. <Pause 4 seconds> You can actually pick up and move some objects in the virtual world – such as the ball on the pedestal. You do this by putting your hand near the object and pressing and holding the trigger of the hand-held joystick. Please pick up the ball from the pedestal by pressing and holding the trigger. <Pause 4 seconds> Examine the ball and hold it in front of you.. <Pause 9 seconds> While still holding the ball in front of you, turn to your left, and locate the target on the floor near the wooden door. Now walk over and drop the ball on the target. You can drop the ball by releasing the trigger. <Pause 10 seconds>

In a few moments, you will proceed into the next room where there will be a circular target on the lower floor. There are three balls that you will drop onto that target. One ball is located on the counter next to the window in this room. You will find the other two balls in the next room.

In a minute we will open up the door, have you pick up the ball from the counter, and take it to the next room. When you walk into the next room, the target will be directly in front of and below you.

After you drop the first ball, please walk over to the second ball that will be on your left. Please pick the ball up, walk back to the target, and drop the ball on the target. Then locate the third ball which will be on your right and drop that ball on the target. Please try to be accurate when dropping the balls.

After you have dropped all three balls, please return to the training room. Please do all of this at your own relaxed pace.

Unless absolutely necessary, no one will talk to you until you come back into this room.

Please proceed and be sure to take a step up as you enter the next room.

Remember: pick up the ball on the counter first, then the ball on the left, then the ball on the right.

Grid Condition Directions

We will now give you a brief tour of the environment and let you get accustomed to the equipment.

Please turn your head and look all around the room you are in. <Pause 10 seconds> Also notice that you have a virtual right hand. The virtual hand will follow the movements of your real hand. Please move your right hand in front of you so that you can *see* how it moves. <Pause 5 seconds>

Please locate the chair in the corner. Walk over and take a good look at the chair. <Pause for 10 seconds> Now turn to your right, walk over to the counter, and look out the window. <Pause 10 seconds> Note that you can feel the counter in front of you <Pause 4 seconds>

To your right, in the center of the room there is a pedestal with a ball on it. Please turn and walk to the pedestal. <Pause 4 seconds> You can actually pick up and move some objects in the virtual world – such as the ball on the pedestal. You do this by putting your hand near the object and pressing and holding the trigger of the hand-held joystick. Please pick up the ball from the pedestal by pressing and holding the trigger. <Pause 4 seconds> Examine the ball and hold it in front of you. <Pause 9 seconds> While still holding the ball in front of you, turn to your left, and locate the circular target on the <Pause 5 seconds>. Now walk over and drop the ball on the target. You can drop the ball by releasing the trigger. <Pause 10 seconds>

In a few moments, you will proceed into the next room where there will be a circular target on the lower floor. There are three balls that you will drop onto that target. One ball is located on the counter next to the window in this room. You will find the other two balls in the next room.

In a minute we will open up the door, have you pick up the ball from the counter, and take it to the next room. When you walk into the next room, the target will be directly in front of and below you.

After you drop the first ball, please walk over to the second ball that will be on your left. Please pick the ball up, walk back to the target, and drop the ball on the target. Then locate the third ball which will be on your right and drop that ball on the target. Please try to be accurate when dropping the balls.

After you have dropped all three balls, please return to the training room. Please do all of this at your own relaxed pace.

Unless absolutely necessary, no one will talk to you until you come back into this room.

Please proceed and be sure to take a step up as you enter the next room.

Remember: pick up the ball on the counter first, then the ball on the left, then the ball on the right.

C.2 The Gallery Experiment Directions

Directions were played from headphones in the head-mounted display while the participant was in the Training Room.

First Exposure

Welcome to the virtual environment.

We will now give you a brief tour of the environment and let you get accustomed to the equipment.

At this point, you should be looking at a painting of flowers on the wall directly in front of you.

We will be asking you to look at different objects in this room.

Do NOT look at an object by moving your eyes only. Please turn your HEAD toward the object you want to look at. You may also move about the environment freely and walk toward the object you wish to see.

Please locate the gray vase on the table to your right. Try walking up to this object.

<Pause 10 seconds> Now, turning towards your left, please turn all the way around and look at the painting on the wall directly behind you. <5 seconds> Please walk towards this painting and examine it.

<Pause 10 seconds> Now step back from the alcove and look at the vase on the stand to your left past the divider.

<Pause 10 seconds> Now keep turning to your *right* until you locate the door in this room. In a few moments, this door will open and you will be asked to explore the environment in next room.

You will have two minutes of viewing time.

Unless absolutely necessary, no one will talk to you until your session is finished.

Please remember that you can walk freely about the room and that when you want to look at an object, that you must do so by turning your HEAD towards the object, not just by moving your eyes.

Please proceed into the next room once the door has opened.

Subsequent Exposures

Welcome back to the virtual environment.

At this point, you should be looking at a painting of flowers on the wall directly in front of you.

We will be asking you to look at different objects in this room.

Do NOT look at an object by moving your eyes only. Please turn your HEAD toward the object you want to look at. You may also move about the environment freely and walk toward the object you wish to see.

Now Please look to your left and locate an object you wish to examine. Try walking up to this object.

Now please turn to your right and locate an object on the table behind you. Try walking up to the object you want to look at.

<Pause 10 seconds> Now keep turning to your right until you locate the door in this room. In a few moments, this door will open and you will be asked to explore the environment in next room.

You will have two minutes of viewing time.

Unless absolutely necessary, no one will talk to you until your session is finished.

Please remember that you can walk freely about the room and that when you want to look at an object, that you must do so by turning your HEAD towards the object, not just by moving your eyes.

Please proceed once the door has opened.

After 2 Minute Exposure Completed

Your time is up, please walk back into the room where you started.

C.3 The Knot Experiment Directions

Directions were played from headphones in the head-mounted display while the participant was sitting on a chair in graphics laboratory. The participant viewed the virtual environment (with a blank table and blank search object image) in the head-mounted display while hearing the directions.

Welcome to the virtual environment.

In this experiment, you will be finding objects on tables. Sometimes the object to search for will be on the table. Sometimes it will not be on the table.

You will begin a trial by pressing the trigger on the joystick in your right hand.

At the beginning of a trial an image of a search object will appear for 10 seconds.

Study the image of the search object during this time.

After 10 seconds the image of the search object will disappear and objects will appear on a table before you.

Look at the objects on the table and determine if the search object is on the table or not on the table as quickly as possible. Press the trigger of the joystick as soon as you have made your decision.

After you have pressed the trigger, please select the object with the joystick or select the button labeled 'object not on table'.

You can select a button or item by pressing the trigger.

After you have selected your object or selected the 'object not on table' button. The table will reset and you will need to press the trigger again to start the next trial.

Please press the trigger now to begin your first trial.

Appendix D: Questionnaires

D.1 Informed Consent Form – The Pit Experiment

Although the Consent Form below provides permission for video taping of participants, video taping was not used in the Pit Experiment.

Informed Consent Form: Participant's Copy

Introduction and purpose of the study:

We are inviting you to participate in a study of effect in virtual environment (VE) systems. The experiment is entitled, "The Influence of Rendering Quality on Presence and Task Performance in a Virtual Environment." The purpose of this research is to measure how presence in (or believability of) VEs changes with differing rendering methods. We hope to learn things that will help VE researchers and practitioners using VEs to treat people.

The principal investigator is Paul Zimmons (UNC Chapel Hill, Department of Computer Science, 344 Sitterson Hall, 914-1900, email: zimmons@cs.unc.edu). The faculty advisor in the Psychology Department is Dr. Abigail Panter (UNC Chapel Hill, Department of Psychology, CB #3270 Davie Hall, 962-4012, email: panter@unc.edu).

What will happen during the study:

We will ask you to come to the laboratory for one session, which will last approximately one hour. During the session, you will perform a few simple tasks within the VE. You will also be given questionnaires asking about your perceptions and feelings during and after the VE experience. Approximately 50 people will take part in this study.

We will use computers to record your hand, head, and body motion during the VE experience. We will use sensors on your fingers and chest to record heart rate and other physiological measures. We will also make video and audio recordings of the sessions. These video records will be kept for 2 years in case re-examination is needed at a later date. The video tapes will be secured in a locked cabinet.

Protecting your privacy:

We will make every effort to protect your privacy. We will not use your name in any of the data recording or in any research reports. We will use a code number rather than your name. No images from the videotapes in which you are personally recognizable will be used in any presentation of the results.

Risks and discomforts:

While using the virtual environment systems, some people experience slight symptoms of disorientation, nausea, or dizziness. These can be similar to motion sickness or to feelings experienced in wide-screen movies and theme park rides. We do not expect these effects to be strong or to last after you leave the laboratory. If at any time during the study you feel uncomfortable and wish to stop the experiment you are free to do so.

Your rights:

You have the right to decide whether or not to participate in this study, and to withdraw form the study at any time without penalty. You will receive 1 hour of Psych 10 experiment credit for participating in the study.

Institutional Review Board approval:

The Academic Affairs Institutional Review Board (AA-IRB) of the University of North Carolina at Chapel Hill has approved this study. If you have any concerns about your rights in this study you may contact the Chair of the AA-IRB, Barbara Davis Goldman, CB#4100, 201 Bynum Hall, UNC-CH, Chapel Hill, NC 27599-4100, (919) 962-7761, or email: aa-irb@unc.edu.

Summary:

I understand that this is a research study to measure the change in presence (or believability) over subsequent exposures to a virtual environment. I understand that if I agree to be in this study:

- I will visit the laboratory once for approximately 1 hour.
- I will wear a virtual environment headset to perform tasks, and my movements, physiological signals (via sensors on my fingers and chest), and behavior will be recorded by computer and on videotape, and I will respond to questionnaires between and after the sessions.
- I may experience slight feelings of disorientation, nausea, or dizziness during or shortly after the VE experiences.
- I certify that I am at least 18 years of age.
- I have had a chance to ask any questions I have about this study and those questions have been answered for me.

I have read the information in this consent form, and I agree to be in the study. I understand that I will get a copy of this consent form after I sign it.

________________________________ Signature of Participant   ________________ Date

I am willing for videotapes showing me performing the experiment to be included in presentations of the research. ☐ Yes ☐ No

D.2 Informed Consent Form – The Gallery Experiment

Informed Consent Form: Participant's Copy

Introduction and purpose of the study:

We are inviting you to participate in a study of the effect of light in virtual environment (VE) systems. The experiment is entitled, "Lighting and Presence in a Virtual Environment." The purpose of this research is to measure how presence in (or believability of) VEs changes with differing rendering methods. We hope to learn things that will help VE researchers and practitioners.

The principal investigator is Paul Zimmons (UNC Chapel Hill, Department of Computer Science, 344 Sitterson Hall, 914-3854, email: zimmons@cs.unc.edu). The faculty advisor in the Psychology Department is Dr. Abigail Panter (UNC Chapel Hill, Department of Psychology, CB #3270 Davie Hall, 962-4012, email: panter@unc.edu).

What will happen during the study:

We will ask you to come to the laboratory for one session, which will last approximately two hours. During that session, you will be exposed to the virtual environment five times and will be asked to perform a few simple tasks within the VE. You will also be given questionnaires asking about your perceptions and feelings prior to your first VE exposure and the after each subsequent VE exposure. Approximately 20 people will take part in this study.

We will use computers to record your head and body motion during the VE experience.

Protecting your privacy:

We will make every effort to protect your privacy. We will not use your name in any of the data recording or in any research reports. We will use a code number rather than your name.

Risks and discomforts:

While using the virtual environment systems, some people experience slight symptoms of disorientation, nausea, or dizziness. These can be similar to motion sickness or to feelings experienced in wide-screen movies and theme park rides. We do not expect these effects to be strong or to last after you leave the laboratory. If at any time during the study you feel uncomfortable and wish to stop the experiment you are free to do so.

Your rights:

You have the right to decide whether or not to participate in this study, and to withdraw from the study at any time. You will receive 2 hours of Psych 10 experiment credit for completing the study. If you decide to withdraw from participation during the experiment, you will be given credit on a pro-rated basis.

Institutional Review Board approval:

The Academic Affairs Institutional Review Board (AA-IRB) of the University of North Carolina at Chapel Hill has approved this study. If you have any concerns about your rights in this study you may contact the Chair of the AA-IRB, Barbara Davis Goldman at (919) 962-7761 or email: aa-irb@unc.edu.

Summary:

I understand that this is a research study to measure the change in presence (or believability) over subsequent exposures to a virtual environment. I understand that if I agree to be in this study:

- I will visit the laboratory once for approximately 2 hours.
- I will wear a virtual environment headset to perform tasks, and my movements and behavior will be recorded by computer, and I will respond to questionnaires before and after the sessions.
- I may experience slight feelings of disorientation, nausea, or dizziness during or shortly after the VE experiences.
- I certify that I am at least 18 years of age.
- I have had a chance to ask any questions I have about this study and those questions have been answered for me.

I have read the information in this consent form, and I agree to be in the study. I understand that I will get a copy of this consent form after I sign it.

________________________________ ________________

Signature of Participant Date

D.3 Informed Consent Form – The Knot Experiment

Informed Consent Form: Experimenter's Copy

Introduction and purpose of the study:

We are inviting you to participate in a study of effect in virtual environment (VE) systems. The experiment is entitled, "Lighting and Task Performance in a Virtual Environment." The purpose of this research is to measure how task performance of VEs changes with differing rendering methods. We hope to learn things that will help VE researchers and practitioners using VEs in task-oriented environments.

The principal investigator is Paul Zimmons (UNC Chapel Hill, Department of Computer Science, 344 Sitterson Hall, 914-1900, email: zimmons@cs.unc.edu). The faculty advisor in the Psychology Department is Dr. Abigail Panter (UNC Chapel Hill, Department of Psychology, CB #3270 Davie Hall, 962-4012, email: panter@unc.edu).

What will happen during the study:

We will ask you to come to the laboratory for one session, which will last approximately one hour. During the session, you will perform a few simple tasks within the VE. You will also be given questionnaires asking about your experience after the VE experience. Approximately 40 people will take part in this study.

We will use computers to record your head, hand, and body motion during the VE experience.

Protecting your privacy:

We will make every effort to protect your privacy. We will not use your name in any of the data recording or in any research reports. We will use a code number rather than your name.

Risks and discomforts:

While using the virtual environment systems, some people experience slight symptoms of disorientation, nausea, or dizziness. These can be similar to motion sickness or to feelings experienced in wide-screen movies and theme park rides. We do not expect these effects to be strong or to last after you leave the laboratory. If at any time during the study you feel uncomfortable and wish to stop the experiment you are free to do so.

Your rights:

You have the right to decide whether or not to participate in this study, and to withdraw from the study at any time. You will receive 1 hour of Psych 10 experiment credit for completing the study. If you decide to withdraw from participation during the experiment, you will be given credit on a pro-rated basis.

Institutional Review Board approval:

The Academic Affairs Institutional Review Board (AA-IRB) of the University of North Carolina at Chapel Hill has approved this study. If you have any concerns about your rights in this study you may contact the Chair of the AA-IRB, Barbara Davis Goldman at (919) 962-7761 or email: aa-irb@unc.edu.

Summary:

I understand that this is a research study to measure the change in presence (or believability) over subsequent exposures to a virtual environment. I understand that if I agree to be in this study:

- I will visit the laboratory once for approximately 1 hour.
- I will wear a virtual environment headset to perform tasks, and my movements and behavior will be recorded by computer, and I will respond to questionnaires before and after the sessions.
- I may experience slight feelings of disorientation, nausea, or dizziness during or shortly after the VE experiences.
- I certify that I am at least 18 years of age.
- I have had a chance to ask any questions I have about this study and those questions have been answered for me.

I have read the information in this consent form, and I agree to be in the study. I understand that I will get a copy of this consent form after I sign it.

________________________________ ________________
Signature of Participant Date

D.4 Participant Health Questionnaire

This questionnaire is identical to the one used by Meehan (2001). The participant filled out this questionnaire before conducting any of the trials to determine if he was well enough to continue with the experiment.

Participant Health Questionnaire
ID # ________

> ***Instructions***: Please check off your answers to the following questions and fill in the blanks if necessary.

1. **Are you in your usual state of good fitness (health)?**

   ❑ Yes ❑ No

   If not, please explain: ____
   ____

2. **In the past 24 hours, which, if any, of the following substances (including alcohol or prescription drugs) have you used?**

   Please check off all that apply.

   ❑ Sedatives or tranquilizers
   ❑ Decongestants
   ❑ Anti-histamines
   ❑ Other
   ❑ None

D.5 Demographics Questionnaire

This questionnaire was administered after the Participant Health Questionnaire in the Gallery and Knot Experiments. In the Pit Experiment, these questions were integrated with the Virtual Environment Questionnaire.

Demographics Questionnaire
ID # ________

> ***Instructions***: Using the responses provided below, please indicate your response to each question or fill in the blank.

1. Gender, Age, and Race/ Ethnicity:

   ❑ Male ❑ Female Age: _______

   Race/ Ethnicity (please check *one*):
   - ❑ American Indian or Alaskan Native
   - ❑ Asian or Pacific Islander
   - ❑ Black, not of Hispanic Origin
   - ❑ Hispanic
   - ❑ White, not of Hispanic Origin
   - ❑ Other

2. What is your University status?

   My status is as follows (please check *one*):
   - ❑ Undergraduate student
   - ❑ Graduate student
   - ❑ Research Associate
   - ❑ Staff member - systems/technical staff
   - ❑ Faculty
   - ❑ Administrative staff
   - ❑ Other (please write in): ________________________________

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

   I use a computer...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Not at All						Very Much

4. To what extent do you play computer games?

I play computer games...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Not at All						Very Much

5. How many hours per week do you exercise?

During an average week, I exercise... (please check *one*)

- ❑ Less than 0.5 hours
- ❑ 0.5 hours
- ❑ 1 hour
- ❑ 1.5 hours
- ❑ 2 hours
- ❑ 2.5 hours
- ❑ 3 or more hours

D.6 Simulator Sickness Questionnaire

The Simulator Sickness Questionnaire (SSQ) was originally developed by Kennedy et al. (1993) and also used in Meehan (2001). Kennedy et al. suggested using post-exposure Simulator Sickness scores for evaluating sickness as well as comparing pre and post exposure scores.

In the Pit Experiment, the SSQ was administered before and after exposure to the virtual environment. In the Gallery Experiment, the SSQ was administered before trials began and after each subsequent trial in the experiment.

The Simulator Sickness Questionnaire was named "Current Condition Questionnaire" when given to the participants. A separate sheet of definitions was also given to the participant explaining some of the terms used on the questionnaire.

Each response in the SSQ is given a score of 0,1,2,3 for "none", "slight", "moderate", and "severe" respectively.

The sickness scores are then calculated as follows:

Column1 = Σ(Questions 1,6,7,8,9,15,16)
Column2 = Σ(Questions 1,2,3,4,5,9,11)
Column3 = Σ(Questions 5,8,10,11,12,13,14)

Nausea = 9.54 * Column1
Ocular Discomfort = 7.58 * Column2
Disorientation = 13.92 * Column3
Simulator Sickness = 3.74 * (Column1+Column2+Column3)

The Simulator Sickness score can range from 0 to 235.62.

Current Condition Questionnaire
ID # ________

> ***Instructions***: For each of the following conditions, please indicate how you are feeling right now on the scale of none through severe. Please check one response per question.

1. General Discomfort	❑ None	❑ Slight	❑ Moderate	❑ Severe
2. Fatigue	❑ None	❑ Slight	❑ Moderate	❑ Severe
3. Headache	❑ None	❑ Slight	❑ Moderate	❑ Severe
4. Eye Strain	❑ None	❑ Slight	❑ Moderate	❑ Severe
5. Difficulty Focusing	❑ None	❑ Slight	❑ Moderate	❑ Severe
6. Increased Salivation	❑ None	❑ Slight	❑ Moderate	❑ Severe
7. Sweating	❑ None	❑ Slight	❑ Moderate	❑ Severe
8. Nausea	❑ None	❑ Slight	❑ Moderate	❑ Severe
9. Difficulty Concentrating	❑ None	❑ Slight	❑ Moderate	❑ Severe
10. Fullness of Head	❑ None	❑ Slight	❑ Moderate	❑ Severe
11. Blurred Vision	❑ None	❑ Slight	❑ Moderate	❑ Severe
12. Dizzy (with your eyes open)	❑ None	❑ Slight	❑ Moderate	❑ Severe
13. Dizzy (with your eyes closed)	❑ None	❑ Slight	❑ Moderate	❑ Severe
14. Vertigo	❑ None	❑ Slight	❑ Moderate	❑ Severe
15. Stomach Awareness	❑ None	❑ Slight	❑ Moderate	❑ Severe
16. Burping	❑ None	❑ Slight	❑ Moderate	❑ Severe

In the space below, please list any additional symptoms you are experiencing (continue on the back if necessary).

Definitions for Current Condition Questionnaire

Explanation of Conditions

General Discomfort	
Fatigue	Weariness or exhaustion of the body
Headache	
Eye Strain	Weariness or soreness of the eyes
Difficulty Focusing	
Increased Salivation	
Sweating	
Nausea stomach distress	
Difficulty Concentrating	
Fullness of Head	A feeling of stuffiness similar to a cold
Blurred Vision	
Dizzy (with your eyes open)	
Dizzy (with your eyes closed)	
Vertigo	Surroundings seem to swirl
Stomach Awareness	A feeling just short of nausea
Burping	

D.7 Height Anxiety Questionnaire

The Height Anxiety Questionnaire was administered in the Pit Experiment before the participant was exposed to the virtual environment. The Height Anxiety Questionnaire was originally developed by Cohen (1977) and was also used by Meehan (2001).

In the Pit Experiment, the Height Avoidance Questionnaire was administered as “Height Questionnaire 1”.

Each question has a range of response values from 0 to 6. The Height Anxiety Questionnaire is scored by summing the responses to the questions.

Height Questionnaire 1
ID # ________

Instructions: Below, we have compiled a list of situations involving height. We are interested in knowing how anxious (tense, uncomfortable) you would feel in each situation. Please indicate how you would feel by choosing one of the following numbers (0,1,2,3,4,5,6) in the space below each statement: 0 Not at all anxious; calm and relaxed 1 2 Slightly anxious 3 4 Moderately anxious 5 6 Extremely anxious

1. Diving off the low board at a swimming pool.

❑0 Not at All Anxious	❑1	❑2	❑3	❑4	❑5	❑6 Extremely Anxious

2. Stepping over rocks crossing a stream.

❑0 Not at All Anxious	❑1	❑2	❑3	❑4	❑5	❑6 Extremely Anxious

3. Looking down a circular stairway from several flights up.

❑0 Not at All Anxious	❑1	❑2	❑3	❑4	❑5	❑6 Extremely Anxious

4. Standing on a ladder leaning against a house, second story.

❑0 Not at All Anxious	❑1	❑2	❑3	❑4	❑5	❑6 Extremely Anxious

5. Sitting in the front row of an upper balcony of a theater.

❑0 Not at All Anxious	❑1	❑2	❑3	❑4	❑5	❑6 Extremely Anxious

6. Riding a Ferris wheel.

❑0 Not at All Anxious ❑1 ❑2 ❑3 ❑4 ❑5 ❑6 Extremely Anxious

7. Walking up a steep incline in country hiking.

❑0 Not at All Anxious ❑1 ❑2 ❑3 ❑4 ❑5 ❑6 Extremely Anxious

8. Airplane trip (to San Francisco).

❑0 Not at All Anxious ❑1 ❑2 ❑3 ❑4 ❑5 ❑6 Extremely Anxious

9. Standing next to an open window on the third floor.

❑0 Not at All Anxious ❑1 ❑2 ❑3 ❑4 ❑5 ❑6 Extremely Anxious

10. Walking on a footbridge over a highway.

❑0 Not at All Anxious ❑1 ❑2 ❑3 ❑4 ❑5 ❑6 Extremely Anxious

11. Driving over a large bridge (Golden Gate, George Washington).

❑0 Not at All Anxious ❑1 ❑2 ❑3 ❑4 ❑5 ❑6 Extremely Anxious

12. Being away from a window in an office on the 15th floor of a building.

❑0 Not at All Anxious ❑1 ❑2 ❑3 ❑4 ❑5 ❑6 Extremely Anxious

13. Seeing window washers 10 flights up on a scaffold.

❑0 Not at All Anxious ❑1 ❑2 ❑3 ❑4 ❑5 ❑6 Extremely Anxious

14. Walking over a sidewalk grating.

❑0	❑1	❑2	❑3	❑4	❑5	❑6
Not at All Anxious						Extremely Anxious

15. Standing on the edge of a subway platform.

❑0	❑1	❑2	❑3	❑4	❑5	❑6
Not at All Anxious						Extremely Anxious

16. Climbing a fire escape to the 3rd floor landing.

❑0	❑1	❑2	❑3	❑4	❑5	❑6
Not at All Anxious						Extremely Anxious

17. Standing on the roof of a 10 story apartment building.

❑0	❑1	❑2	❑3	❑4	❑5	❑6
Not at All Anxious						Extremely Anxious

18. Riding the elevator to the 50th floor.

❑0	❑1	❑2	❑3	❑4	❑5	❑6
Not at All Anxious						Extremely Anxious

19. Standing on a chair to get something off a shelf.

❑0	❑1	❑2	❑3	❑4	❑5	❑6
Not at All Anxious						Extremely Anxious

20. Walking up the gangplank of an ocean liner.

❑0	❑1	❑2	❑3	❑4	❑5	❑6
Not at All Anxious						Extremely Anxious

D.8 Height Avoidance Questionnaire

The Height Avoidance Questionnaire was administered in the Pit Experiment before the participant was exposed to the virtual environment. The Height Avoidance Questionnaire was originally developed by Cohen (1977) and was also used by Meehan (2001).

In the Pit Experiment, the Height Avoidance Questionnaire was administered as “Height Questionnaire 2”.

Each question has a range of response values from 0 to 2. The Height Avoidance Questionnaire is scored by summing the responses to the questions.

Height Questionnaire 2
ID # ________

> ***Instructions***: Now that you have rated each item according to anxiety, we would like you to rate them as to avoidance. Indicate, in the space below the statements, how much you would avoid the situation if it arose.
>
> 0 Would not avoid doing it
> 1 Would try to avoid doing it
> 2 Would not do it under any circumstances

1. Diving off the low board at a swimming pool.

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

2. Stepping over rocks crossing a stream.

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

3. Looking down a circular stairway from several flights up.

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

4. Standing on a ladder leaning against a house, second story.

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

5. Sitting in the front row of an upper balcony of a theater.

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

6. Riding a Ferris wheel.

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

7. Walking up a steep incline in country hiking.

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

8. Airplane trip (to San Francisco).

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

9. Standing next to an open window on the third floor.

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

10. Walking on a footbridge over a highway.

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

11. Driving over a large bridge (Golden Gate, George Washington).

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

12. Being away from a window in an office on the 15th floor of a building.

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

13. Seeing window washers 10 flights up on a scaffold.

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

14. Walking over a sidewalk grating.

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

15. Standing on the edge of a subway platform.

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

16. Climbing a fire escape to the 3rd floor landing.

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

17. Standing on the roof of a 10 story apartment building.

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

18. Riding the elevator to the 50th floor.

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

19. Standing on a chair to get something off a shelf.

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

20. Walking up the gangplank of an ocean liner.

❑0	❑1	❑2
Would Not Avoid It		Would Not Do it Under Any Circumstances

D.9 University of College London Presence Questionnaire

The Presence Questionnaire is reproduced below. It is similar to the one used in Usoh et al. (1999) and Meehan (2001) but with some additional questions for the Pit Experiment and the Gallery Experiment.

The Pit Experiment included questions about memory and the depth of the virtual pit. The questionnaire was administered after exposure to the virtual environment.

The Gallery Experiment included questions about the lighting in the virtual environment and was given after each trial.

Each question in the University of College London (UCL) Presence Questionnaire is scored on a scale from 1 to 7. For each question the number of high responses was summed. A high response was considered to be a score of 5, 6, or 7. For Question 1, the scale is reversed. For that question, a score of 1, 2, or 3 was considered high. Usoh (1999) used a response of 6 or 7 as high, and Meehan (2001) investigated using 6 or 7 and 5, 6, or 7 as a high response.

The scores related to the UCL Presence Questionnaire were calculated as follows.

In the Pit Experiment, the scoring method was:

Reported Presence = Σ (High 2, 5, 12, 14, 15, 17, 18)
Reported Behavioral Presence = Σ (High 1, 8, 10)
Reported Ease of Locomotion = Σ (High 4, 6, 9)

In the Gallery Experiment, the same scoring was used as in the Pit Experiment, but the demographics questions were removed. Using the remapped questions, the scoring method was:

Reported Presence = Σ (High 2, 4, 10, 12, 13, 14, 15)
Reported Behavioral Presence = Σ (High 1, 7, 9)
Reported Ease of Locomotion = Σ (High 3, 5, 8)

Presence Questionnaire – The Pit Experiment

Virtual Environment Questionnaire
ID # ________

> ***Instructions***: Using the scales provided below, please indicate your response to each question or fill in the blank.

The following questions relate to your experience.

1. Please rate the extent to which you were aware of background sounds in the real laboratory in which this experience was actually taking place. Rate this on the scale from 1 to 7 (where for example 1 means that you were hardly aware at all of the background sounds and 7 means that you were very much aware of the background sounds):

   While in the virtual reality I was aware of background sounds from the laboratory:

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Not at All						Very Much

2. Please rate your sense of being in the room that has the window on the following scale from 1 to 7, where 7 represents your normal experience of being in a place.

   I had a sense of being in the room with the window:

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Not at All						Very Much

3. Gender, Age, and Race/ Ethnicity:

   ❑ Male ❑ Female Age: _______

   Race/ Ethnicity (please check *one*):
   - ❑ American Indian or Alaskan Native
   - ❑ Asian or Pacific Islander
   - ❑ Black, not of Hispanic Origin
   - ❑ Hispanic
   - ❑ White, not of Hispanic Origin
   - ❑ Other

4. Did you find it relatively simple or relatively complicated to move through the computer-generated world?

To move through the computer-generated world was...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Very Complicated						Very Simple

5. To what extent were there times during the experience when the virtual rooms you were in became the "reality" for you, and you almost forgot about the "real world" of the laboratory in which the whole experience was really taking place?

There were times during the experience when the virtual rooms became more real for me compared to the "real world"...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
At No Time						Almost All The Time

6. How complicated or straightforward was it for you to get from place to place?

To get from place to place was...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Very Complicated						Very Straight-forward

7. To what extent did you associate with the computer-generated limbs as being "your limbs" while in the virtual reality?

I associated with the computer-generated body...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Not at All						Very Much

8. To what extent was your reaction when looking down into the pit in virtual reality the same as it would have been in a similar situation in real life?

Compared to real life my reaction was...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Not at All Similar						Very Similar

9. The act of moving from place to place in the computer-generated world can seem to be relatively natural or relatively unnatural. Please rate your experience of this.

The act of moving from place to place seemed to be...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Very Unnatural						Very Natural

10. Please rate any sense of fear of falling you experienced when looking down over the virtual precipice.

The sense of fear of falling I experienced was...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Not at All						Very Much

11. What is your University status?

My status is as follows (please check *one*):

- ❑ Undergraduate student
- ❑ Graduate student
- ❑ Research Associate
- ❑ Staff member - systems/technical staff
- ❑ Faculty
- ❑ Administrative staff
- ❑ Other (please write in): ___________________________________

12. When you think back to your experience, do you think of the virtual rooms more as images that you saw, or more as somewhere that you visited?

The virtual rooms seem to me to be more like...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Images that I Saw						Somewhere that I Visited

13. Have you experienced virtual reality before?

I have experienced virtual reality...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Never Before						A Great Deal

14. During the time of the experience, which was stronger on the whole, your sense of being in the virtual rooms or of being in the real world of the laboratory?

I had a stronger sense of being in...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
The Real World of the Laboratory						The Virtual World

15. Consider your memory of being in the virtual rooms. 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 the memory" consider things like the extent to which you have a visual memory of the virtual rooms, whether that memory is in color, 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.

I think of the virtual rooms as a place in a way similar to other places that I've been today...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Not at All						Very Much

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

I use a computer...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Not at All						Very Much

17. Please rate your sense of being in the room with the pit on the following scale from 1 to 7, where 7 represents your normal experience of being in a place.

I had a sense of being in the room with the pit:

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Not at All						Very Much

18. During the time of the experience, did you often think to yourself that you were actually just standing in a laboratory wearing a helmet or really in the virtual rooms?

During the experience, I often thought that I was really standing in the lab wearing a helmet...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Most of the Time, I Realized I was in the Lab						Never, Because I Believed I was in the Virtual Environment

19. Please list all the objects you remember at the in the training room and the bottom of the pit room:

***Training* Room Objects**: ____________________ ____________________
____________________ ____________________
____________________ ____________________
____________________ ____________________
____________________ ____________________
____________________ ____________________

***Pit* Room Objects**: ____________________ ____________________
____________________ ____________________
____________________ ____________________
____________________ ____________________
____________________ ____________________
____________________ ____________________

20. To what extent do you play computer games?

I play computer games...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Not at All						Very Much

21. How many hours per week do you exercise?

During an average week, I exercise... (please check *one*)

- ❑ Less than 0.5 hours
- ❑ 0.5 hours
- ❑ 1 hour
- ❑ 1.5 hours
- ❑ 2 hours
- ❑ 2.5 hours
- ❑ 3 or more hours

22. How far below you was the pit room floor in the virtual environment?

The pit room floor was ______ feet below me.

Further Comments

Please write down any further comments that you wish to make about your experience. All answers will be treated entirely confidentially.
In particular:

What things helped to give you a sense of "really being" in the virtual rooms?

What things acted to "pull you out" and make you more aware of "reality"?

Thank you once again for participating in this study and helping with our research. Please do not discuss this with anyone for two weeks. This is because the study is continuing, and you may happen to speak to someone who may be taking part.

Presence Questionnaire – The Gallery Experiment

Virtual Environment Questionnaire
ID # ________

> ***Instructions***: Using the scales provided below, please indicate your response to each question or fill in the blank.

The following questions relate to your experience.

1. Please rate the extent to which you were aware of background sounds in the real laboratory in which this experience was actually taking place. Rate this on the scale from 1 to 7 (where for example 1 means that you were hardly aware at all of the background sounds and 7 means that you were very much aware of the background sounds):

   While in the virtual reality I was aware of background sounds from the laboratory:

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Not at All						Very Much

2. Please rate your sense of being in training room (the room you started in) on the following scale from 1 to 7, where 7 represents your normal experience of being in a place.

   I had a sense of being in the training room:

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Not at All						Very Much

3. Did you find it relatively simple or relatively complicated to move through the computer-generated world?

   To move through the computer-generated world was...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Very Complicated						Very Simple

4. To what extent were there times during the experience when the virtual rooms you were in became the "reality" for you, and you almost forgot about the "real world" of the laboratory in which the whole experience was really taking place?

There were times during the experience when the virtual rooms became more real for me compared to the "real world"...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
At No Time						Almost All The Time

5. How complicated or straightforward was it for you to get from place to place?

To get from place to place was...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Very Complicated						Very Straight-forward

6. To what extent did you associate with the computer-generated limbs as being "your limbs" while in the virtual reality?

I associated with the computer-generated body...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Not at All						Very Much

7. To what extent was your reaction when looking around in the gallery the same as it would have been in a similar situation in real life?

Compared to real life my reaction was...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Not at All Similar						Very Similar

8. The act of moving from place to place in the computer-generated world can seem to be relatively natural or relatively unnatural. Please rate your experience of this.

The act of moving from place to place seemed to be...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Very Unnatural						Very Natural

9. Please rate your impression of the lighting in the gallery room.

The lighting in the gallery room was...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Plain						Dramatic

10. When you think back to your experience, do you think of the virtual rooms more as images that you saw, or more as somewhere that you visited?

The virtual rooms seem to me to be more like...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Images that I Saw						Somewh ere that I Visited

11. Have you experienced virtual reality before?

I have experienced virtual reality...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Never Before						A Great Deal

12. During the time of the experience, which was stronger on the whole, your sense of being in the virtual rooms or of being in the real world of the laboratory?

I had a stronger sense of being in...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
The Real World of the Laboratory						The Virtual World

13. Consider your memory of being in the virtual rooms. 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 the memory" consider things like the extent to which you have a visual memory of the virtual rooms, whether that memory is in color, 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.

I think of the virtual rooms as a place in a way similar to other places that I've been today...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Not at All						Very Much

14. Please rate your sense of being in the gallery room on the following scale from 1 to 7, where 7 represents your normal experience of being in a place.

I had a sense of being in the gallery room:

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Not at All						Very Much

15. During the time of the experience, did you often think to yourself that you were actually just standing in a laboratory wearing a helmet or really in the virtual rooms?

During the experience, I often thought that I was really standing in the lab wearing a helmet...

❑1	❑2	❑3	❑4	❑5	❑6	❑7
Most of the Time, I Realized I was in the Lab						Never, Because I Believed I was in the Virtual Environment

Further Comments

Please write down any further comments that you wish to make about your experience. All answers will be treated entirely confidentially.
In particular:

What things helped to give you a sense of "really being" in the virtual rooms?

What things acted to "pull you out" and make you more aware of "reality"?

Thank you once again for participating in this study and helping with our research. Please do not discuss this with anyone for two weeks. This is because the study is continuing, and you may happen to speak to someone who may be taking part.

D.10 Guilford-Zimmerman Aptitude Survey – Part 5 Spatial Orientation

The Guilford-Zimmerman Aptitude Survey – Part 5 Spatial Orientation is a multiple choice test that gauges how well the participant can reason spatially. The participant is shown two pictures from the bow of a boat and is asked to choose between five schematic representations of the motion of the boat from one picture to the next.

The questionnaire consists of 67 questions. Questions 1 through 7 are practice questions and are not scored. Questions 8 through 67 are scored by the following formula:

Score = $\sum$ Correct Answers – ¼ $\sum$ Incorrect Answers

Questions that the participant does not answer are not scored. The participant is given 10 minutes to fill out as many questions as he can.

An example question is provided below (reproduced from Tan et al., 2003). The correct response to the sample question is 5.

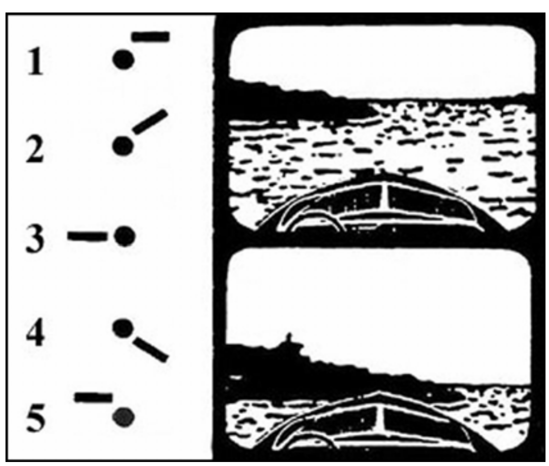


Figure D.1: A sample question from the Guildford-Zimmerman Aptitude Survey – Part 5 Spatial Orientation.

D.11 Lighting Impression Questionnaire

The Lighting Impression Questionnaire was developed by Flynn (1977, 1979) and utilized in Mania (2001).

The questionnaire uses a rating scale of 1 to 7 for different word pairs. The ratings for each pair are summed to arrive at a total score.

Lighting Questionnaire
ID # ________

The following questions relate to your impression of the environment. Please circle the appropriate step on the scale from 1 to 7, for each set of terms.

The lighting in the gallery room was...

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	diffuse
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	cold
pleasant	1	2	3	4	5	6	7	unpleasant
comfortable	1	2	3	4	5	6	7	uncomfortable

D.12 Lighting Memory Questionnaire

The Lighting Memory Questionnaire was administered after exposure to the virtual environment in the Knot Experiment. The questionnaire consists of 10 images of objects with a corresponding question for each image. For each image/question, the participant indicated whether he searched for the object during any of his trials and how confident he was in his response. The objects were shown in the same lighting model as the search objects in the experiment.

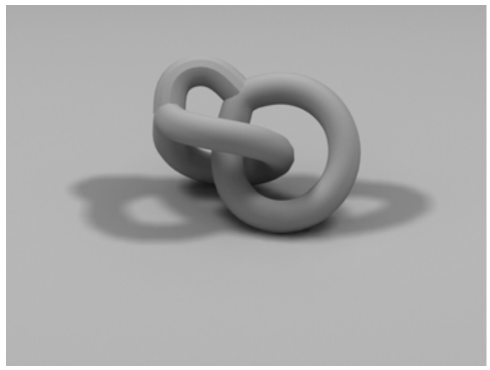
The questionnaire was scored by summing the number of correct responses.

The following is an example of a set of images and the corresponding questionnaire the participant filled out.

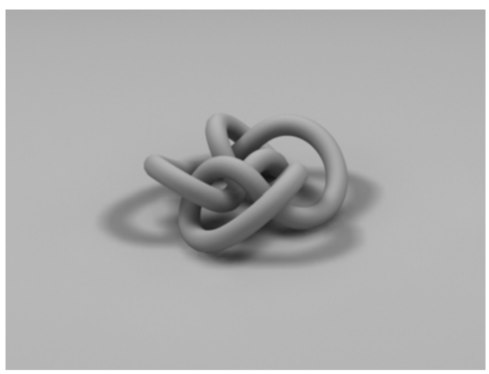
Memory Questionnaire

Sequence 1_1

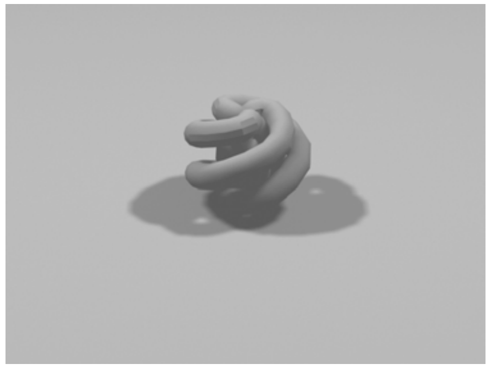
OBJECT 1



OBJECT 2

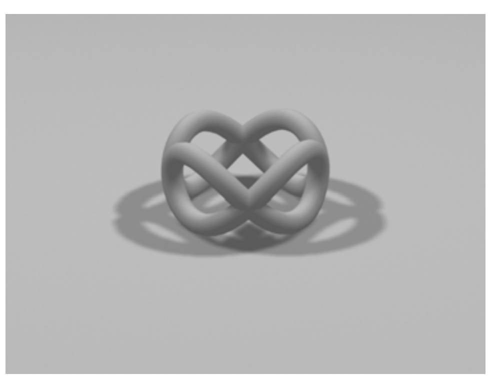


OBJECT 3

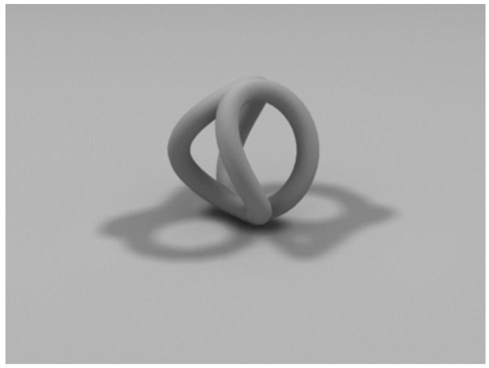


OBJECT 4

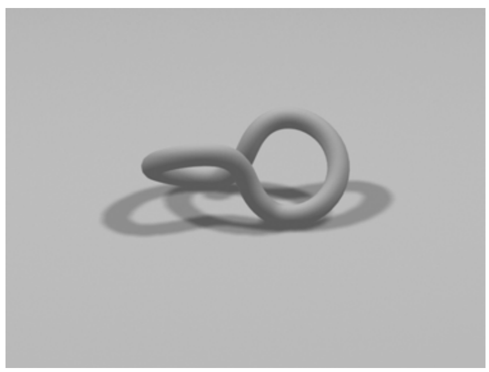
OBJECT 5



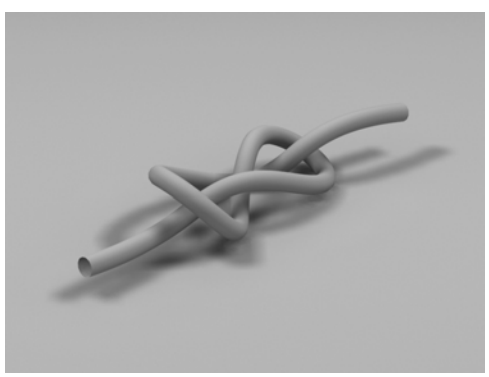
OBJECT 6



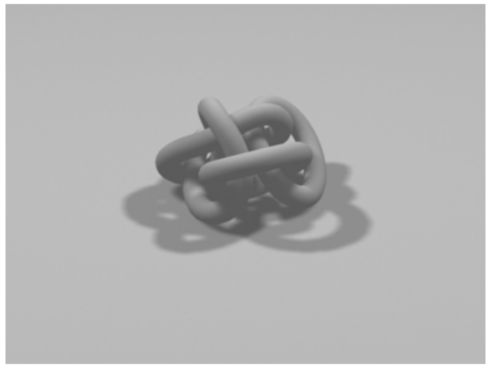
OBJECT 7



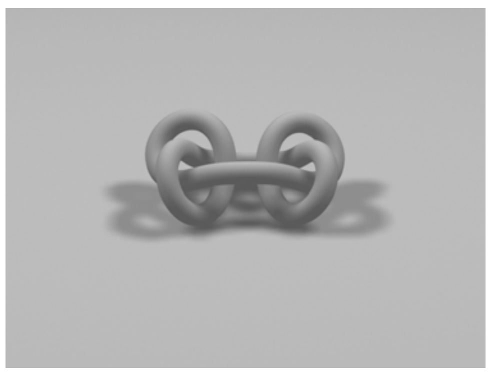
OBJECT 8



OBJECT 9



OBJECT 10



Memory Questionnaire
ID # ________
Image Sequence: ________

Instructions: Using the scales provided below, please indicate your response to each question or fill in the blank.

The following questions are about the objects you looked for on the tables (even if it turned out that object was not on the table).

OBJECT 1. ***Did you search for <u>object 1</u> during your trials?*** ❑ Yes ❑ No

How confident are you that your response is correct?

❑	❑	❑	❑	❑
No Confidence	Low Confidence	Moderately Confident	Confident	Certain

OBJECT 2. ***Did you search for <u>object 2</u> during your trials?*** ❑ Yes ❑ No

How confident are you that your response is correct?

❑	❑	❑	❑	❑
No Confidence	Low Confidence	Moderately Confident	Confident	Certain

OBJECT 3. ***Did you search for <u>object 3</u> during your trials?*** ❑ Yes ❑ No

How confident are you that your response is correct?

❑	❑	❑	❑	❑
No Confidence	Low Confidence	Moderately Confident	Confident	Certain

OBJECT 4. ***Did you search for <u>object 4</u> during your trials?*** ❑ Yes ❑ No

How confident are you that your response is correct?

❑	❑	❑	❑	❑
No Confidence	Low Confidence	Moderately Confident	Confident	Certain

OBJECT 5. ***Did you search for <u>object 5</u> during your trials?*** ❑ Yes ❑ No

How confident are you that your response is correct?

❑ No Confidence	❑ Low Confidence	❑ Moderately Confident	❑ Confident	❑ Certain

OBJECT 6. ***Did you search for <u>object 6</u> during your trials?*** ❑ Yes ❑ No

How confident are you that your response is correct?

❑ No Confidence	❑ Low Confidence	❑ Moderately Confident	❑ Confident	❑ Certain

OBJECT 7. ***Did you search for <u>object 7</u> during your trials?*** ❑ Yes ❑ No

How confident are you that your response is correct?

❑ No Confidence	❑ Low Confidence	❑ Moderately Confident	❑ Confident	❑ Certain

OBJECT 8. ***Did you search for <u>object 8</u> during your trials?*** ❑ Yes ❑ No

How confident are you that your response is correct?

❑ No Confidence	❑ Low Confidence	❑ Moderately Confident	❑ Confident	❑ Certain

OBJECT 9. ***Did you search for <u>object 9</u> during your trials?*** ❑ Yes ❑ No

How confident are you that your response is correct?

❑ No Confidence	❑ Low Confidence	❑ Moderately Confident	❑ Confident	❑ Certain

OBJECT 10. ***Did you search for <u>object 10</u> during your trials?*** ❑ Yes ❑ No

How confident are you that your response is correct?

❑ No Confidence	❑ Low Confidence	❑ Moderately Confident	❑ Confident	❑ Certain

D.13 Positive and Negative Affect Scale (PANAS) Questionnaire

The Positive and Negative Affect Scale was developed by Watson et al. (1988) to measure how people feel at a given moment. The PANAS Questionnaire can be administered multiple times in order to understand how people's attitudes or moods change over time or after different events.

Each term in the questionnaire is rated on a scale from 1 to 5. There are two scores associated with the questionnaire, the Positive Affect Score and Negative Affect Score. The formulae for the two scores are given below.

Positive Affect = Σ (interested, alert, excited, inspired, strong, determined, attentive, enthusiastic, proud, jittery)

Negative Affect = Σ (irritable, distressed, ashamed, upset, nervous, guilty, scared, hostile, jittery, afraid)

Affect Questionnaire
ID # ________

This scale consists of a number of words that describe different feelings and emotions. Read each item and then mark the appropriate answer in the space next to the word. Indicate to what extent you feel this way right now, that is, at the present moment. Use the following scale to record your answers.

1	2	3	4	5
very slightly or not at all	a little	moderately	quite a bit	extremely

______ interested	______ irritable
______ distressed	______ alert
______ excited	______ ashamed
______ upset	______ inspired
______ strong	______ nervous
______ guilty	______ determined
______ scared	______ attentive
______ hostile	______ jittery
______ enthusiastic	______ active
______ proud	______ afraid

Appendix E: Knot Experiment Objects

The following are images of the objects and tables that were used for the Knot Experiment.

E.1 Search Object Images – Object on the Table - Training Trials (Global)

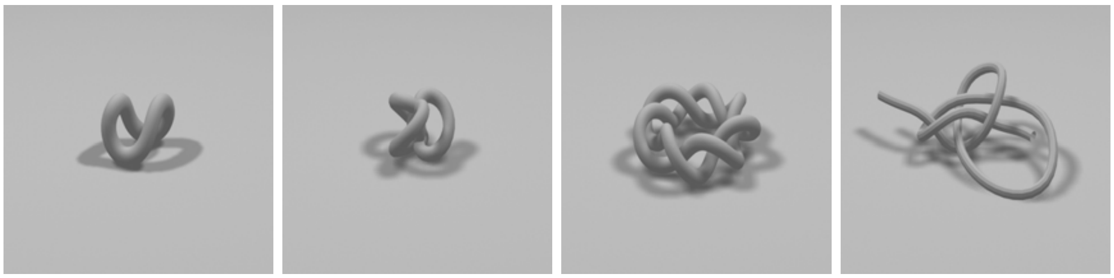


Figure E.1: Search Objects which were on Tables 1 through 4 respectively during the Training Trials.

E.2 Search Object Images – Object on the Table - Real Trials (Global)

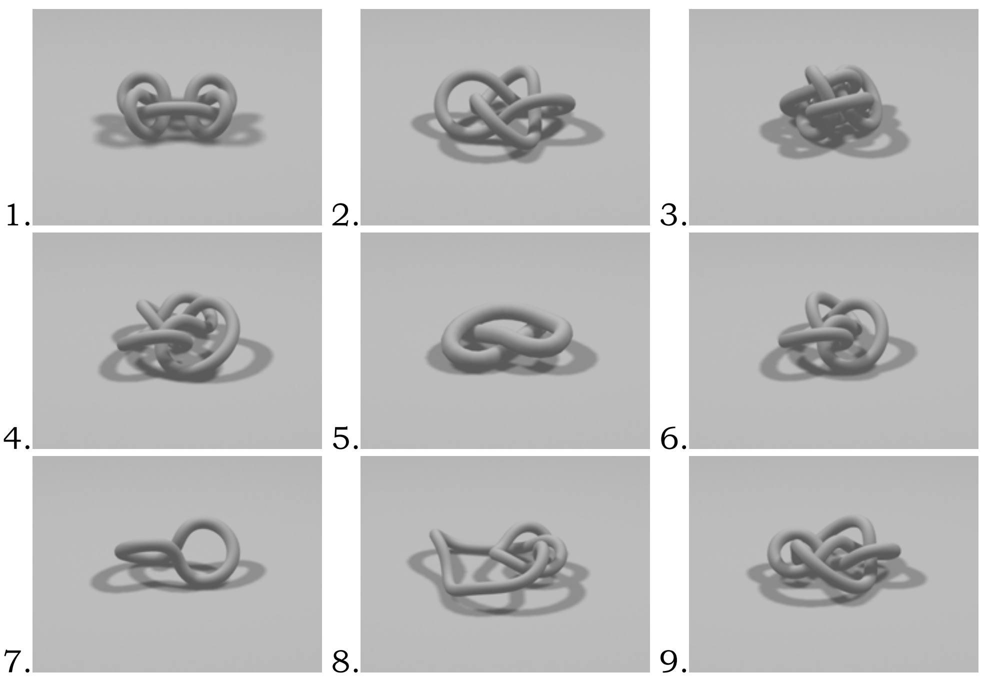


Figure E.2: Search Objects which were on Tables 1 through 9 during the Real Trials.

E.3 Search Object Images – Object not on the Table - Training Trials (Global)

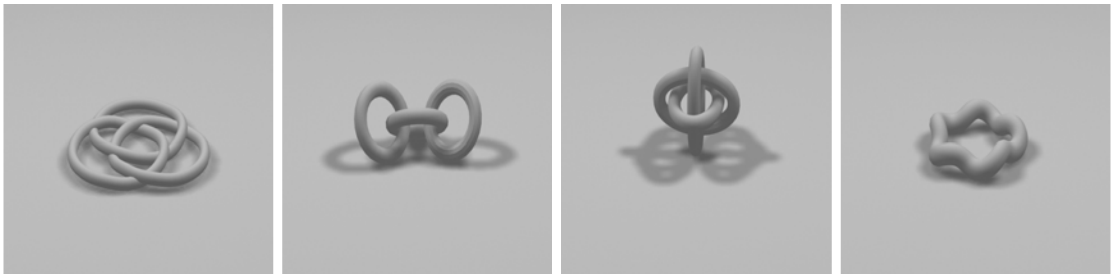


Figure E.3: Search Objects which were *not* on Tables 1 through 4 respectively during the Training Trials.

E.4 Search Object Images – Object not on the Table - Real Trials (Global)

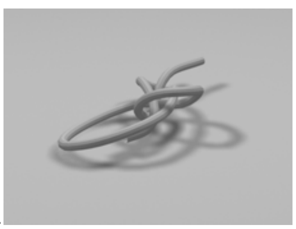
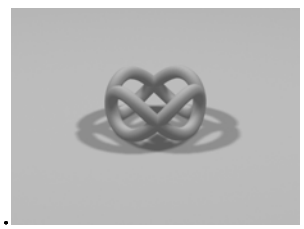
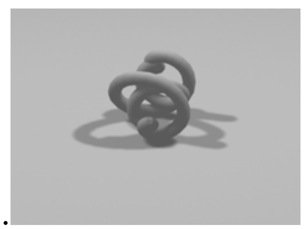
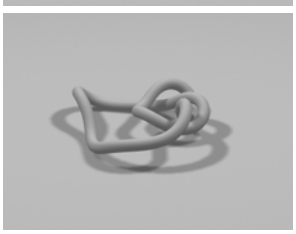
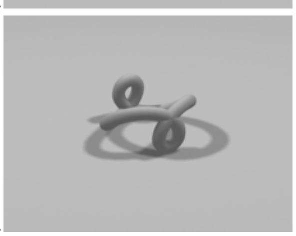
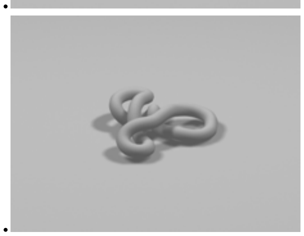
1. 
2. 
3. 
4. 
5. 
6. 
7. 
8. 
9. 

Figure E.4: Search Objects which were *not* on Tables 1 through 9 during the Real Trials.

E.5 Search Object Images – Object on the Table - Training Trials (Local)

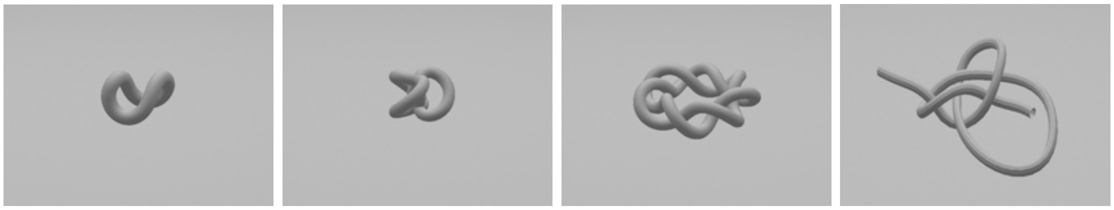


Figure E.5: Search Objects which were on Tables 1 through 4 respectively during the Training Trials.

E.6 Search Object Images – Object on the Table - Real Trials (Local)

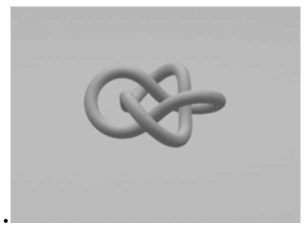
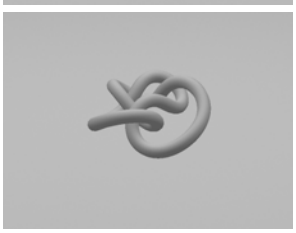
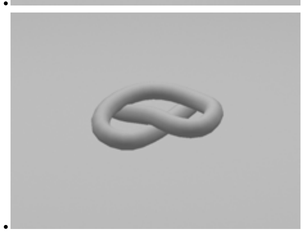
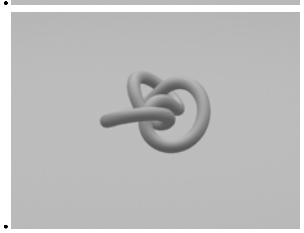
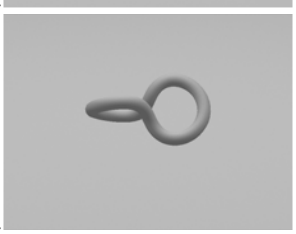
1. 
2. 
3. 
4. 
5. 
6. 
7. 
8. 
9. 

Figure E.6: Search Objects which were on Tables 1 through 9 during the Real Trials.

E.7 Search Object Images – Object not on the Table - Training Trials (Local)

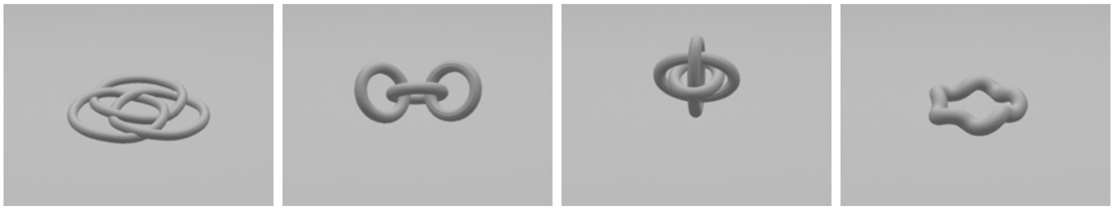


Figure E.7: Search Objects which were *not* on Tables 1 through 4 respectively during the Training Trials.

E.8 Search Object Images – Object not on the Table - Real Trials (Local)

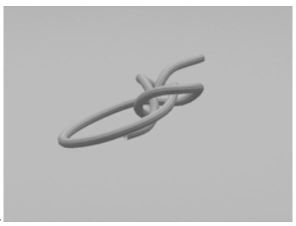
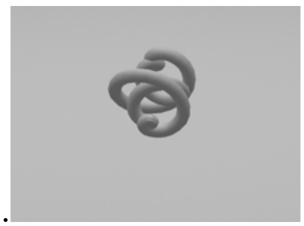
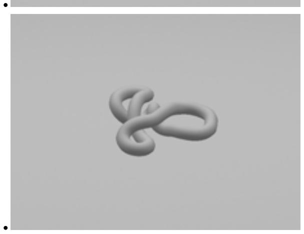
1. 
2. 
3. 
4. 
5. 
6. 
7. 
8. 
9. 

Figure E.8: Search Objects which were *not* on Tables 1 through 9 during the Real Trials.

E.9 Search Object Images – Object on the Table - Training Trials (Ambient)

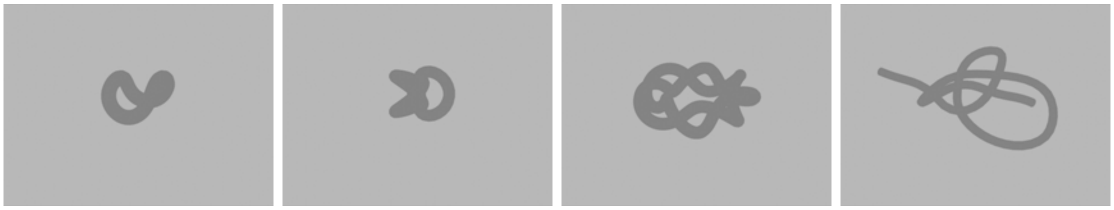


Figure E.9: Search Objects which were on Tables 1 through 4 respectively during the Training Trials.

E.10 Search Object Images – Object on the Table - Real Trials (Ambient)

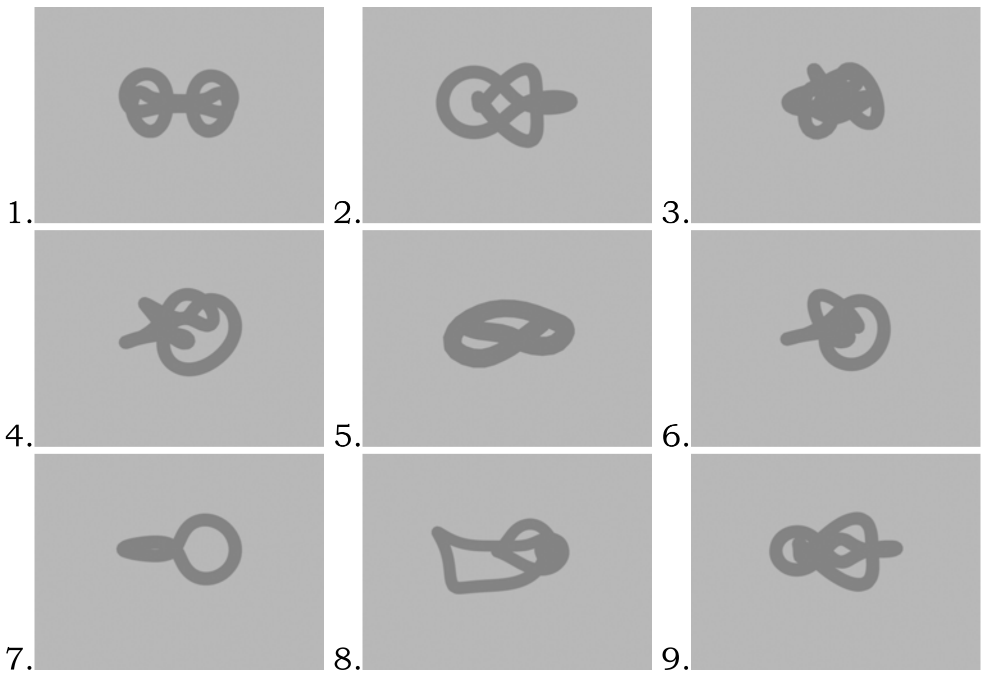


Figure E.10: Search Objects which were on Tables 1 through 9 during the Real Trials.

E.11 Search Object Images – Object not on the Table - Training Trials (Ambient)

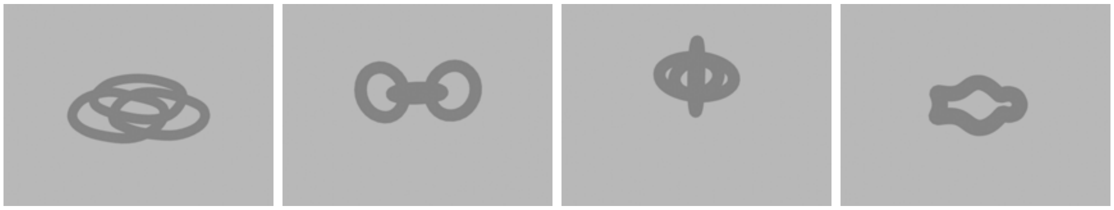


Figure E.11: Search Objects which were *not* on Tables 1 through 4 respectively during the Training Trials.

E.12 Search Object Images – Object not on the Table - Real Trials (Ambient)

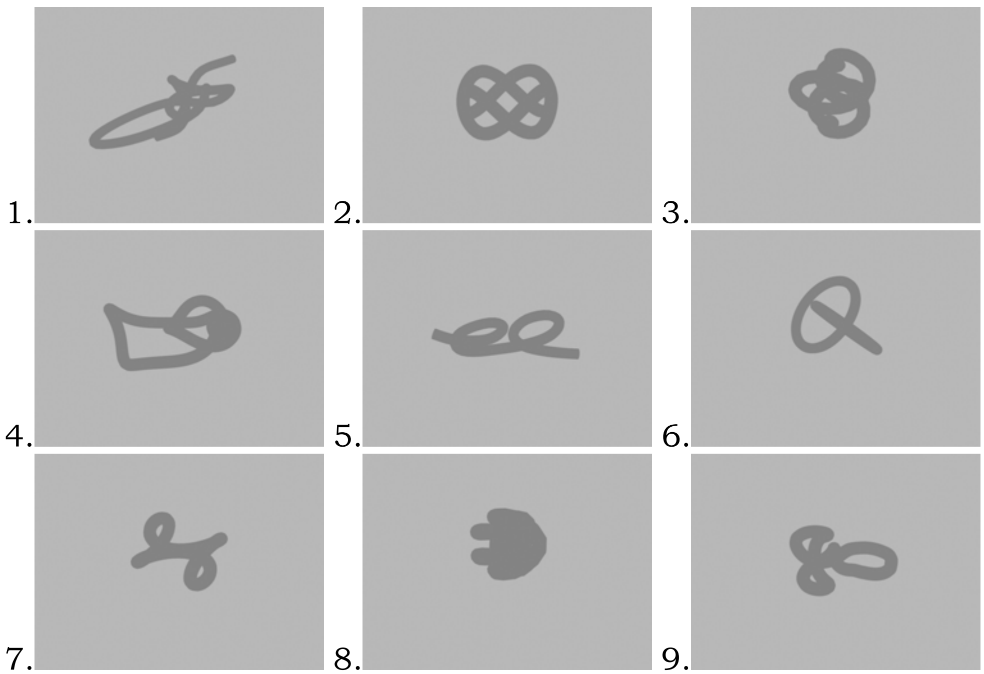
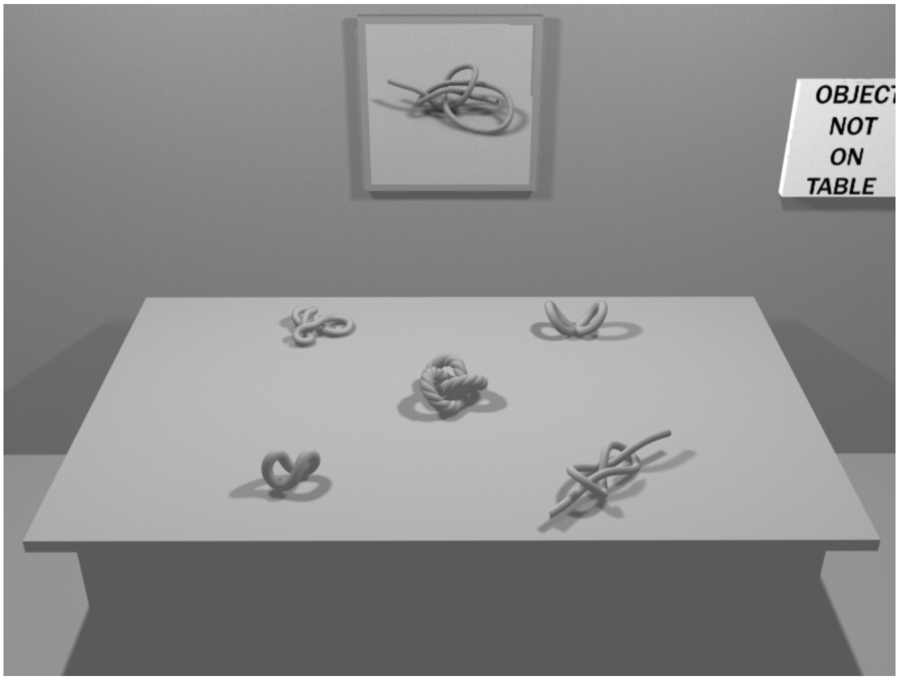
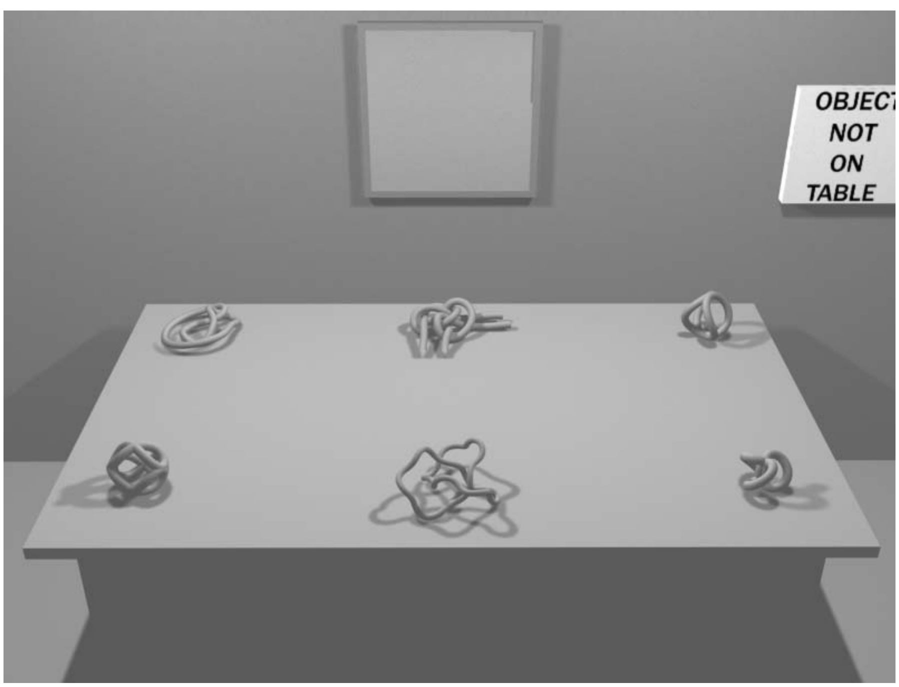


Figure E.12: Search Objects which were *not* on Tables 1 through 9 during the Real Trials.

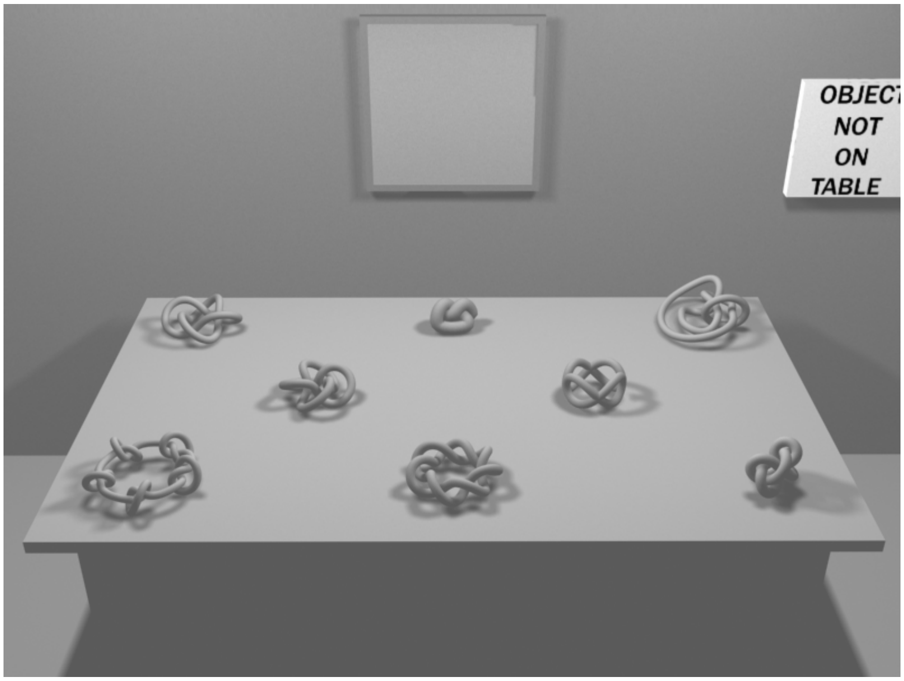
E.13 Tables – Global Illumination



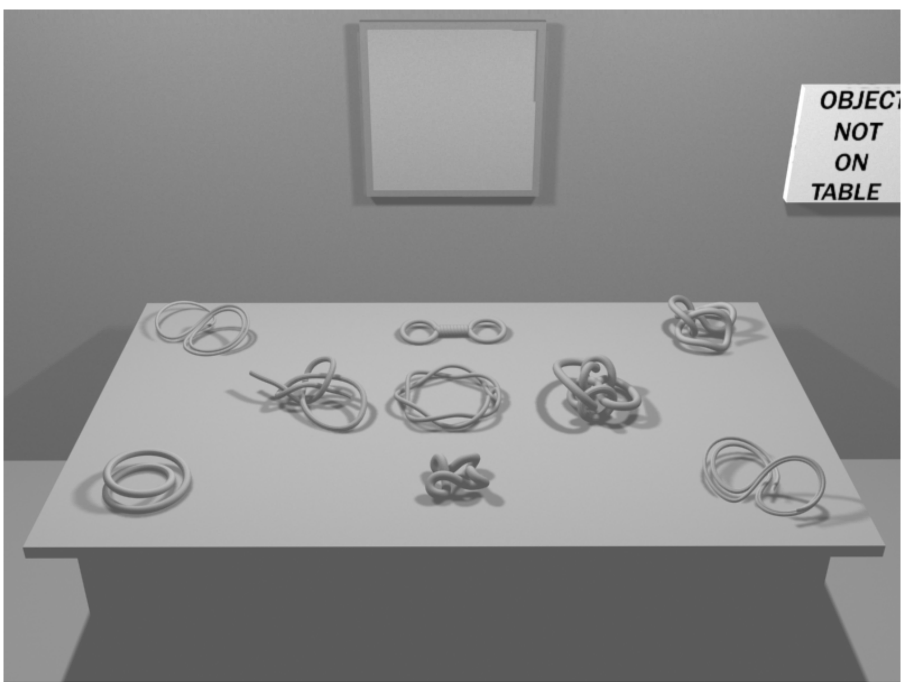
Training Table 1 (with Search Object image)



Training Table 2



Training Table 3



Training Table 4

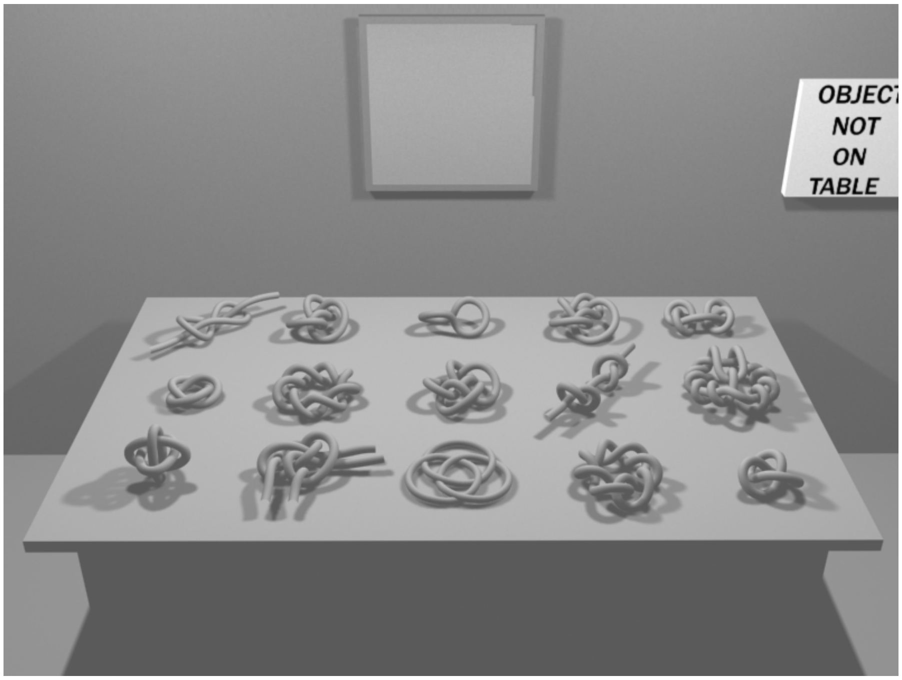


Table 1

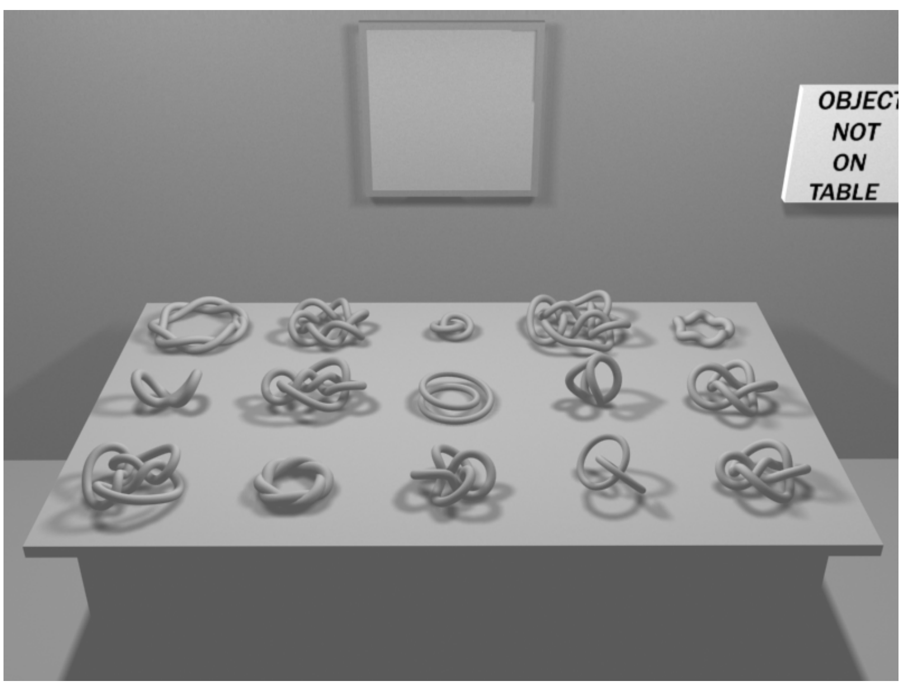


Table 2

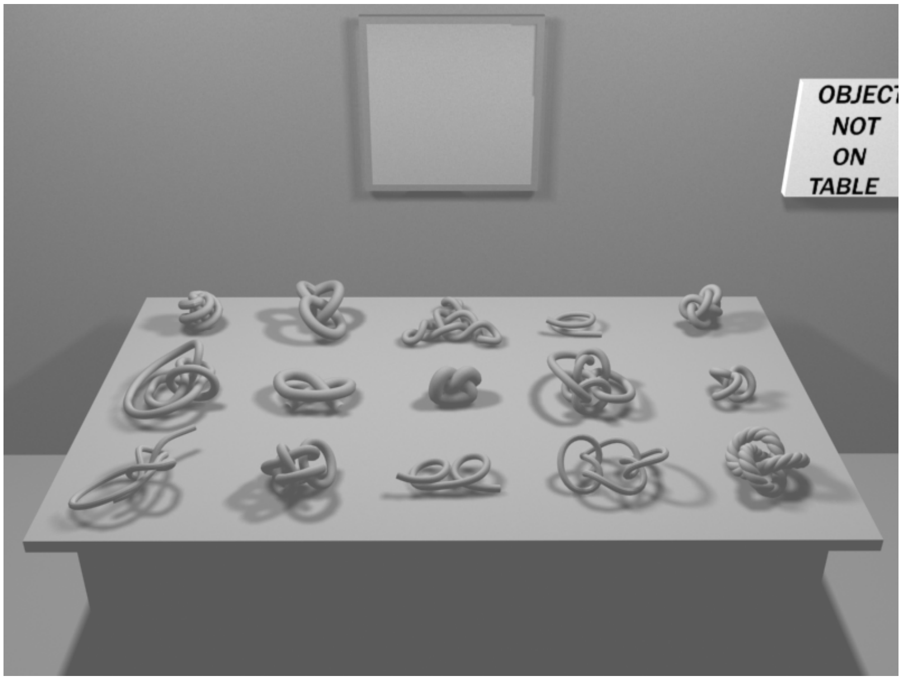


Table 3

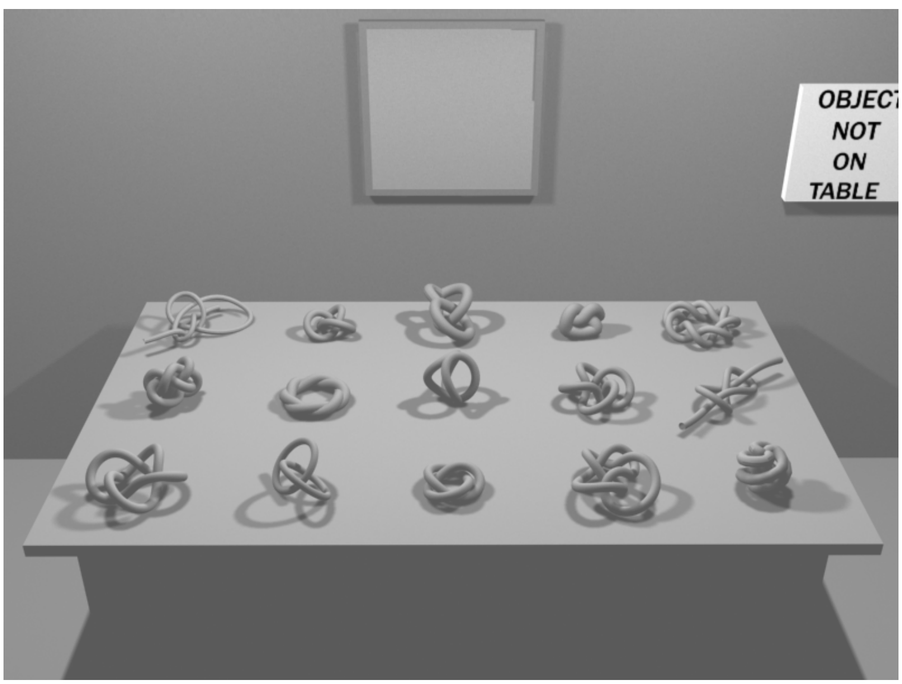


Table 4

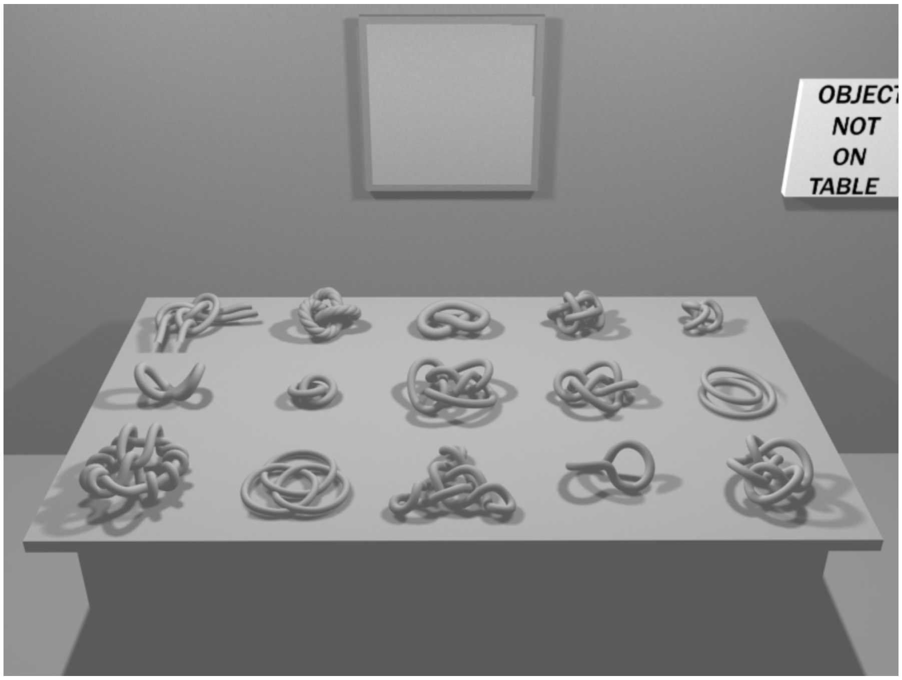


Table 5

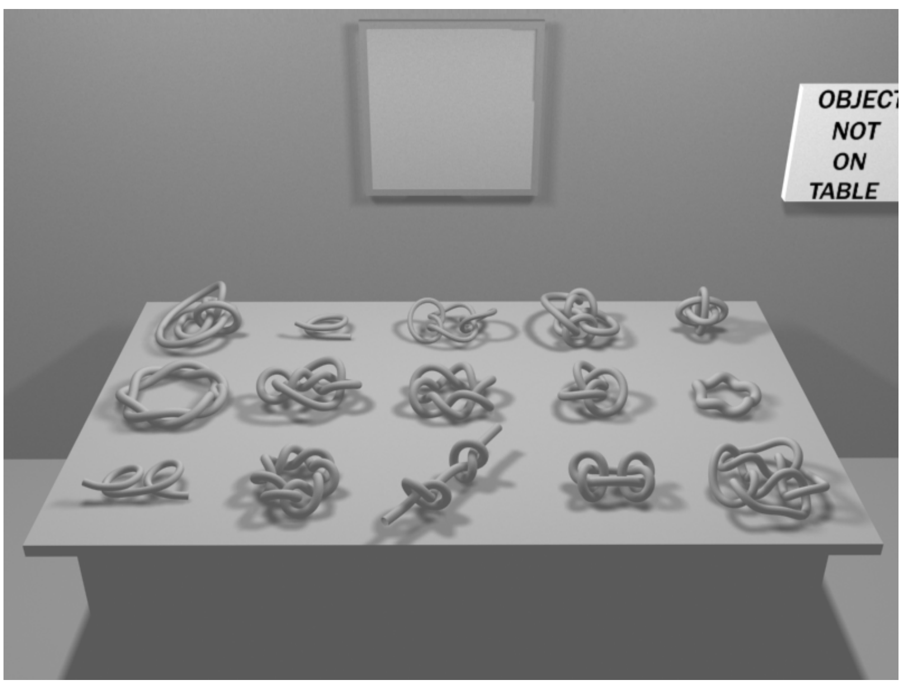


Table 6

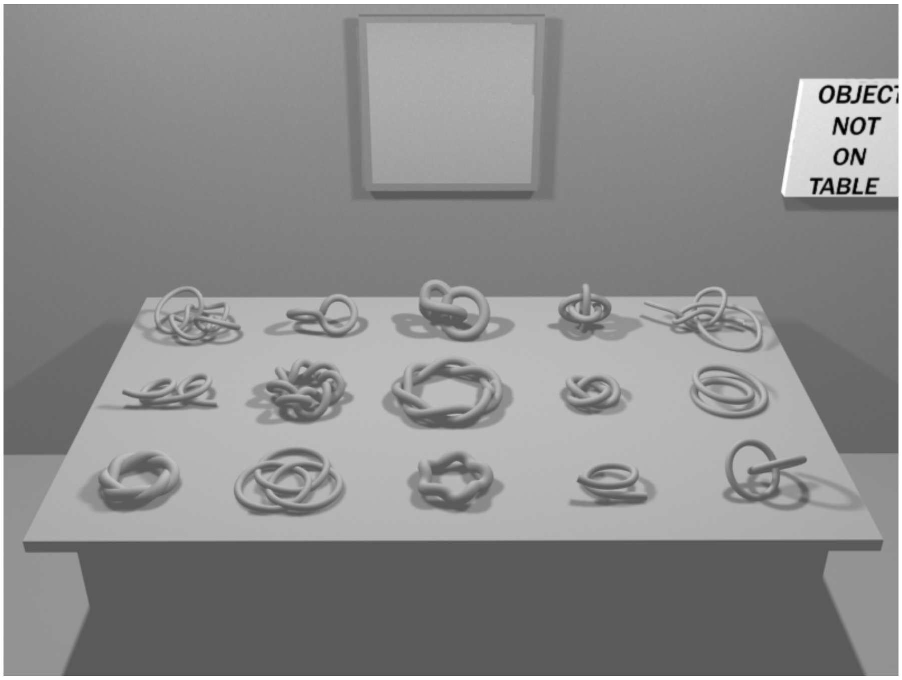


Table 7

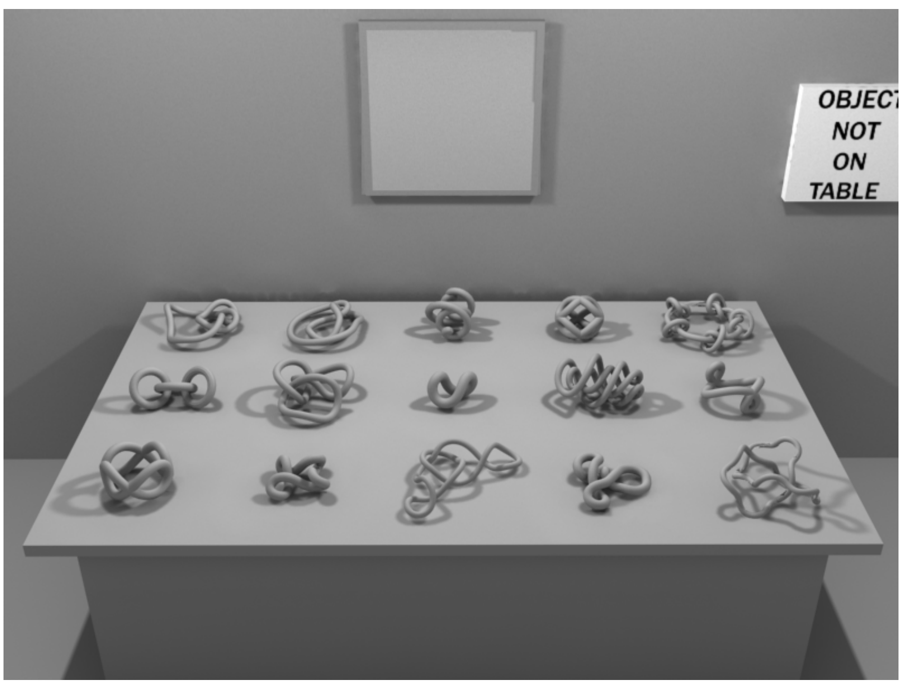


Table 8

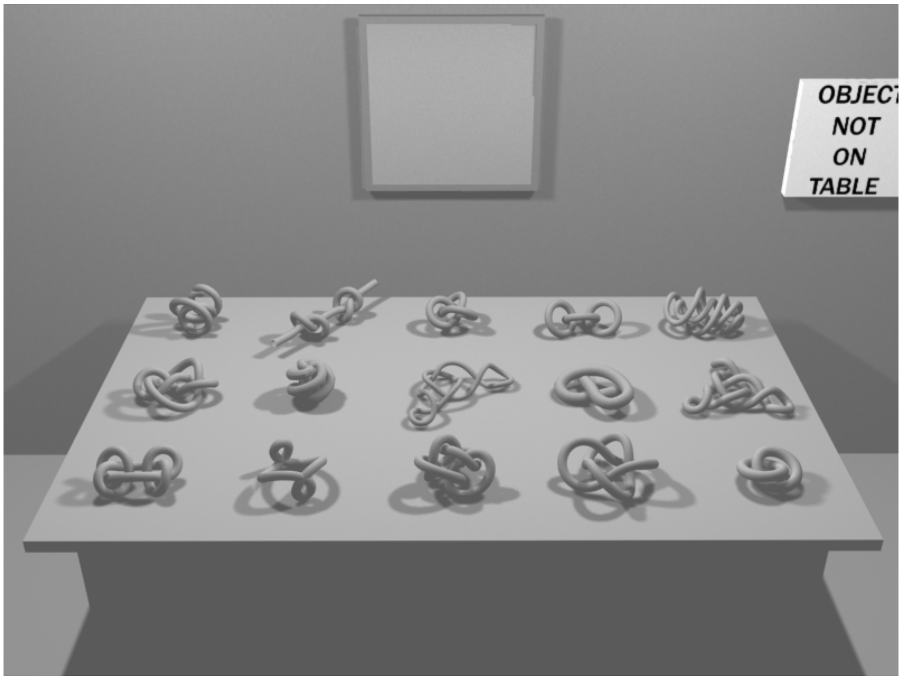
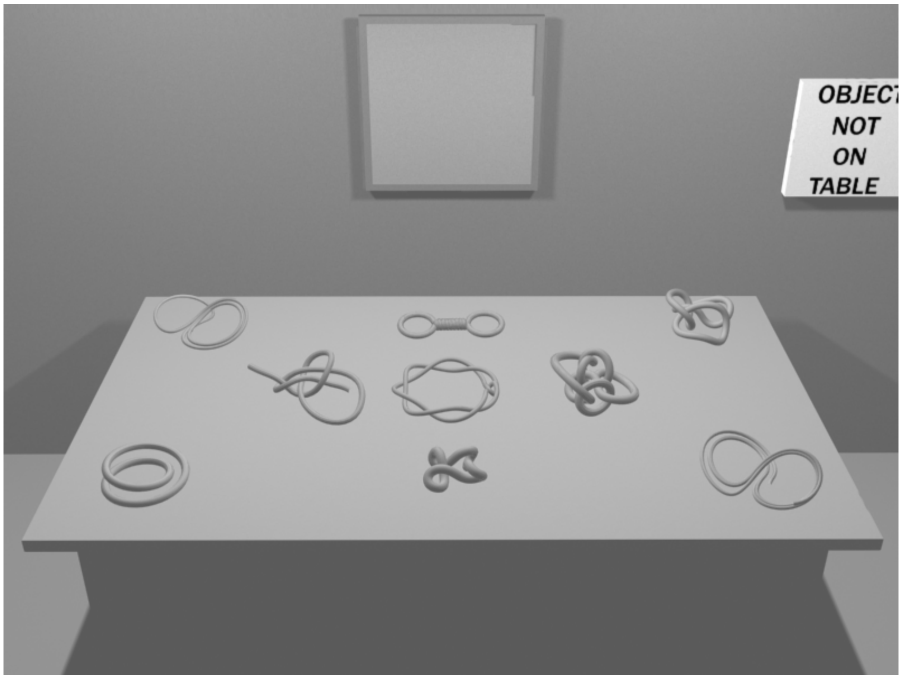


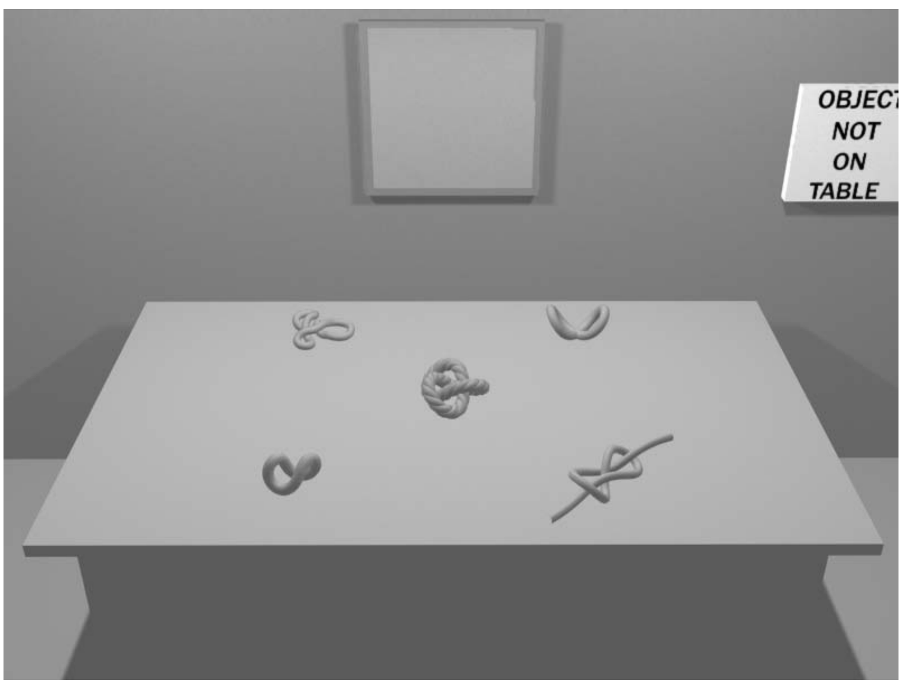
Table 9

Figure E.13: Images of the 13 tables used for the Training and Real Trials in global illumination.

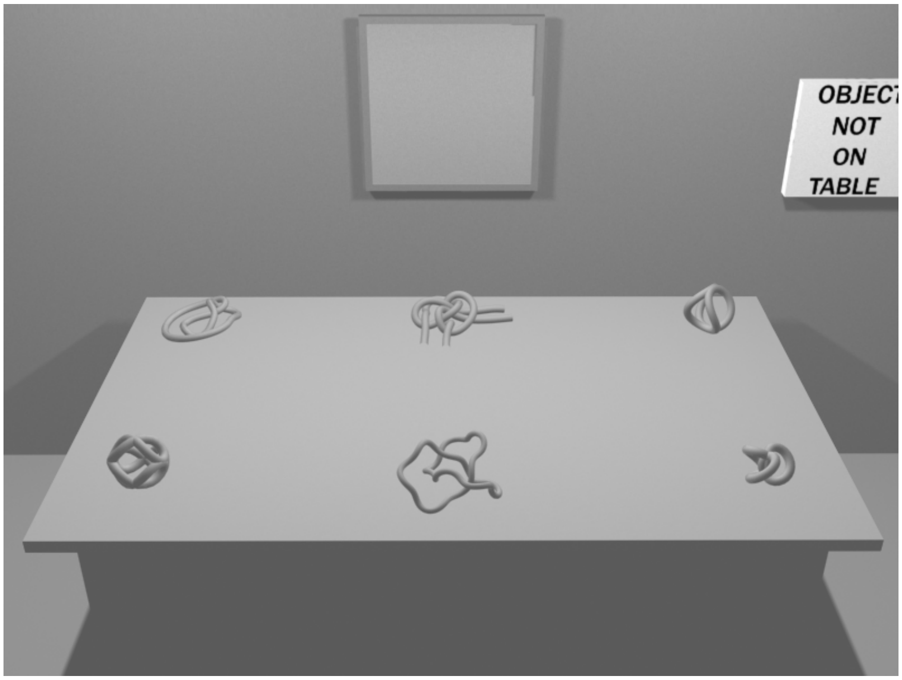
E.14 Tables – Local Illumination



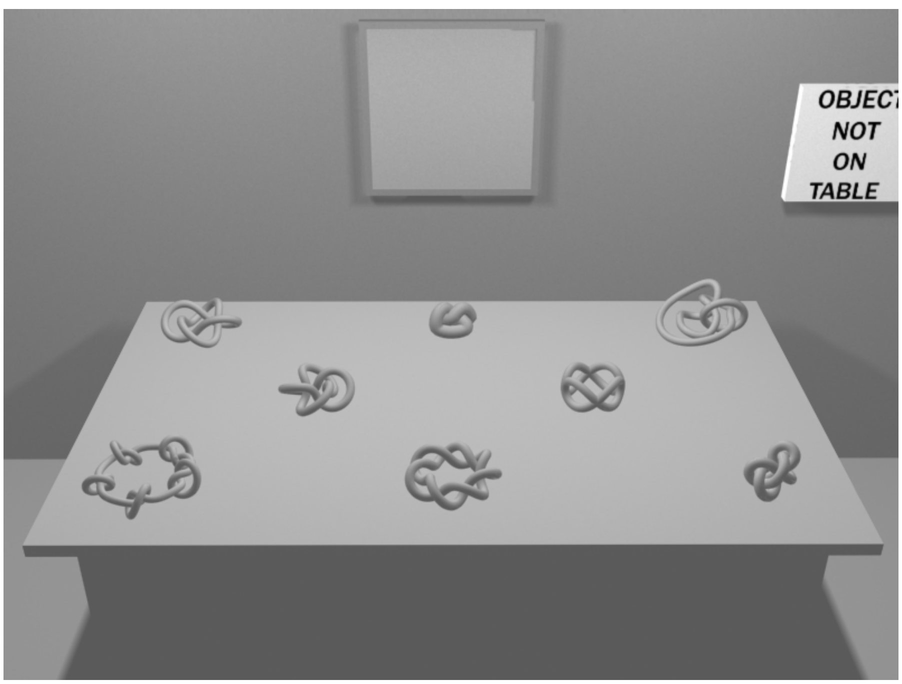
Training Table 1 (with Search Object image)



Training Table 2



Training Table 3



Training Table 4

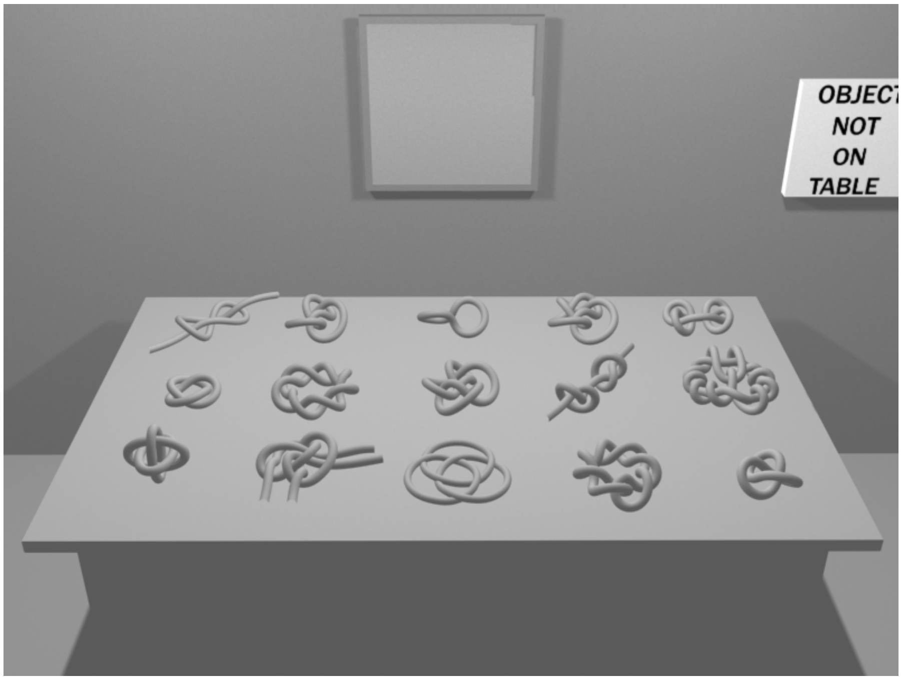


Table 1

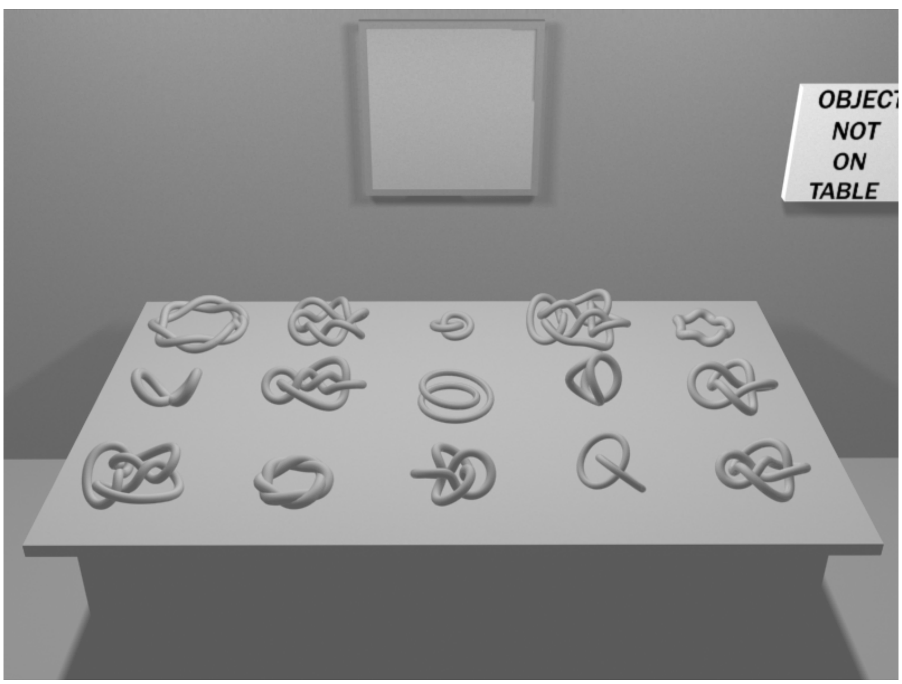


Table 2

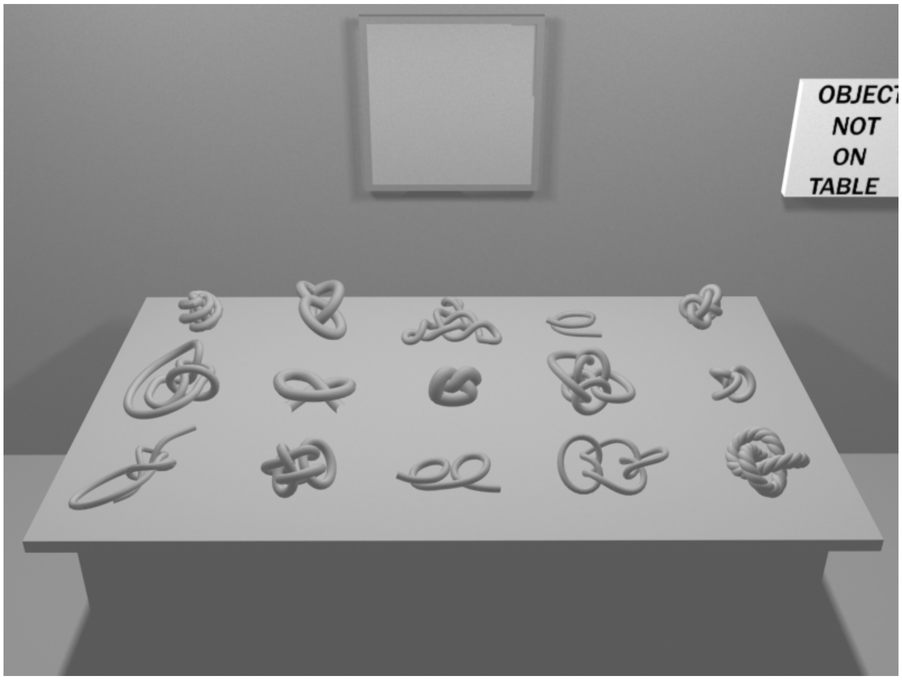


Table 3

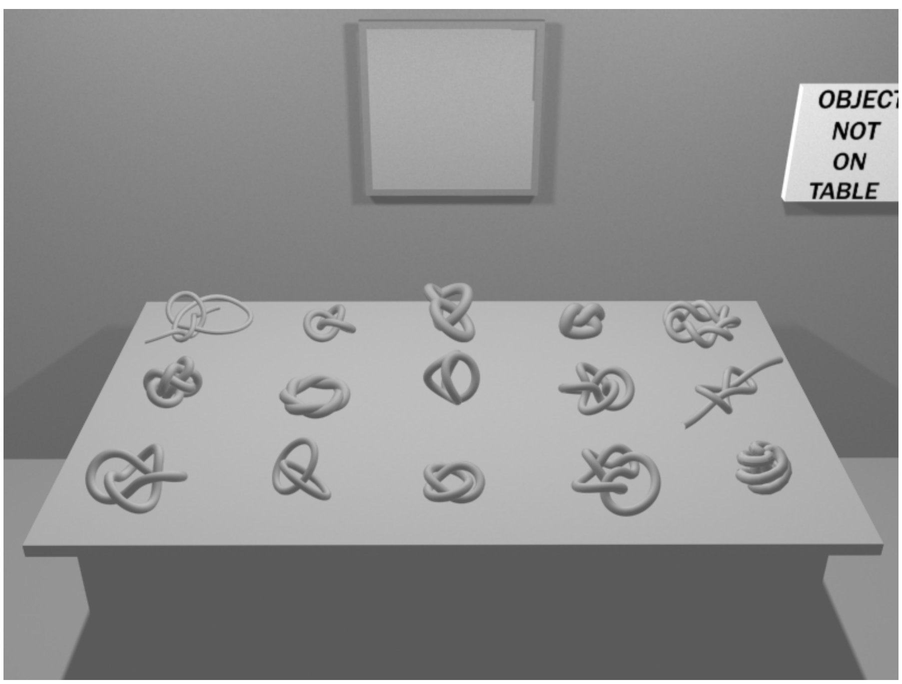


Table 4

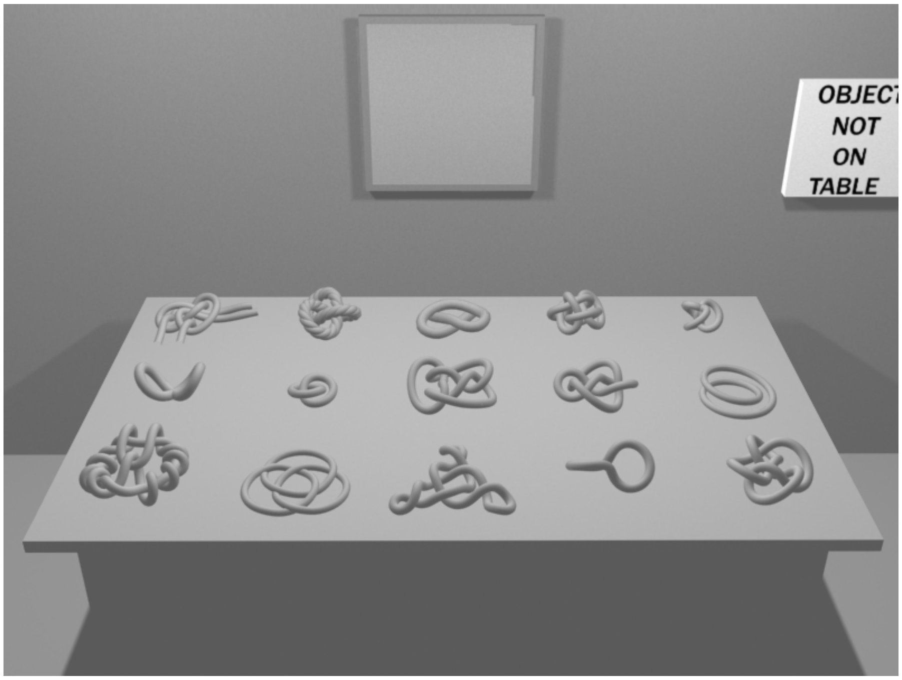


Table 5

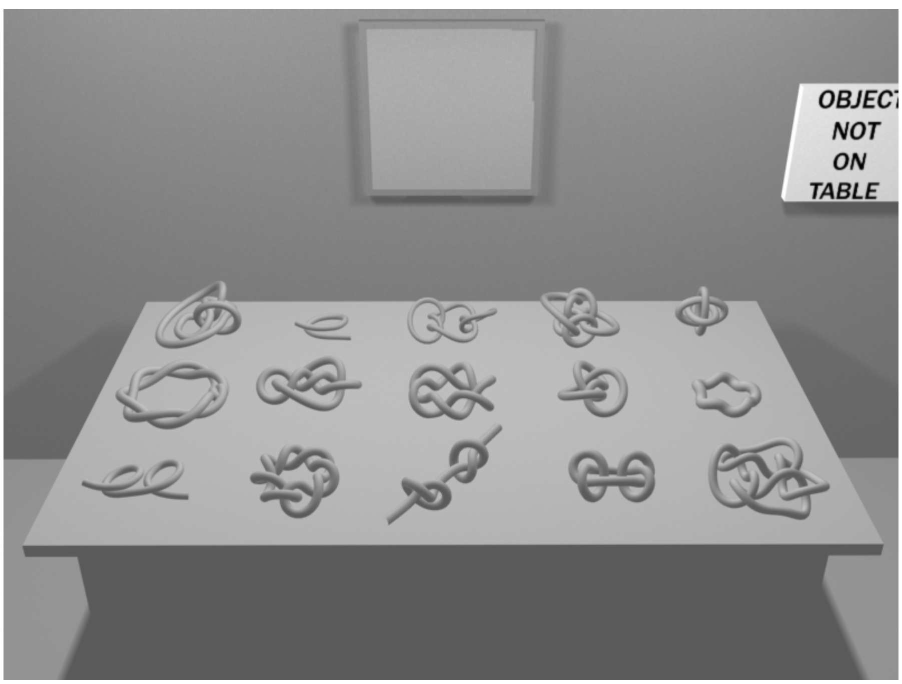


Table 6

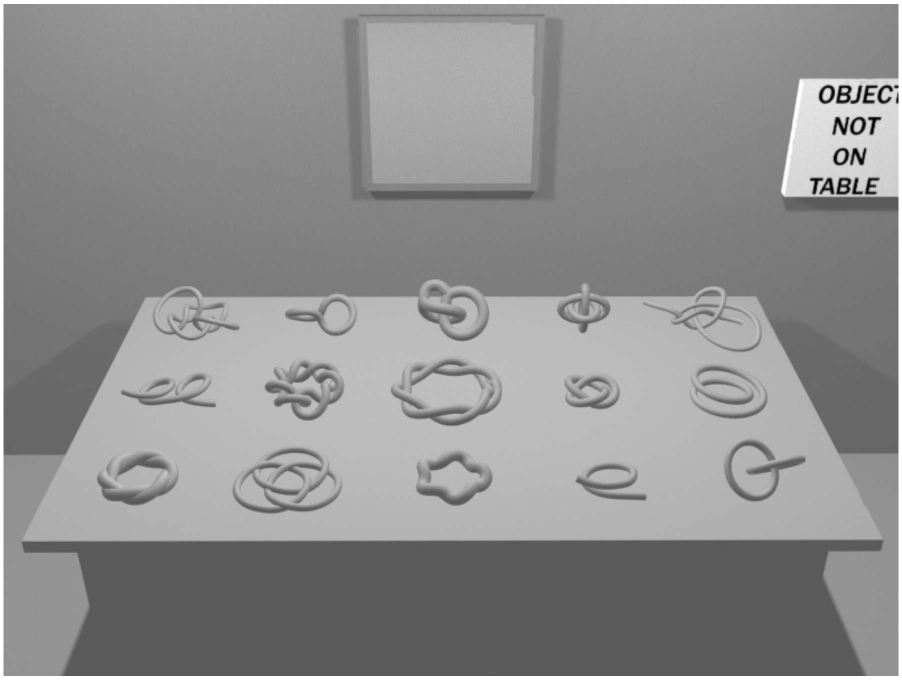
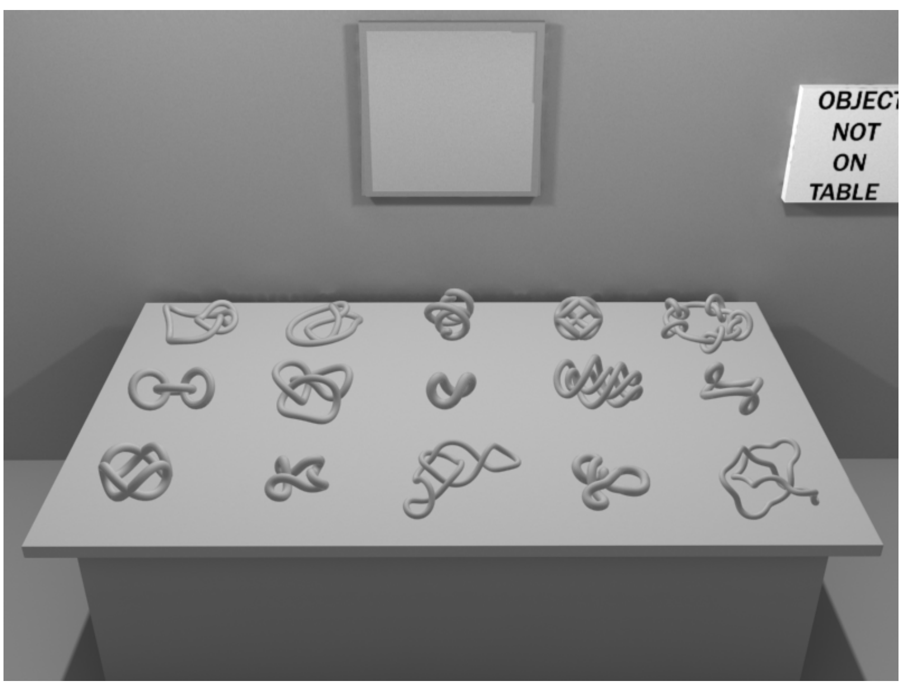


Table 7



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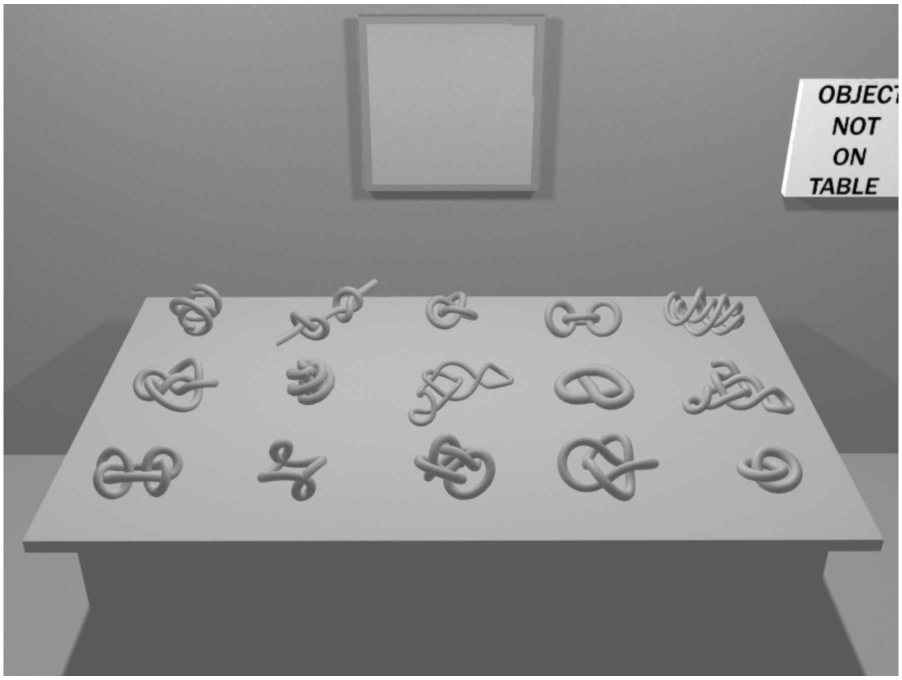
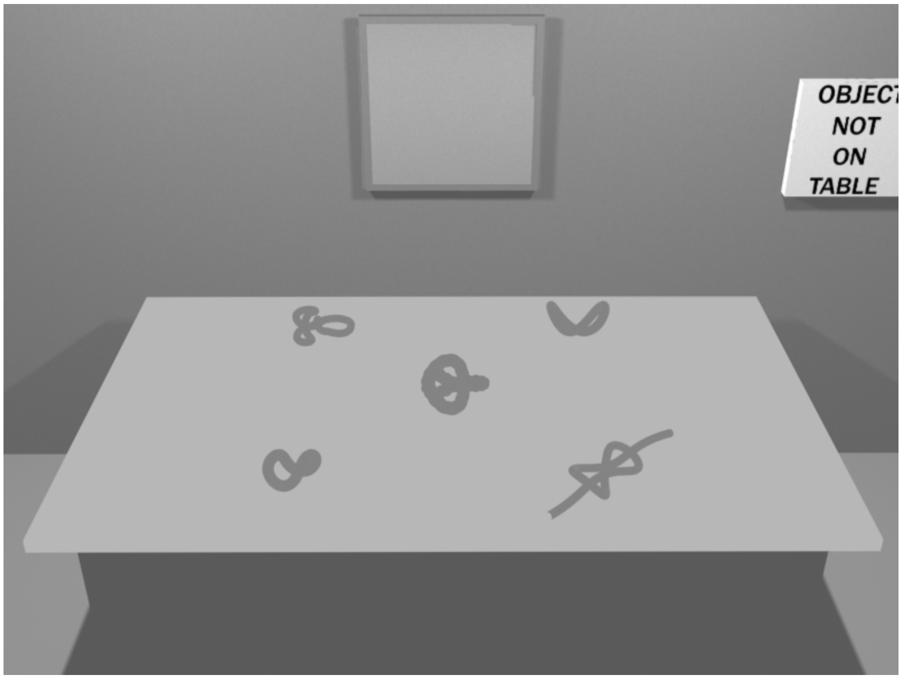


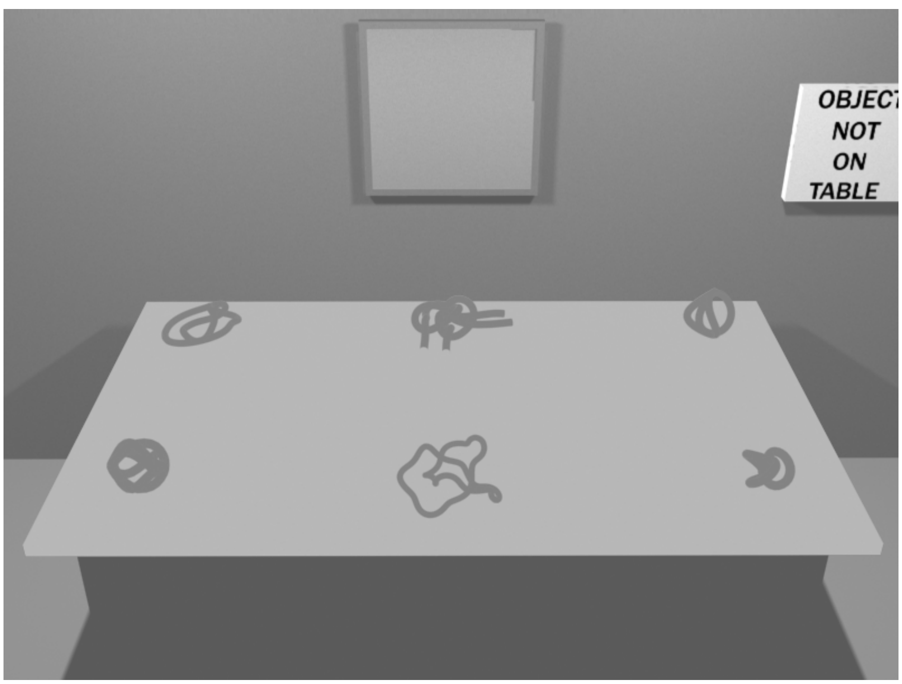
Table 9

Figure E.14: Images of the 13 tables used for the Training and Real Trials in local illumination.

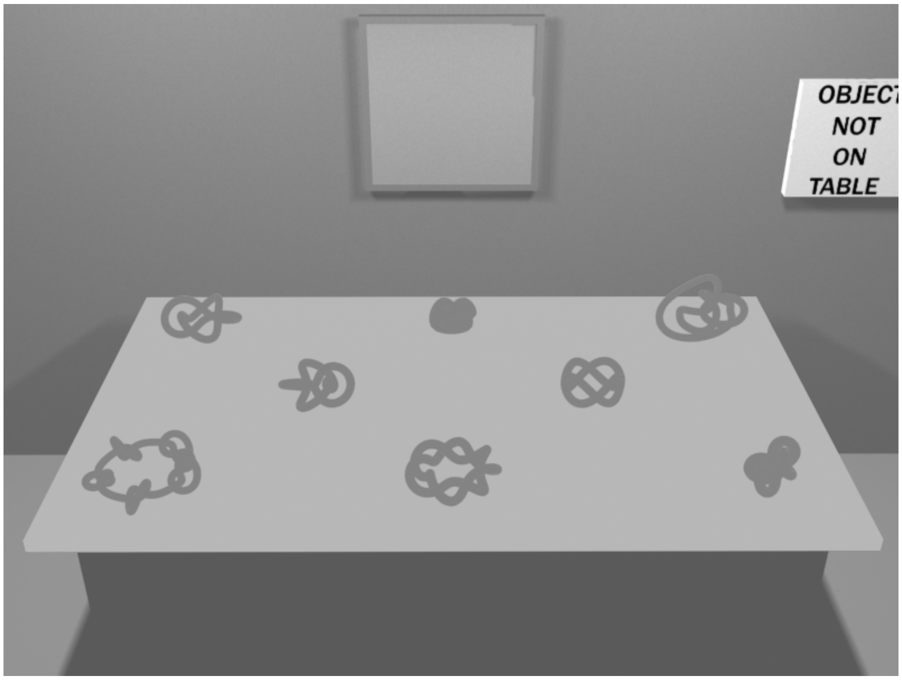
E.15 Tables – Ambient Illumination



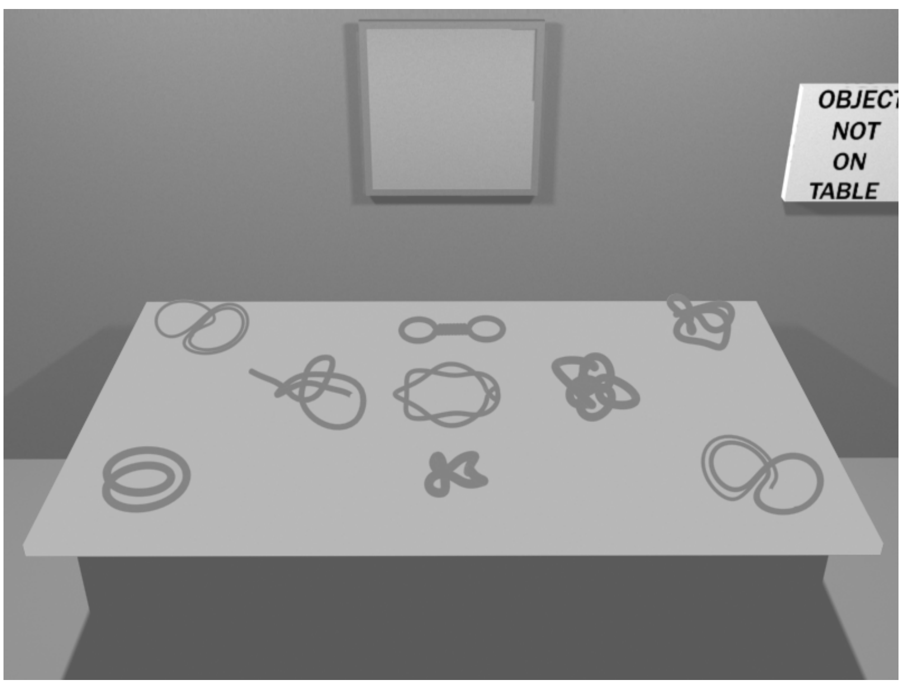
Training Table 1



Training Table 2



Training Table 3



Training Table 4

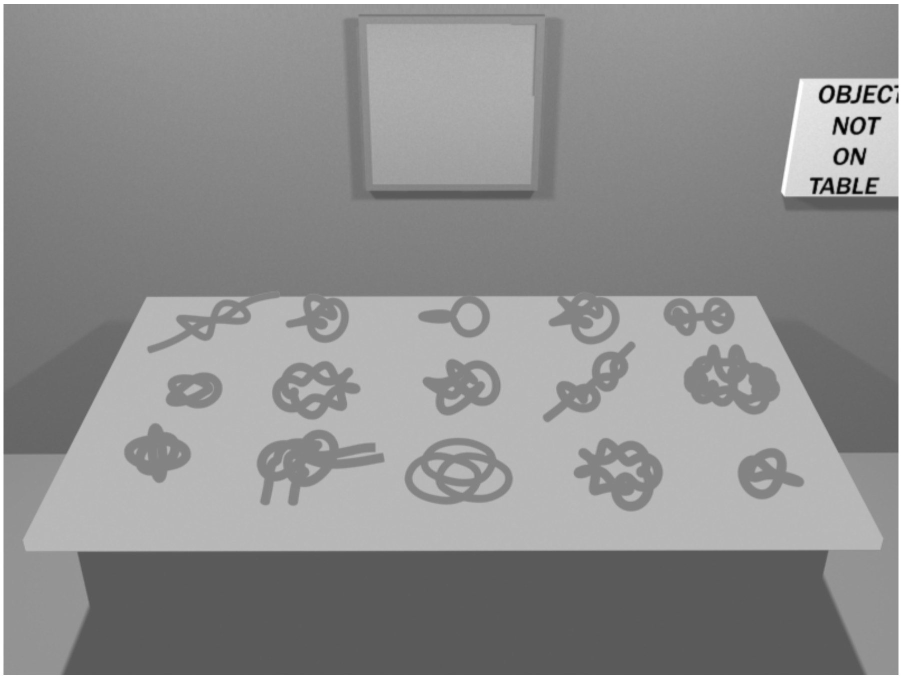


Table 1

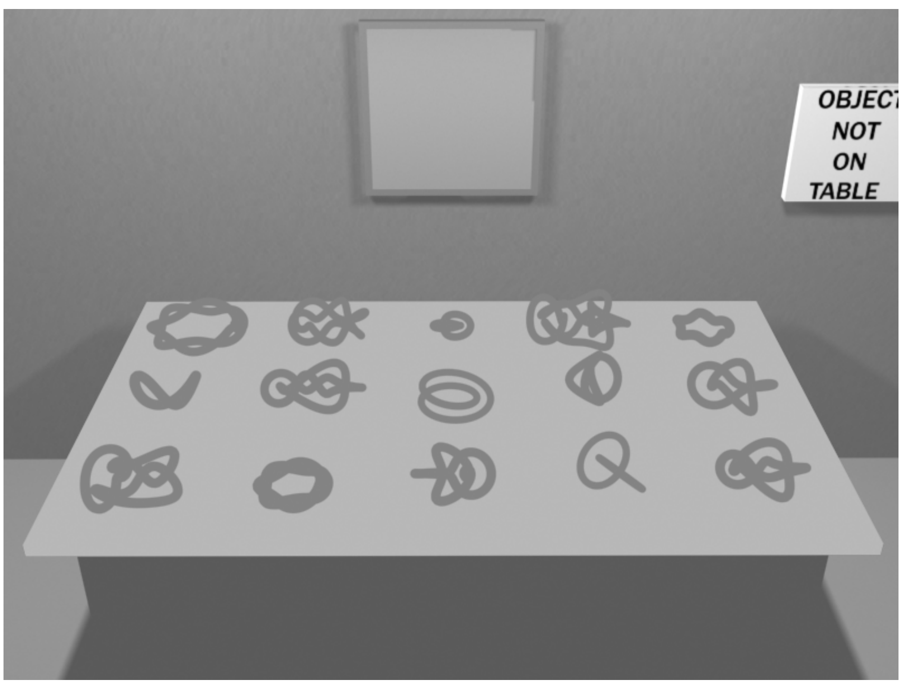


Table 2

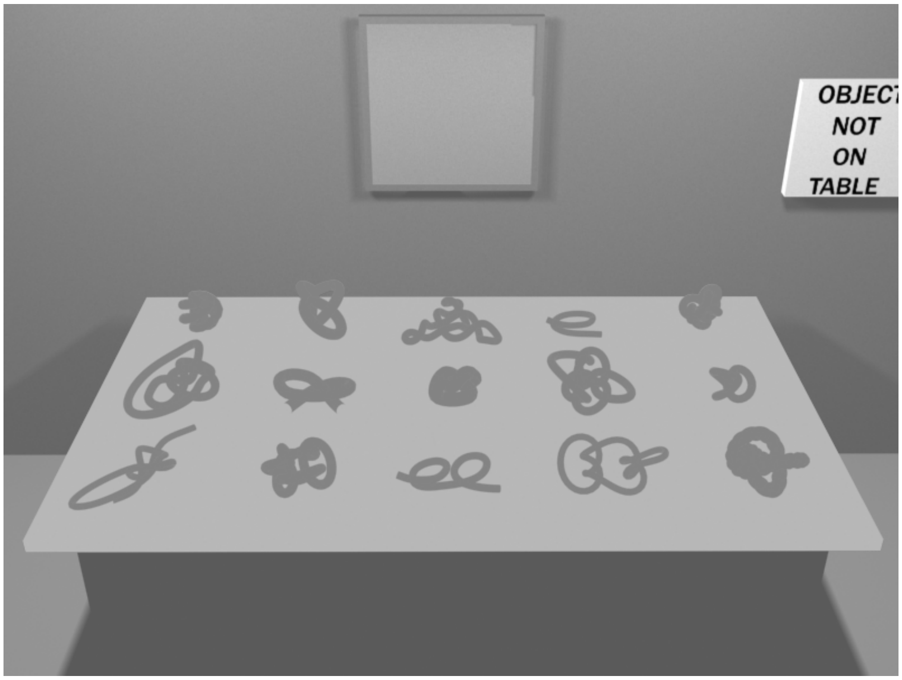


Table 3

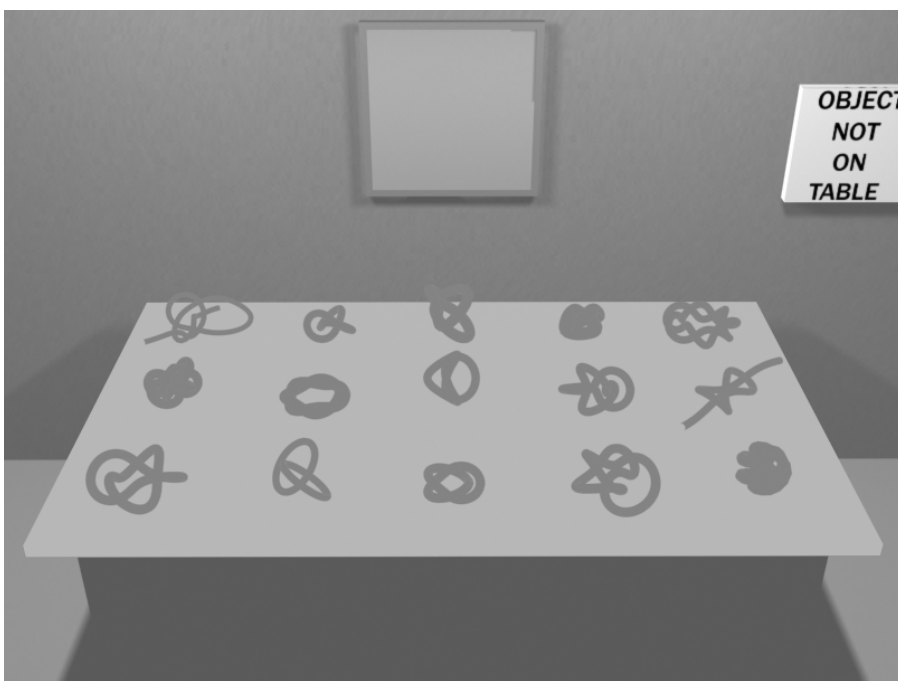


Table 4

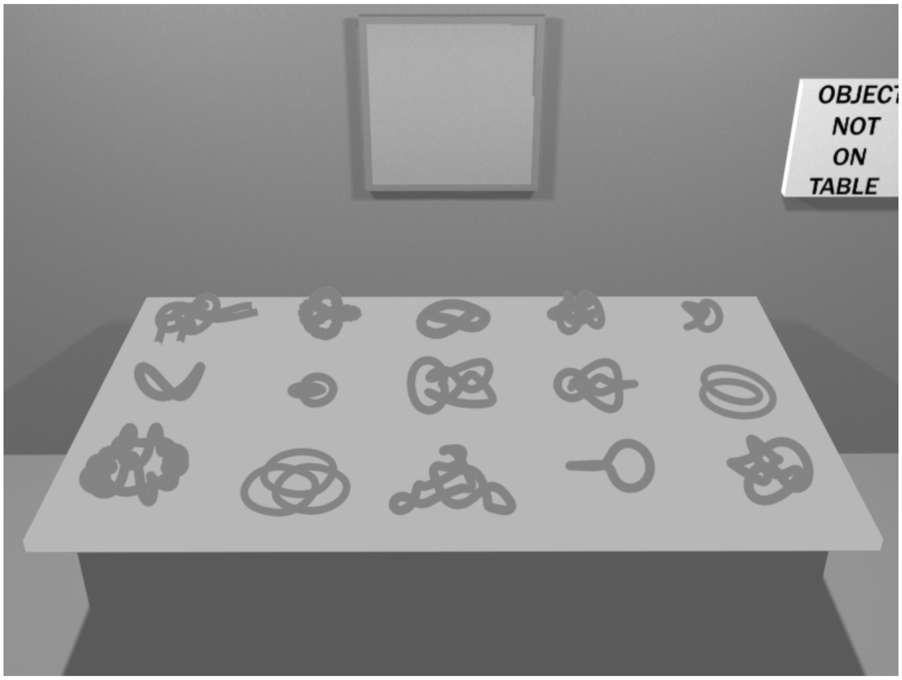


Table 5

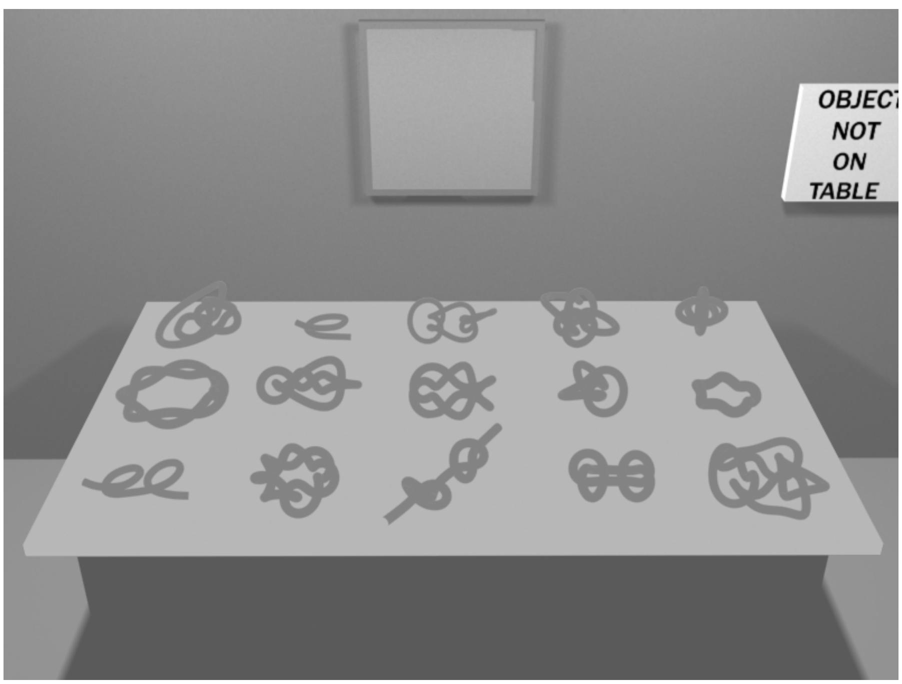


Table 6

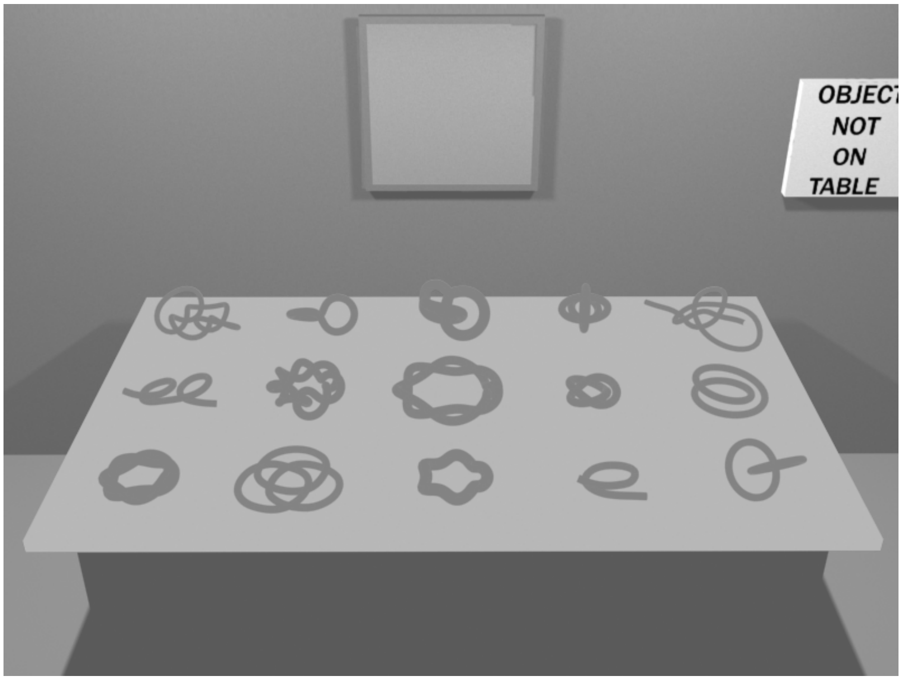


Table 7

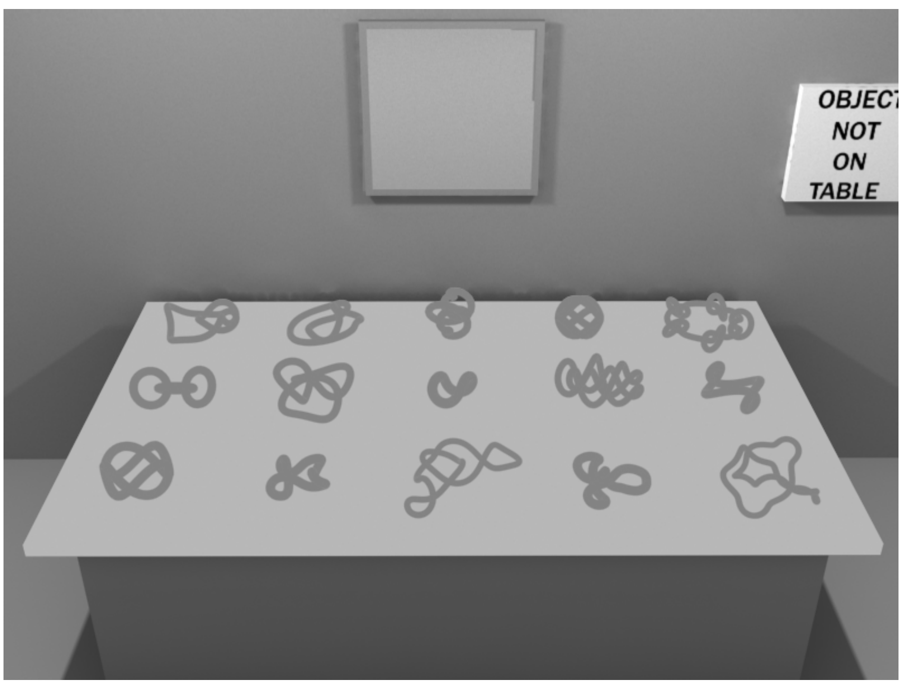


Table 8

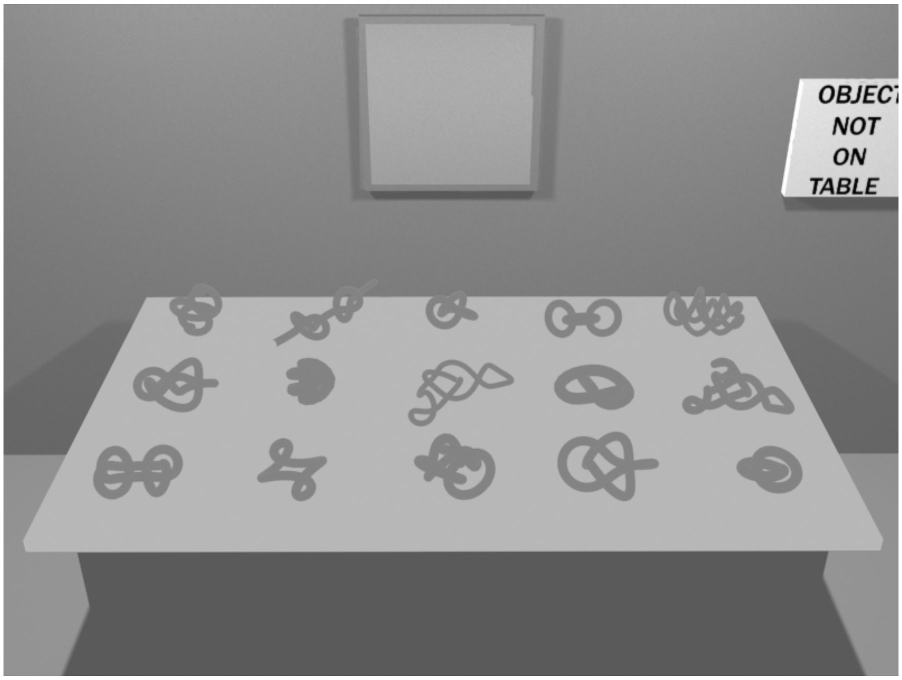


Table 9

Figure E.15: Images of the 13 tables used for the Training and Real Trials in ambient illumination.

Appendix F: Experimental Data

F.1 The Pit Experiment – Part 1

ID	Condition	Simulator Sickness Nasuea Score (Pre)	Siulator Sickness Ocular Discomfort Score (Pre)	Simulator Sickness Disorientation Score (Pre)	Simulator Sickness Total Score (Pre)	Height Anxiety Questionnaire Score	Height Avoidance Questionnaire Score	Guildford-Zimmerman Spatial Ability Score	Simulator Sickness Nasuea Score (Post)	Simulator Sickness Ocular Discomfort Score (Post)	Simulator Sickness Disorientation Score (Post)	Simulator Sickness Total Score (Post)	Gender (0=male, 1=female)	Age	Race (0=Indian,1=Asian,2=Af. Am.,3=Hisp.,4=Cauc.,5=Other)	University Status (0=undergrad,6=other)	Computer Use	Computer Game Play	Hours of Exercise Per Week	Report Depth of the Pit (feet)
1	1	9.54	30.32	41.76	29.92	21	3	9.5	66.78	37.9	83.52	67.32	1	18	4	0	7	1	2	8
2	0							0												
3	2	28.62	0	0	11.22	0	0	19	19.08	0	27.84	14.96	0	20	1	0	6	4	2.5	17
4	3							0												
5	4	0	0	0	0	18	2	31.5	0	0	0	0	1	19	4	0	7	1	1	10
6	3	0	0	0	0	23	4	25	0	0	0	0	0	19	4	0	7	2	<0.5	15
7	4	0	7.58	0	3.74	17	0	21.25	0	7.58	0	3.74	0	18	4	0	6	4	2	10
8	3	9.54	0	0	3.74	6	2	17	9.54	0	0	3.74	0	23	4	0	7	3	2	18
9	1	0	0	0	0	21	0	11	0	0	0	0	1	18	4	0	7	1	0.5	6
10	0	9.54	7.58	0	7.48	22	3	18	0	7.58	27.84	11.22	1	20	4	0	7	1	3+	15
11	2	19.08	0	0	7.48	5	0	15.25	0	0	13.92	3.74	0	18	4	0	5	1	2	20
12	1	0	0	0	0	63	7	0.25	9.54	0	0	3.74	1	18	4	0	7	4	3+	20
13	0	9.54	22.74	0	14.96	20	5	15	0	7.58	41.76	14.96	0	19	4	0	7	2	2	20
14	2	9.54	15.16	13.92	14.96	11	0	17.5	0	15.16	13.92	11.22	0	20	4	0	6	2	<0.5	10
15	1	9.54	15.16	27.84	18.7	33	8	33.75	38.16	22.74	13.92	29.92	1	19	4	0	7	4	2	25
16	0	38.16	30.32	0	29.92	31	8	4.75	9.54	7.58	0	7.48	1	18	2	0	7	2	<0.5	10
17	2	9.54	7.58	0	7.48	38	11	14	47.7	22.74	27.84	37.4	0	20	4	0	7	5	3+	15
18	4	9.54	15.16	27.84	18.7	17	4	20.25	9.54	22.74	13.92	18.7	0	19	4	0	7	1	<0.5	15
19	3	0	7.58	0	3.74	21	1	6	0	0	0	0	1	19	4	0	7	2	2	20
20	4	0	7.58	0	3.74	7	2	6.75	0	0	0	0	1	18	2	0	7	1	<0.5	13
21	4	0	7.58	13.92	7.48	16	0	24.25	0	0	0	0	0	20	4	0	7	2	3+	20
22	3	0	0	0	0	20	3	22	0	0	0	0	1	21	1	6	7	3	2	15
23	2	0	7.58	0	3.74	2	0	14.25	0	7.58	0	3.74	0	19	4	0	7	7	2.5	20
24	1	0	15.16	0	7.48	21	2	19.75	9.54	22.74	13.92	18.7	0	19	5	0	7	5	3+	22
25	0	38.16	22.74	27.84	33.66	4	0	15.75	85.86	60.64	125.2	97.24							.	
26	4	47.7	15.16	0	26.18	12	0	18.75	9.54	0	0	3.74	0	20	5	0	7	7	<0.5	15
27	3							0												
28	0	9.54	0	0	3.74	6	1	35.25	0	0	0	0	0	19	4	0	6	5	1	8
29	1	0	7.58	0	3.74	12	5	32.75	38.16	37.9	55.68	48.62	1	18	4	0	7	4	3+	50
30	2							0												
31	1	28.62	7.58	0	14.96	10	1	36.75	9.54	7.58	13.92	11.22	0	19	4	0	6	6	1.5	15
32	2	0	0	0	0	11	1	10.75	38.16	7.58	0	18.7	1	19	4	0	7	3	<0.5	30
33	3	19.08	7.58	0	11.22	22	4	15	9.54	30.32	13.92	22.44	0	19	2	0	7	7	2.5	9
34	0	19.08	15.16	0	14.96	19	8	24.25	38.16	45.48	27.84	44.88	1	18	4	0	6	2	3+	5
35	2	9.54	7.58	0	7.48	19	4	0.75					1	18	4	0	7	2	1	8
36	3	9.54	0	0	3.74	14	4	4	9.54	0	0	3.74	0	19	2	0	7	5	3+	25
37	4	0	7.58	0	3.74	78	9	12.75	104.9	75.8	111.36	108.46	1	20	4	0	7	1	3+	20
38	1	57.24	37.9	41.76	52.36	30	0	8.5	0	0	0	0	0	22	4	0	5	7	3+	10
39	2	0	7.58	0	3.74	26	2	35.75	0	7.58	0	3.74	0	21	4	0	7	4	1.5	10
40	3	38.16	15.16	0	22.44	22	0	14.25	9.54	0	0	3.74	1	18	4	0	6	2	2	12
41	4	0	7.58	0	3.74	19		8	0	7.58	0	3.74	1	19	2	0	7	1	2	10
42								0												
43	0	19.08	15.16	13.92	18.7	7	2	9	0	0	0	0	0	20	4	0	7	6	1	25

44	1	28.62	22.74	0	22.44	3	5	19.75	9.54	7.58	0	7.48	1	19	4	0	7	3	1	10
45	2	0	15.16	0	7.48	16	4	22.5	0	0	0	0	1	19	3	0	5	2	3+	20
46	3	0	0	0	0	0	0	9	9.54	0	0	3.74	1	20	4	0	7	1	3+	6
47	1	9.54	7.58	0	7.48	19	0	17.75	0	7.58	0	3.74	1	19	1	0	7	2	1	20
48	2	9.54	15.16	0	11.22	8	2	15	76.32	45.48	69.6	71.06	1	18	4	0	7	2	3+	12
49	0	0	7.58	0	3.74	53	4	31.5	9.54	15.16	13.92	14.96	0	19	4	0	6	4	1.5	35
50	3	0	0	0	0	31	12	25.5	0	0	0	0	1	20	4	0	7	3	2	20
51	4							0												
52	0	47.7	60.64	27.84	56.1	40	37	29.5	28.62	37.9	83.52	52.36	0	19	4	0	7	4	3+	15
53	4	9.54	37.9	0	22.44	39	4	14	0	15.16	0	7.48	1	18	4	0	6	2	1	
54	4	9.54	15.16	0	11.22	16	1	21	19.08	60.64	55.68	52.36	0	19	4	0	7	2	3+	12
55	1	0	22.74	0	11.22	14	0	1	0	22.74	0	11.22	1	21	4	0	7	2	3+	10
56	1	0	15.16	0	7.48	19	1	24.25	0	7.58	0	3.74	0	18	4	0	2	1	3+	10
57	0	9.54	22.74	13.92	18.7	22	4	26.75	28.62	30.32	13.92	29.92	1	18	4	0	6	2	2.5	10
58	1	9.54	0	0	3.74	5	0	28.25	9.54	0	0	3.74	0	18	4	0	6	4	1.5	10
59	3	19.08	45.48	0	29.92	7	5	25.75	19.08	15.16	0	14.96	1	19	4	0	6	4	3+	30
60	4	0	7.58	0	3.74	4	4	17	0	7.58	0	3.74	1	20	4	0	6	4	3+	13
61	0	0	22.74	0	11.22	56	15	15.25	0	22.74	0	11.22	1	19	2	0	7	3	1.5	3

Table F.1: Pit Experiment Data Part 1.

F.2 The Pit Experiment – Part 2

ID	Condition	Behavioral Presence	Ease of Locomotion	Heart Rate (Pre-Pit) (BPM)	Heart Rate (in Pit Room) (BPM)	Heart Rate (Post-Pit) (BPM)	Heart Rate Increase	Skin Conductance (Pre-Pit) (mS)	Skin Conductance (Pit Room) (mS)	Skin Conductance (Post-Pit) (mS)	Skin Conductance Increase	Ball 1 Error (meters)	Ball 2 Error (meters)	Ball 3 Error (meters)	Interpupilary Distance (cm)
1	1	2	3	64.298	92.029	61.459	27.732	7.9423	10.451	9.1249	2.5082	0.3379	0.361	0.4117	6.1
2	0	2	3												
3	2	0	2	68.532	84.226	67.722	15.694	17.82	22.966	19.027	5.1459	0.2889	0.2537	0.2469	6
4	3	2	3												
5	4	2	1	96.784	93.798	100.92	-2.985	7.7773	16.438	13.02	8.6608	0.266	0.1604	0.1092	5.4
6	3	1	3	88.635	109.64	90.086	21.009	21.043	25.512	24.2	4.4692	0.2313	0.2383	0.1074	6
7	4	1	3	71.661	101.71	79.829	30.051	14.087	19.609	17.024	5.522	0.3547	0.1156	0.0991	6
8	3	1	1	85.888	99.142	87.735	13.254	13.372	25.382	22.281	12.01	0.2968	0.2362	0.1506	5.8
9	1	1	3	68.868	68.739	60.928	-0.129	10.159	16.961	14.25	6.8023	0.2193	0.1832	0.1105	6.2
10	0	2	3	49.511	109	103.53	59.486	8.749	16.007	13.781	7.2579	1.012	0.8137		5.7
11	2	3	1	84.601	88.214	86.322	3.6127	15.34	21.032	16.473	5.6921	0.2063	0.0203	0.1126	6.2
12	1	3	0	88.638	100.71	88.148	12.069	12.177	21.854	21.09	9.6767	1.4641	1.6399	1.3914	5.8
13	0	3	3	66.612	79.575	66.509	12.963	8.0056	19.216	17.236	11.211	0.2363	0.1796	0.0822	6
14	2	3	1	100.98	92.897	94.192	-8.087	17.485	24.218	20.44	6.7325	0.3101	0.192	0.1	6.5
15	1	3	3	66.633	102.71	67.58	36.076	9.3801	15.055	16.449	5.6753	0.1206	0.1261	0.0963	5.8
16	0	3	2	100.86	103.99	105.54	3.1263	4.9364	10.864	8.5366	5.9274	1.411	0.9525	0.3601	6
17	2	3	3	72.469	105.04	80.602	32.571	9.4868	21.441	17.243	11.954	0.1531	0.047	0.1283	6.2
18	4	3	2	75.435	84.728	77.156	9.293	13.896	18.768	17.165	4.8721	0.321	0.1433	0.1467	5.9
19	3	3	0	99.443	135.59	99.373	36.143	17.578	37.351	29.376	19.773	0.3656	0.1492	0.1848	5.8
20	4	1	2	64.033	95.585	62.349	31.551	3.9679	8.9289	7.343	4.961	0.1797	0.1043	0.2457	6.2
21	4	2	3	65.466	81.405	70.902	15.939	7.0324	12.091	10.796	5.0582	0.247	0.2503	0.1683	6
22	3	2	3	85.634	94.056	83.307	8.4223	7.843	17.508	14.557	9.6646	0.2579	0.1629	0.0508	5.9
23	2	3	3	77.039	77.216	79.656	0.1767	9.8454	15.822	14.316	5.9761	0.2655	0.1466	0.0646	5.9
24	1	2	1									0.1929	0.1157	0.0209	6.4
25	0	2	3												6.5
26	4	3	3					9.2454	14.517	14.021	5.2715	0.0849	0.1199	0.0834	5.7
27	3	2	3												
28	0	2	2					11.565	32.581	20.057	21.015	0.2845	0.1682	0.1005	5.8
29	1	3	2					14.54	31.804	25.616	17.263	0.357	0.8564	0.8013	5.6
30	2	2	3												
31	1	2	1					12.062	18.955	16.272	6.8933	0.3001	0.1188	0.0789	6.2
32	2	3	3					11.679	18.338	16.38	6.6584	0.263	0.1259	0.093	5.7
33	3	0	2					13.556	19.971	16.418	6.4149	0.3241	0.1521	0.1558	6.3
34	0	3	3					13.621	17.231	15.112	3.6102	0.3017	0.2274	0.1814	5.7
35	2	2	0					10.999	18.67	16.445	7.6702	0.2856	0.3595	0.1637	5.6
36	3	3	3					16.373	19.635	18.73	3.2616	0.2657	0.7569	0.7724	6.2
37	4	2	1					16.673	29.547	24.107	12.874	1.1059	0.8636	0.7997	5.9
38	1	3	3					10.905	14.867	12.412	3.9616	0.3746	1.0074	0.8749	5.7
39	2	3	2	92.011	93.299	85.4	1.2882	7.3065	14.505	11.656	7.1988	0.1044	0.1481	0.0664	5.9
40	3	3	2	80.609	117.95	82.818	37.346	10.99	22.344	19.032	11.354	0.2752	0.1939	0.0572	5.8
41	4	1	3	90.98	91.744	87.121	0.7641	3.2401	2.9402	2.9157	-0.3	0.3144	3.2962	0.3762	6.5
42	.	2	3												
43	0	2	1	104.67	104.01	107.32	-0.665	13.414	22.059	19.577	8.645	0.1325	0.0311	0.0216	6.3
44	1	2	0	90.884	93.632	86.647	2.7478	1.8336	6.777	7.463	4.9434	0.2913	0.236	0.2822	5.6
45	2	3	1	73.302	89.757	65.097	16.455	7.4988	17.531	13.349	10.033	0.2809	0.2877	0.1585	5.9
46	3	1	2	92.647	109.73	99.871	17.079	6.3569	18.403	12.935	12.046	0.3864	0.2698	0.1391	6
47	1	3	3	99.039	111.85	94.319	12.807	1.1731	1.3445	1.2763	0.1713	0.3297	0.8986	0.9358	5.8
48	2	1	2	76.932	92.429	85.831	15.497	13.691	20.085	20.573	6.3941	0.226	0.9633	0.1845	5.9
49	0	2	3	72.494	78.555	71.34	6.0611	7.0628	19.901	18.193	12.838	0.3372	0.1896	0.249	5.9

50	3	3	3	87.005	122.77	85.888	35.763	11.444	16.088	14.73	4.6444	1.0742	0.8137	0.9438	6
51	4	2	3												
52	0	1	2	97.354	96.522	90.754	-0.832	13.678	18.729	16.324	5.0513	0.0855	0.0514		5.7
53	4	2	2	81.828	96.475	76.715	14.647	6.2377	14.059	11.839	7.8214	0.3704	0.1061	0.2174	5.3
54	4	3	3	80.6	84.797	79.156	4.1966	6.541	13.681	12.524	7.1402	0.1622	0.0788		5.6
55	1	3	3	85.967	105.45	92.11	19.483	6.3775	10.808	9.1261	4.4304	0.1821	0.1373	0.1817	5.3
56	1	1	2	61.942	79.245	61.301	17.304	7.2439	19.585	12.634	12.341	0.1724	0.1025	0.0707	5.8
57	0	1	3	71.542	86.603	61.702	15.061	8.0619	11.352	12.202	3.2896	0.2688	0.2729	0.8991	5.9
58	1	2	3	74.074	83.972	75.215	9.8975	8.8454	14.145	10.035	5.2993	0.3083	0.2476	0.1705	5.7
59	3	2	2	95.281	111.54	82.887	16.262	7.7496	12.536	9.6092	4.7864	0.3389	0.239	0.298	5.6
60	4	1	3	84.755	89.422	82.523	4.667	6.0003	15.528	10.864	9.5281	0.3093	0.1831	0.1038	5.7
61	0	3	2	98.254	114.8	106.63	16.551	8.2559	14.712	12.822	6.456	1.2359	0.9563	0.7198	5.9

Table F.2: Pit Experiment Data Part 2.

F.3 The Gallery Experiment – Part 1 (Pre-Trial)

ID	Gender (0=M,1=F)	University Status (1=undergraduate, 2=graduate)	Computer Use	Game Playing	Exercise (Hours per Week)	Simulator Sickness Nausea	Simulator Sickness Ocular Disconfort	Simulator Sickness Disorientation	Simulator Sickness Total
1	0	1	5	2	2	9.54	15.16	13.92	14.96
2	1	1	5	1	3+	9.54	7.58	0	7.48
3	1	1	6	2	2	0	7.58	27.84	11.22
4	0	1	6	4	1.5	9.54	7.58	27.84	14.96
5	0	1	3	3	3+	0	0	0	0
6	1	1	7	2	3+	0	0	0	0
7	1	1	5	3	2	0	7.58	0	3.74
8	0	1	5	3	1.5	0	0	0	0
9	1	1	6	4	2	0	7.58	13.92	7.48
10	0	1	7	5	3+	9.54	0	0	3.74
11	1	1	7	1	1.5	0	0	0	0
12	0	1	4	2	2	0	0	0	0
21	0	1	3	2	2	0	7.58	0	3.74
22	1	1	6	1	3+	9.54	30.32	13.92	22.44
23	1	1	7	3	1	9.54	15.16	0	11.22
24	0	1	6	2	3+	0	7.58	0	3.74
25	1	1	5	1	2	9.54	7.58	0	7.48
26	0	1	7	7	3+	28.62	15.16	0	18.7
27	1	1	4	2	2	9.54	15.16	0	11.22
28	0	1	5	5	2.5	9.54	30.32	13.92	22.44
29	1	1	6	3	1	9.54	15.16	13.92	14.96
30	0	1	6	2	3+	0	0	0	0
31	1	1	5	1	< 0.5	9.54	7.58	0	7.48
32	0	1	5	2	1	0	15.16	0	7.48
33	1	1	7	3	3+	0	22.74	0	11.22
34	0	1	5	2	3+	0	7.58	0	3.74
35	1	1	5	1	2.5	38.16	75.8	69.6	71.06
36	0	1	5	1	2.5	9.54	45.48	55.68	41.14
50	1	1	7	2	3+	9.54	53.06	41.76	41.14
51	0	2	6	5	1.5	9.54	15.16	0	11.22
52	0	1	5	4	1	38.16	22.74	13.92	29.92
53	1	1	7	5	< 0.5	9.54	0	0	3.74
54	0	1	7	4	2	0	7.58	0	3.74
55	1	1	6	2	< 0.5	0	7.58	0	3.74
56	1	1	6	1	3+	0	15.16	0	7.48
57	1	1	7	1	3+	0	15.16	0	7.48
58	1	1	7	2	3+	19.08	7.58	0	11.22
59	1	1	7	2	3+	0	7.58	0	3.74
60	0	1	4	1	3+	28.62	22.74	0	22.44
61	0	2	2	3	1	0	0	0	0
62	0	1	5	2	1.5	9.54	0	0	3.74
63	0	1	6	1	3+	9.54	30.32	13.92	22.44
64	1	1	6	1	2	38.16	15.16	0	22.44
65	0								
66	1	1	7	4	3+	19.08	15.16	0	14.96
67	0	1	6	3	3+	0	7.58	0	3.74
68	0	1	5	3	3+	9.54	22.74	0	14.96

69	1	1	7	2	3+	0	15.16	0	7.48
70	0	2	7	2	2	0	0	0	0
71	1	1	7	2	3+	0	0	0	0
72	0	1	7	2	< 0.5	28.62	22.74	41.76	33.66
73	0	2	7	5	< 0.5	0	7.58	0	3.74
74	0	1	5	5	2	19.08	7.58	13.92	14.96
75	1	1	4	2	0.5	0	0	0	0
76	0	2	7	7	1.5	9.54	7.58	0	7.48
77	1	2	5	2	3+	0	15.16	0	7.48
78	1	1	7	1	3+	0	7.58	0	3.74
79	0	1	7	4	3+	38.16	75.8	41.76	63.58
80	0	2	7	4	< 0.5	0	0	0	0
81	1	2	7	3	3+	0	0	0	0
82	1	1	7	4	2	0	15.16	0	7.48
83	0	1	7	5	3+	0	0	0	0
84	0	1	7	4	3+	0	0	0	0

Table F.3: Gallery Experiment Data (Pre-Trial).

F.4 The Gallery Experiment – Part 2

ID	Total Session Time <130s	Illumination (1=global,2=local)	Condition (1=plvr 2:1, 2=plvr 7:1, 3=prvl 2:1, 4=prvl 7:1)	Trial	Simulator Sickness Nausea	Simulator Sickness Ocular Discomfort	Simulator Sickness Disorientation	Simulator Sickness Total	Reported Presence	Behavioral Presence	Ease of Locomotion	Lighting Impression Score	Positive Affect Score	Negative Affect Score	Gaze Time - Left Painting (sec)	Gaze Time - Right Painting (sec)	Gaze Time - North Vase (sec)	Gaze Time - South Vase (sec)	Movement - Left of Door Quadrant Occupancy (sec)	Movement - Right of Door Quadrant Occupancy (sec)	Movement - Left of Divider Quadrant Occupancy (sec)	Movement - Right of Divider Quadrant Occupancy (sec)
1	1	1	1	1	28.62	22.74	13.92	26.18	6	2	3	2.8	32	14	29.62	17.78	3.87	6.22	89.11	25.47	5.14	0.28
2	1	1	2	1	9.54	22.74	27.84	22.44	2	2	1	2.87	36	17	11.74	18.60	13.14	17.96	24.60	48.17	24.63	22.63
3	1	1	3	1	19.08	30.32	153.12	63.58	1	1	0	4.07	22	17	18.78	14.26	6.85	11.47	62.83	29.20	2.40	25.61
4	1	1	4	1	9.54	15.16	27.84	18.7	4	0	3	2.93	38	17	25.42	26.95	3.47	5.14	41.68	55.96	12.56	9.82
5	1	1	5	1	0	7.58	55.68	18.7	0	1	2	3.67	32	15	17.43	37.04	14.98	0.00	59.76	52.99	7.26	0.02
6	1	1	4	1	38.16	15.16	55.68	37.4	3	0	1	3.27	26	20	33.42	31.37	8.67	14.29	26.61	76.51	0.00	16.91
7	1	1	5	1	0	15.16	0	7.48	4	1	3	3.53	19	11	22.95	15.33	12.76	12.11	37.36	30.42	33.87	18.38
8	1	1	1	1	19.08	7.58	0	11.22	2	1	2	3.8	34	10	24.93	27.47	10.89	10.17	59.26	60.76	0.00	0.02
9	1	1	2	1	19.08	22.74	13.92	22.44	4	1	2	2.8	25	11	27.04	21.53	7.37	0.00	41.76	56.01	0.00	22.27
10	1	1	3	1	0	7.58	0	3.74	6	2	3	3.13	23	11	18.63	20.35	4.30	13.73	52.44	43.58	5.07	18.93
11	1	1	3	1	0	0	0	0	4	2	3	2.13	37	10	15.93	21.58	8.76	14.08	43.06	37.96	23.52	15.84
12	1	1	2	1	19.08	30.32	55.68	37.4	2	2	1	3.53	25	15	13.99	26.00	12.31	8.22	31.69	52.17	21.10	15.08
21	1	1	1	1	0	7.58	0	3.74	5	2	3	2.53	34	10	15.26	14.74	11.62	17.03	49.63	28.64	18.36	23.42
22	1	1	2	1	28.62	15.16	27.84	26.18	1	0	2	3.07	23	13	18.46	29.44	9.22	11.07	37.81	75.38	6.80	0.02
23	1	1	3	1	19.08	15.16	27.84	22.44	2	2	1	4.13	19	13	21.61	33.29	9.22	8.02	61.22	39.99	10.08	8.70
24	1	1	4	1	0	7.58	0	3.74	6	2	3	2.2	31	10	13.14	13.96	12.89	7.82	33.97	44.32	28.42	14.08
25	1	1	5	1	19.08	15.16	27.84	22.44	6	2	0	2.8	27	10	21.25	17.53	9.43	6.72	48.70	37.16	11.28	22.88
26	1	1	4	1	28.62	15.16	13.92	22.44	7	2	3	3.07	35	12	18.63	16.03	7.40	4.82	43.68	50.68	13.13	12.54
27	1	1	5	1	9.54	15.16	0	11.22	6	2	3	2.2	34	10	23.17	22.57	5.84	10.93	91.01	27.05	0.00	1.95
28	1	1	1	1	0	15.16	0	7.48	5	2	2	2.93	31	11	18.36	23.48	4.75	3.77	56.79	62.09	0.93	0.22
29	1	1	2	1	9.54	15.16	13.92	14.96	4	2	2	3.27	22	10	15.43	33.14	4.09	15.71	78.21	20.45	20.51	0.85
30	1	1	3	1	9.54	22.74	41.76	26.18	7	1	3	2.67	34	11	18.45	14.89	9.32	9.09	45.56	42.68	17.20	14.60
31	1	1	1	1	9.54	0	0	3.74	5	1	0	3.6	23	10	21.85	16.26	8.14	7.96	23.92	47.68	11.88	36.54
32	1	1	2	1	9.54	22.74	41.76	26.18	4	2	3	3.27	39	12	19.00	12.96	4.77	15.78	32.82	53.47	10.92	22.80
33	1	1	3	1	0	15.16	0	7.48	7	1	2	2.13	41	10	23.80	30.75	5.69	9.64	38.81	57.59	8.06	15.56
34	1	1	4	1	9.54	7.58	0	7.48	5	1	3	3.13	33	10	19.88	20.35	11.05	9.39	58.24	40.78	13.58	7.44
35	1	1	5	1	38.16	53.06	55.68	56.1	1	0	0	3.53	31	22	20.60	14.34	8.36	5.77	65.61	54.39	0.00	0.02
36	1	1	4	1	19.08	53.06	69.6	52.36	4	2	3	2.6	24	15	14.71	20.88	9.77	3.35	29.47	73.23	8.91	8.42
50	1	2	1	1	19.08	45.48	27.84	37.4	2	1	2	2.73	29	11	12.74	15.19	9.89	10.66	55.97	29.34	21.65	13.06
51	1	2	2	1	9.54	15.16	0	11.22	7	2	3	2.47	28	12	11.01	12.09	13.51	18.15	39.96	26.05	34.56	19.46
52	1	2	3	1	9.54	22.74	41.76	26.18	4	1	2	3.53	30	23	16.71	13.56	14.49	16.90	39.63	35.71	27.05	17.63
53	1	2	4	1	9.54	30.32	13.92	22.44	1	1	2	2.67	31	10	26.94	22.93	10.39	9.91	53.12	40.41	13.79	12.69
54	1	2	5	1	0	0	27.84	7.48	4	2	0	3.6	29	12	16.76	20.11	9.79	0.78	42.63	58.19	19.18	0.02
55	1	2	4	1	0	7.58	0	3.74	6	2	3	2.47	41	14	27.69	13.18	11.88	15.03	34.34	31.74	28.54	25.40
56	1	2	5	1	28.62	45.48	55.68	48.62	2	1	2	3.6	17	12	15.98	19.20	8.07	7.57	31.84	62.53	15.31	10.34
57	1	2	1	1	9.54	30.32	13.92	22.44	2	2	3	3.53	33	23	38.01	21.28	7.97	6.52	48.27	53.90	8.04	9.81
58	1	2	2	1	9.54	7.58	13.92	11.22	2	2	3	3.2	18	11	22.18	24.22	10.04	9.36	57.97	45.70	15.19	1.15
59	1	2	3	1	0	0	0	0	2	2	3	3	33	10	31.74	17.64	9.57	7.07	32.84	68.15	1.25	17.78
60	1	2	1	1	9.54	22.74	13.92	18.7	2	2	3	2.6	31	10	17.80	15.98	7.64	5.79	57.94	34.76	17.33	9.99
61	1	2	2	1											25.35	18.50	12.13	15.46	33.52	43.23	28.27	14.99
62	1	2	3	1	9.54	0	0	3.74	4	2	1	1.87	24	11	18.25	16.24	11.97	12.79	37.74	43.55	12.14	26.59
63	1	2	4	1	19.08	22.74	41.76	29.92	4	0	2	3.33	32	11	19.83	7.51	8.31	7.07	40.75	40.50	25.23	13.54
64	1	2	5	1	38.16	45.48	97.44	63.58	3	0	3	4.2	36	17	8.92	8.27	18.56	26.32	20.93	26.12	43.67	29.30
65	1	2	4	1	0	7.58	0	3.74	5	1	3	1.93	37	11	10.34	19.08	8.02	10.26	37.91	56.36	6.20	19.56
66	1	2	5	1	19.08	15.16	0	14.96	6	1	3	2.13	34	14	18.03	27.47	11.11	3.57	37.29	55.69	14.56	12.47

67	1	2	1	1	9.54	0	13.92	7.48	4	2	3	3.6	26	11	15.41	16.18	10.37	8.94	46.12	49.92	16.28	7.71
68	1	2	2	1	9.54	22.74	0	14.96	5	2	2	2.6	35	13	13.03	15.06	7.71	12.69	49.63	40.96	13.79	15.63
69	1	2	3	1	0	22.74	41.76	22.44	2	1	3	3.2	16	10	6.67	32.44	8.36	8.84	30.50	48.17	19.95	21.42
70	1	2	1	1	0	0	0	0	6	2	3	2.53	23	10	17.01	31.39	12.39	12.18	41.78	36.64	21.98	19.61
71	1	2	2	1	0	0	0	0	4	1	2	3.93	19	11	18.28	19.05	9.99	15.34	28.35	35.24	28.22	28.20
72	1	2	3	1	19.08	15.16	41.76	26.18	1	1	3	4.33	22	10	22.20	10.14	7.67	24.82	39.28	37.31	18.30	25.13
73	1	2	4	1	0	0	0	0	3	2	3	3.07	25	11	25.90	16.09	19.11	5.22	22.95	50.54	29.37	17.16
74	1	2	5	1	9.54	15.16	41.76	22.44	6	1	3	4.53	36	15	15.63	8.94	14.21	16.24	62.58	14.19	19.46	23.78
75	1	2	4	1	0	0	0	0	2	1	0	1.8	27	12	7.09	3.27	8.97	0.00	35.88	84.14	0.00	0.02
76	1	2	5	1	9.54	7.58	13.92	11.22	4	2	3	4.6	13	11	14.01	27.02	7.61	10.99	51.14	30.89	29.70	8.29
77	1	2	1	1	0	7.58	0	3.74	0	1	1	3.93	15	11	17.43	27.15	7.65	3.12	37.04	55.37	4.30	23.32
78	1	2	2	1	0	7.58	0	3.74	4	2	3	3.87	30	10	18.65	15.16	10.34	7.96	32.53	60.68	11.62	15.19
79	1	2	3	1	9.54	45.48	27.84	33.66	4	2	2	4.27	46	21	17.61	24.07	9.61	14.63	51.80	23.82	29.87	14.53
80	1	2	1	1	9.54	0	13.92	7.48	6	1	2	3.53	20	11	12.05	27.20	9.74	12.39	29.37	56.22	19.23	15.19
81	1	2	2	1	19.08	37.9	55.68	41.14	7	1	3	1.93	38	11	18.78	17.95	13.46	13.86	31.16	42.50	9.74	36.64
82	1	2	3	1	0	15.16	0	7.48	1	0	3	4.2	22	10	22.48	36.31	12.99	8.52	30.57	58.39	16.26	14.81
83	1	2	4	1	0	0	0	0	4	2	3	2.87	23	10	22.52	19.35	17.56	18.90	48.47	30.82	21.30	19.45
84	1	2	5	1	0	0	0	0	7	1	3	3.93	43	10	13.44	12.76	14.88	12.02	49.02	20.80	28.75	21.46
1	1	1	2	2	19.08	30.32	27.84	29.92	6	1	3	2.67	28	12	5.19	21.57	8.86	17.75	32.37	24.94	35.83	26.92
2	1	1	3	2	38.16	22.74	41.76	37.4	2	1	2	3	31	14	34.06	5.15	10.19	17.10	42.46	18.08	30.19	29.30
3	1	1	4	2	19.08	22.74	41.76	29.92	0	0	0	4.07	21	13	5.12	20.20	17.35	10.79	30.12	39.44	36.03	14.41
4	1	1	5	2	28.62	15.16	41.76	29.92	5	0	3	5.6	29	14	23.55	21.38	13.54	12.64	47.67	22.28	4.82	45.23
5	1	1	1	2	9.54	22.74	55.68	29.92	1	1	3	3.6	24	13	18.78	13.93	22.08	9.57	29.52	40.85	19.38	30.29
6	1	1	3	2	28.62	22.74	41.76	33.66	2	0	1	4.93	25	17	29.55	14.09	9.61	8.57	24.50	31.36	19.90	44.26
7	1	1	4	2	0	15.16	0	7.48	1	1	3	2.73	17	12	17.21	16.81	10.39	11.52	32.94	39.36	14.39	33.32
8	1	1	5	2	9.54	0	0	3.74	3	2	3	5.4	36	10	12.78	23.83	7.49	8.27	39.39	44.35	26.58	9.72
9	1	1	1	2	9.54	22.74	27.84	22.44	3	2	2	2.33	18	10	22.50	15.79	7.72	7.47	48.28	45.10	9.57	17.08
10	1	1	2	2	0	0	0	0	5	1	3	3	20	15	17.93	19.28	26.25	7.51	22.93	39.78	40.39	16.93
11	1	1	2	2	0	0	0	0	3	0	3	2	37	10	24.18	35.24	5.30	5.15	50.27	42.85	22.87	4.05
12	1	1	3	2	19.08	37.9	55.68	41.14	1	0	0	4.87	24	12	17.60	17.85	14.48	11.67	40.41	39.61	17.00	23.00
21	1	1	2	2	0	7.58	0	3.74	7	2	3	2.53	35	10	19.53	9.79	14.84	11.69	40.81	32.89	30.72	15.61
22	1	1	3	2	9.54	15.16	41.76	22.44	1	0	2	4.47	19	13	33.07	25.92	5.39	12.26	37.47	58.27	11.07	13.23
23	1	1	4	2	28.62	37.9	41.76	41.14	2	0	2	2.87	17	12	17.20	22.06	7.07	6.42	60.50	39.31	12.26	7.96
24	1	1	5	2	0	7.58	0	3.74	6	1	3	3.53	35	10	8.87	18.01	14.68	15.73	19.96	46.70	36.59	16.76
25	1	1	1	2	9.54	0	27.84	11.22	6	2	3	2.47	32	10	4.95	9.26	16.75	13.69	20.67	48.95	20.36	30.04
26	1	1	3	2	38.16	7.58	13.92	22.44	7	2	3	3.73	32	10	23.40	12.44	11.56	8.92	7.23	61.41	32.76	21.27
27	1	1	4	2	28.62	22.74	0	22.44	5	2	3	3.33	21	10	12.96	35.05	4.85	4.50	46.37	50.17	12.28	14.09
28	1	1	5	2	0	15.16	0	7.48	4	1	2	3.33	27	11	10.77	14.32	25.78	16.68	43.24	23.90	31.12	21.77
29	1	1	1	2	9.54	15.16	13.92	14.96	1	2	2	4	15	10	60.14	12.96	7.26	5.87	64.76	43.96	8.64	2.67
30	1	1	2	2	9.54	30.32	69.6	37.4	5	2	2	2.6	17	10	10.22	16.70	6.61	12.14	40.19	48.58	21.52	14.66
31	1	1	2	2	0	0	0	0	4	0	0	4.2	19	10	18.05	13.80	7.94	7.57	42.41	43.36	17.70	16.55
32	1	1	3	2	9.54	7.58	27.84	14.96	5	2	2	3.27	32	11	17.71	24.65	1.27	13.34	29.65	58.26	10.97	21.15
33	1	1	4	2	0	15.16	0	7.48	7	2	3	1.2	37	10	26.39	21.23	8.97	8.17	53.15	36.53	17.20	13.14
34	1	1	5	2	0	0	0	0	6	1	2	3.27	36	10	8.14	33.22	13.11	10.46	36.03	57.09	16.78	10.14
35	1	1	1	2	38.16	45.48	27.84	44.88	1	0	0	3.27	31	24	25.32	24.82	4.35	6.97	34.89	65.09	19.85	0.18
36	1	1	3	2	19.08	53.06	55.68	48.62	2	1	3	4	21	11	22.31	14.31	16.16	16.41	39.53	28.77	15.08	36.64
50	1	2	2	2	9.54	30.32	27.84	26.18	3	0	2	3.4	21	10	16.76	13.86	12.68	3.92	36.39	45.52	15.99	22.12
51	1	2	3	2	28.62	15.16	0	18.7	7	2	3	4.6	29	11	22.90	9.24	9.34	29.27	38.14	29.97	21.20	30.72
52	1	2	4	2	38.16	53.06	139.2	78.54	4	2	3	4.73	24	23	19.86	36.63	0.00	6.45	53.19	55.96	0.00	10.87
53	1	2	5	2	19.08	60.64	69.6	56.1	1	1	3	6.4	23	11	29.55	27.65	4.69	2.25	39.11	72.70	6.52	1.68
54	1	2	1	2	9.54	0	27.84	11.22	2	1	2	2.93	27	11	22.58	21.32	14.36	14.98	47.25	27.22	24.90	20.65
55	1	2	3	2	0	7.58	0	3.74	6	2	3	4	38	12	28.64	28.13	12.79	6.77	27.24	70.93	20.08	1.77
56	1	2	4	2	38.16	83.38	125.28	89.76	1	0	0	3.93	15	13	8.72	16.58	9.46	10.34	40.08	29.37	35.83	14.74
57	1	2	5	2	9.54	37.9	27.84	29.92	0	2	3	4.47	24	19	10.27	55.32	4.12	5.45	42.58	63.56	5.81	8.07
58	1	2	1	2	19.08	15.16	27.84	22.44	2	1	3	2.87	21	11	12.34	29.52	14.29	11.62	34.04	52.69	29.05	4.24
59	1	2	2	2	0	15.16	13.92	11.22	2	1	2	2.73	33	10	22.68	14.66	8.69	10.96	46.20	32.96	11.74	29.14

60	1	2	2	2	0	30.32	27.84	22.44	0	2	2	2.67	25	10	7.99	12.29	5.12	9.06	53.92	32.61	14.46	19.03
61	0	2	3	2											66.65	10.56	5.22	9.77	70.17	79.24	13.84	10.32
62	1	2	4	2	9.54	7.58	27.84	14.96	4	2	1	1.4	23	11	15.98	14.38	12.93	13.28	33.37	47.18	13.14	26.32
63	1	2	5	2	28.62	60.64	83.52	63.58	0	0	0	4.6	27	12	11.87	8.09	7.16	6.50	35.39	44.98	20.15	19.50
64	1	2	1	2	57.24	60.64	83.52	74.8	2	0	2	3.73	29	15	33.04	25.55	1.92	3.32	78.52	41.48	0.00	0.02
65	1	2	3	2	9.54	22.74	13.92	18.7	6	2	3	2.2	38	11	2.42	16.76	18.10	33.59	10.96	41.11	25.45	42.50
66	1	2	4	2	19.08	37.9	27.84	33.66	7	1	3	6.13	32	13	29.14	18.20	5.50	14.43	30.89	59.73	6.67	22.73
67	1	2	5	2	9.54	7.58	13.92	11.22	3	1	3	5.13	26	11	11.37	21.10	21.77	9.04	31.17	35.61	32.24	21.00
68	1	2	1	2	9.54	22.74	0	14.96	6	2	3	2.67	35	13	10.46	18.35	13.03	13.06	45.75	32.89	24.57	16.81
69	1	2	2	2	0	30.32	41.76	26.18	0	1	3	3.4	17	10	30.70	9.29	5.25	0.00	49.08	35.94	33.02	1.99
70	1	2	2	2	0	7.58	0	3.74	7	2	3	2.6	14	10	15.08	13.58	12.93	13.19	46.60	36.86	17.95	18.61
71	1	2	3	2	0	0	0	0	4	1	2	3.53	17	10	12.66	17.50	11.41	15.03	41.10	39.46	23.17	16.31
72	1	2	4	2	38.16	37.9	55.68	48.62	3	1	0	4.33	20	11	15.09	11.59	10.26	17.71	25.47	50.84	23.02	20.71
73	1	2	5	2	0	0	0	0	2	2	2	3.67	17	11	20.58	23.48	21.70	5.84	65.61	19.98	19.28	15.14
74	1	2	1	2	19.08	22.74	27.84	26.18	5	2	3	3.27	24	14	13.79	12.53	10.29	10.09	49.13	36.04	19.31	15.53
75	1	2	3	2	0	7.58	13.92	7.48	2	1	0	2.07	29	10	17.48	9.02	8.90	4.54	76.69	24.90	5.25	13.18
76	1	2	4	2	9.54	15.16	27.84	18.7	5	2	3	3.6	11	12	9.54	29.09	16.28	10.19	34.21	38.01	35.51	12.29
77	1	2	5	2	0	7.58	0	3.74	0	0	3	4.2	15	10	20.35	22.83	12.44	15.59	24.48	54.91	22.92	17.71
78	1	2	1	2	0	15.16	13.92	11.22	1	1	2	3.87	30	10	11.04	14.56	12.94	14.29	36.61	41.21	26.20	15.99
79	1	2	2	2	19.08	68.22	69.6	59.84	2	2	2	3.13	38	17	15.34	21.03	7.91	11.13	65.38	23.03	16.11	15.49
80	1	2	2	2	47.7	53.06	83.52	67.32	0	1	2	4.4	10	17	19.83	23.98	10.45	22.32	37.13	45.05	14.86	22.98
81	1	2	3	2	19.08	37.9	55.68	41.14	5	0	3	4.07	35	10	15.11	27.78	11.39	11.91	30.97	53.50	13.78	21.77
82	1	2	4	2	0	15.16	0	7.48	2	1	3	2.8	17	10	25.87	22.87	4.10	6.99	59.98	37.51	2.90	19.65
83	1	2	5	2	0	0	0	0	3	2	3	5	18	10	13.13	19.80	11.44	10.82	39.66	38.61	24.27	17.48
84	1	2	1	2	0	0	27.84	7.48	6	1	3	4	38	10	17.22	12.16	6.45	12.43	11.93	77.47	14.03	16.58
1	1	1	5	3	28.62	37.9	27.84	37.4	5	1	3	2.8	34	14	16.34	50.54	4.89	0.00	17.66	86.48	11.10	4.78
2	1	1	1	3	28.62	37.9	41.76	41.14	3	0	2	2.87	27	12	27.30	19.13	8.66	4.35	52.12	25.30	21.48	21.13
3	1	1	2	3	19.08	30.32	41.76	33.66	0	0	0	3.67	17	10	22.78	11.02	1.88	9.21	39.78	50.79	0.00	29.45
4	1	1	3	3	9.54	15.16	13.92	14.96	5	0	3	5.07	26	15	27.40	15.94	4.57	7.47	55.96	34.66	6.35	23.05
5	1	1	4	3	28.62	45.48	83.52	56.1	0	1	2	2.47	24	13	14.28	11.26	13.76	8.12	53.97	27.49	10.42	30.02
6	1	1	5	3	28.62	37.9	55.68	44.88	3	1	0	5.33	24	15	21.97	34.26	19.65	5.57	59.04	23.73	22.12	15.13
7	1	1	1	3	0	22.74	0	11.22	1	2	2	2.87	15	12	26.22	24.78	2.50	15.64	57.54	26.57	3.42	32.51
8	1	1	2	3	0	0	0	0	3	2	3	2.13	33	10	14.26	24.95	6.94	9.09	34.59	53.99	22.57	8.89
9	1	1	3	3	19.08	22.74	27.84	26.18	1	0	0	5.87	13	11	19.31	27.29	0.00	15.99	46.27	48.83	9.76	15.16
10	1	1	4	3	0	15.16	0	7.48	4	0	3	3.07	19	12	16.71	33.26	30.38	4.90	24.08	42.80	33.56	19.60
11	1	1	4	3	0	0	13.92	3.74	2	1	3	2	33	10	17.96	28.84	14.94	6.25	41.81	52.90	25.30	0.02
12	1	1	1	3	19.08	30.32	41.76	33.66	2	1	1	2.93	21	13	13.53	15.66	17.15	8.01	46.70	46.32	15.19	11.82
21	1	1	5	3	0	15.16	0	7.48	7	2	3	5.27	31	10	11.21	25.30	21.20	10.09	35.66	49.63	22.20	12.51
22	1	1	1	3	38.16	22.74	41.76	37.4	1	0	1	4.13	17	12	19.20	22.15	8.24	10.56	32.05	53.02	5.34	29.62
23	1	1	2	3	47.7	45.48	69.6	59.84	2	0	2	3.53	15	12	24.95	14.09	10.32	11.84	59.16	15.26	28.05	17.73
24	1	1	3	3	0	0	0	0	5	2	3	4.8	33	10	26.87	16.94	6.95	17.05	47.58	36.28	4.95	31.22
25	1	1	4	3	9.54	7.58	27.84	14.96	7	2	3	2.67	25	10	12.89	7.39	13.09	50.27	13.28	20.65	10.06	76.03
26	1	1	5	3	19.08	22.74	0	18.7	7	1	3	3.8	26	10	6.47	22.80	5.39	7.86	55.87	50.35	2.89	10.93
27	1	1	1	3	38.16	30.32	0	29.92	3	2	3	3.47	18	10	14.14	16.18	0.00	14.54	64.98	28.74	0.57	25.75
28	1	1	2	3	0	15.16	0	7.48	4	2	3	2.93	27	10	19.38	13.81	0.78	12.03	44.36	55.57	0.00	20.08
29	1	1	3	3	9.54	15.16	13.92	14.96	1	1	2	4.47	13	10	22.08	11.44	3.69	16.78	17.04	83.24	15.53	4.22
30	1	1	4	3	0	0	0	0	2	0	1	3.07	15	12	1.20	6.57	6.89	7.15	5.29	71.82	23.37	19.55
31	1	1	5	3	19.08	15.16	0	14.96	5	1	1	3.8	14	10	32.57	22.40	18.91	6.06	39.86	45.32	31.85	2.99
32	1	1	1	3	19.08	30.32	13.92	26.18	4	1	2	3.93	25	11	16.28	11.51	0.00	11.52	44.81	51.30	4.19	19.71
33	1	1	2	3	0	30.32	0	14.96	5	2	3	2.07	26	10	14.31	12.34	9.14	15.74	42.68	34.72	17.71	24.92
34	1	1	3	3	0	0	0	0	6	1	3	2.53	24	10	19.39	25.82	5.91	24.31	7.19	70.21	4.42	38.20
35	1	1	4	3	47.7	45.48	41.76	52.36	2	0	1	3.13	33	25	15.13	23.36	8.55	10.86	31.90	43.65	11.51	32.97
36	1	1	5	3	19.08	60.64	69.6	56.1	2	2	3	3.93	15	11	20.80	2.40	20.60	13.18	45.93	0.95	35.79	37.36
50	1	2	5	3	9.54	22.74	13.92	18.7	3	1	2	4.53	18	10	11.02	21.67	16.85	15.09	38.81	39.71	16.18	25.32
51	1	2	1	3	28.62	15.16	0	18.7	7	1	3	3.4	21	10	10.72	16.08	5.84	20.88	34.67	43.50	23.58	18.28
52	1	2	2	3	76.32	83.38	153.12	112.2	6	2	3	2.93	28	23	15.54	25.03	17.56	12.16	41.43	30.85	31.62	16.11

53	1	2	3	3	28.62	60.64	83.52	63.58	3	1	3	6.6	18	11	24.60	23.27	5.74	2.27	55.57	57.51	2.25	4.69
54	1	2	4	3	28.62	0	0	11.22	0	1	3	3.93	25	11	16.98	19.28	13.65	14.76	54.49	27.90	23.55	14.08
55	1	2	5	3	0	7.58	0	3.74	7	2	3	3.87	37	10	12.63	36.99	25.20	13.11	6.30	65.28	25.80	22.63
56	1	2	1	3	66.78	113.7	167.04	127.16	0	0	1	4.4	15	17	15.01	19.87	7.82	17.15	43.76	31.22	25.37	19.66
57	1	2	2	3	9.54	30.32	41.76	29.92	0	2	3	3.27	20	11	25.37	11.27	1.37	4.50	55.07	46.32	6.19	12.44
58	1	2	3	3	19.08	22.74	13.92	22.44	2	1	3	5.13	18	11	19.71	15.19	9.84	7.10	53.12	33.09	21.20	12.61
59	1	2	4	3	0	7.58	0	3.74	3	1	2	3.6	30	10	21.28	28.70	4.37	10.25	60.19	15.09	11.74	32.99
60	1	2	5	3	9.54	37.9	27.84	29.92	1	1	2	3.33	21	12	12.46	24.02	10.17	9.17	54.19	35.29	10.34	20.20
61	1	2	1	3	0	0	0	0	1	2	2	3.6	16	11	38.72	10.71	10.37	5.24	17.50	71.95	13.24	17.33
62	1	2	2	3	9.54	45.48	69.6	44.88	0	0	1	3.2	16	10	21.88	16.64	14.59	13.26	37.84	35.51	17.55	29.12
63	1	2	3	3	38.16	68.22	69.6	67.32	2	0	2	4.73	18	13	14.54	8.54	17.08	16.93	30.52	28.27	33.97	27.25
64	1	2	4	3	66.78	75.8	153.12	104.72	1	0	2	3.67	24	14	26.15	2.94	6.70	3.54	69.75	5.39	20.15	24.73
65	1	2	5	3	9.54	30.32	41.76	29.92	6	2	3	2.13	40	10	4.17	21.95	24.65	12.24	14.79	48.93	29.15	27.14
66	1	2	1	3	19.08	45.48	27.84	37.4	7	2	3	1.53	33	17	14.63	27.52	6.37	8.87	69.03	13.36	4.44	33.19
67	1	2	2	3	0	7.58	0	3.74	2	1	3	2.8	28	10	28.02	9.81	7.64	10.97	49.08	21.75	25.33	23.87
68	1	2	3	3	9.54	30.32	0	18.7	6	2	3	4.6	33	13	17.01	14.96	14.58	13.28	33.62	47.70	20.36	18.33
69	1	2	4	3	0	37.9	41.76	29.92	0	1	2	4	13	11	17.61	23.90	14.34	0.00	30.59	71.80	17.63	0.02
70	1	2	5	3	0	7.58	0	3.74	7	2	3	4.6	14	10	14.76	17.16	7.66	12.18	48.17	40.46	9.56	21.85
71	1	2	1	3	0	0	0	0	4	1	3	2.93	18	10	17.31	19.41	7.39	1.93	46.90	65.35	4.44	3.34
72	1	2	2	3	9.54	7.58	0	7.48	5	2	3	2.47	27	10	16.53	15.79	18.41	13.16	44.55	30.64	28.30	16.53
73	1	2	3	3	0	0	0	0	2	2	3	4.13	16	11	54.12	13.96	6.32	11.64	70.27	18.30	1.15	30.32
74	1	2	4	3	19.08	22.74	41.76	29.92	7	1	3	2.93	29	10	22.12	10.24	15.09	16.38	57.87	24.42	19.83	17.90
75	1	2	5	3	0	15.16	13.92	11.22	2	1	0	2.27	29	10	6.79	14.71	31.64	0.00	54.27	29.37	32.79	6.25
76	1	2	1	3	28.62	45.48	27.84	41.14	0	2	3	3.13	10	14	25.52	18.68	15.64	8.44	52.39	27.49	25.13	15.01
77	1	2	2	3	0	15.16	0	7.48	0	0	3	3.87	13	10	6.27	10.92	6.42	4.84	21.75	10.54	57.24	30.49
78	1	2	3	3	0	22.74	27.84	18.7	0	1	3	6	22	10	21.38	16.04	13.78	10.54	43.61	41.26	10.72	24.41
79	0	2	4	3	28.62	75.8	69.6	67.32	1	1	2	2.93	27	15	7.64	16.73	3.17	8.96	6.92	295.68	19.16	9.04
80	1	2	5	3	28.62	60.64	97.44	67.32	0	1	3	5.33	13	14	12.33	30.48	20.35	10.26	21.58	51.44	34.19	12.81
81	1	2	1	3	28.62	45.48	55.68	48.62	7	1	3	2.67	36	11	24.18	22.38	11.89	6.37	48.17	38.93	17.50	15.44
82	1	2	2	3	0	15.16	13.92	11.22	0	1	3	4.07	17	10	45.17	14.44	8.91	16.63	60.68	22.92	25.53	10.89
83	1	2	3	3	0	0	0	0	2	2	3	4.87	12	10	23.22	6.14	6.11	12.39	63.98	27.65	15.19	13.19
84	1	2	4	3	0	15.16	27.84	14.96	7	2	3	4.07	33	10	12.31	16.92	31.41	10.46	43.10	12.01	59.51	5.40
1	1	1	3	4	28.62	37.9	27.84	37.4	6	2	3	2.6	29	13	70.98	11.69	2.25	9.87	86.38	23.43	0.00	10.21
2	1	1	4	4	28.62	60.64	41.76	52.36	2	1	3	3.07	32	13	6.19	36.79	8.14	1.57	15.86	81.82	18.06	4.27
3	1	1	5	4	9.54	30.32	13.92	22.44	0	0	0	4.07	16	10	6.29	16.85	16.26	3.27	34.51	41.18	24.22	20.13
4	1	1	1	4	19.08	0	13.92	11.22	6	1	3	1.33	31	14	19.68	24.70	4.07	2.85	46.42	40.33	16.59	16.68
5	1	1	2	4	38.16	75.8	97.44	78.54	1	2	3	2.33	19	16	31.16	17.48	17.75	5.49	61.96	26.77	24.79	6.50
6	1	1	2	4	9.54	30.32	41.76	29.92	2	1	1	4.6	27	14	21.01	22.93	10.32	15.01	43.95	28.80	1.62	45.65
7	1	1	3	4	0	22.74	13.92	14.96	2	0	2	4.87	15	12	59.87	3.12	5.65	21.01	75.87	7.49	2.52	34.14
8	1	1	4	4	0	0	0	0	3	2	3	3.13	31	10	14.81	25.90	7.49	8.89	30.27	63.61	16.36	9.79
9	1	1	5	4	19.08	45.48	27.84	37.4	1	0	1	5.87	13	13	9.76	36.33	10.69	16.21	24.23	64.63	3.00	28.17
10	1	1	1	4	0	15.16	0	7.48	2	1	3	6.13	17	10	15.26	27.42	3.41	13.73	57.37	11.94	11.96	38.74
11	1	1	1	4	0	0	0	0	2	1	3	2.07	32	10	21.43	30.59	8.44	10.81	29.90	43.48	42.23	4.40
12	1	1	4	4	38.16	37.9	69.6	52.36	1	1	0	3.6	25	12	14.89	11.89	11.52	9.34	57.84	40.16	16.06	5.97
21	1	1	3	4	0	15.16	0	7.48	4	2	3	5.27	31	10	28.44	6.34	11.46	35.31	50.10	19.23	15.21	35.46
22	1	1	4	4	38.16	37.9	41.76	44.88	1	0	1	2.67	16	12	12.08	17.06	17.88	15.78	44.31	27.00	33.11	15.60
23	1	1	5	4	66.78	45.48	55.68	63.58	2	0	2	4.27	14	12	19.83	30.29	6.70	4.14	50.97	52.27	6.72	10.05
24	1	1	1	4	0	0	0	0	6	1	3	3.67	30	10	21.18	16.76	3.05	0.55	19.26	86.46	0.00	14.33
25	1	1	2	4	9.54	7.58	27.84	14.96	5	1	3	2.87	25	10	13.29	1.50	16.87	8.32	80.77	1.45	35.98	1.82
26	1	1	2	4	9.54	7.58	0	7.48	7	2	3	3.8	27	10	22.50	13.44	13.10	27.62	48.05	20.88	14.68	36.43
27	1	1	3	4	38.16	30.32	0	29.92	3	2	3	5.13	16	11	55.47	15.23	1.08	17.71	67.88	23.80	2.42	25.92
28	1	1	4	4	0	15.16	0	7.48	6	2	3	3.07	23	10	8.24	36.11	8.02	5.17	26.62	71.35	20.33	1.72
29	1	1	5	4	9.54	22.74	13.92	18.7	0	1	3	4.4	13	10	9.09	38.14	4.54	2.40	38.81	68.43	6.19	6.59
30	1	1	1	4	9.54	0	55.68	18.7	0	0	2	3.07	12	11	22.61	9.61	12.81	12.84	58.29	34.57	13.14	14.01
31	1	1	3	4	0	15.16	13.92	11.22	5	1	1	4.07	12	10	47.72	10.24	0.73	31.66	51.68	24.27	2.78	41.30
32	1	1	4	4	9.54	30.32	13.92	22.44	4	1	3	3.2	28	10	1.50	22.65	13.34	4.89	6.69	67.53	32.01	13.81

33	1	1	5	4	9.54	68.22	41.76	48.62	7	2	3	4.33	22	12	20.50	18.05	18.71	14.99	38.86	25.95	30.52	24.70
34	1	1	1	4	0	0	0	0	5	1	3	2.93	33	10	14.08	9.57	16.80	8.96	52.60	43.86	16.08	7.49
35	1	1	2	4	38.16	53.06	41.76	52.36	1	0	0	3.33	28	21	4.22	3.24	4.29	83.01	7.31	12.64	13.91	86.18
36	1	1	2	4	19.08	60.64	69.6	56.1	3	2	3	2.33	16	11	22.52	10.72	2.02	19.02	42.26	41.71	2.12	33.94
50	1	2	3	4	19.08	30.32	13.92	26.18	2	1	2	4.4	15	10	35.62	12.39	6.30	6.37	52.47	25.43	13.68	28.45
51	1	2	4	4	28.62	7.58	13.92	18.7	7	2	3	3	27	10	8.16	41.46	19.76	10.16	21.12	55.12	33.87	9.91
52	1	2	5	4	57.24	37.9	97.44	67.32	6	1	3	4.6	33	20	4.50	41.05	16.76	8.51	25.45	45.75	36.43	12.39
53	1	2	1	4	19.08	60.64	69.6	56.1	3	2	3	3	15	10	25.63	19.88	7.68	26.37	34.82	48.70	13.16	23.33
54	1	2	2	4	9.54	7.58	0	7.48	2	1	1	2.8	27	11	16.34	22.22	15.28	20.10	25.65	36.61	35.73	22.03
55	1	2	2	4	0	15.16	13.92	11.22	7	2	3	2.4	38	11	28.74	32.27	6.52	15.76	26.82	64.08	27.50	1.62
56	1	2	3	4	76.32	128.86	194.88	145.86	4	1	0	3.07	13	17	49.95	9.83	3.89	35.46	60.39	17.40	0.00	42.23
57	1	2	4	4	9.54	53.06	55.68	44.88	5	2	3	3.33	15	11	3.49	42.93	6.50	2.18	6.75	55.19	20.81	37.26
58	1	2	5	4	28.62	37.9	13.92	33.66	2	1	3	5.53	15	11	22.72	22.84	10.59	9.41	38.64	52.52	15.13	13.79
59	1	2	1	4	0	0	0	0	3	1	2	4	28	10	27.62	25.55	5.69	4.72	53.51	38.19	6.20	22.12
60	1	2	3	4	28.62	53.06	27.84	44.88	0	1	3	4.8	15	18	11.72	11.43	5.68	9.16	52.12	33.19	16.61	18.10
61	1	2	4	4	0	7.58	0	3.74	1	0	2	2.47	13	12	17.38	38.16	8.74	10.70	32.22	55.71	19.91	12.18
62	1	2	5	4	9.54	37.9	69.6	41.14	1	0	1	5.93	14	10	18.71	18.95	0.00	17.46	46.32	39.84	14.81	19.05
63	1	2	1	4	47.7	90.96	125.28	97.24	3	0	3	1.87	15	11	11.79	9.27	13.28	10.32	41.35	39.39	21.21	18.06
64	1	2	2	4	57.24	75.8	153.12	100.98	1	0	2	3.87	24	15	0.92	9.53	16.61	11.79	8.37	31.61	55.14	24.90
65	1	2	2	4	0	7.58	27.84	11.22	6	2	3	1.93	38	10	18.80	0.20	16.73	27.25	55.84	2.20	31.07	30.90
66	1	2	3	4	19.08	45.48	27.84	37.4	7	1	3	3.2	34	12	45.80	14.81	4.75	14.97	51.64	15.08	33.76	19.56
67	1	2	4	4	0	7.58	0	3.74	0	1	3	4.67	22	10	12.41	21.36	5.24	3.62	49.15	40.06	20.35	10.46
68	1	2	5	4	9.54	30.32	0	18.7	6	2	3	4.6	32	11	8.02	38.91	12.18	11.89	36.91	46.27	28.37	8.49
69	1	2	1	4	9.54	60.64	97.44	59.84	0	1	2	4.27	10	12	1.10	5.60	16.75	28.39	11.94	19.43	25.48	63.16
70	1	2	3	4	19.08	53.06	27.84	41.14	7	2	3	5.87	12	12	16.14	17.03	9.01	10.92	45.28	37.63	13.03	24.08
71	1	2	4	4	0	0	0	0	4	1	3	3.53	16	10	23.25	18.13	15.59	10.46	48.35	28.22	29.77	13.68
72	1	2	5	4	9.54	15.16	27.84	18.7	0	1	3	3.13	19	10	12.81	20.68	17.01	16.26	47.32	30.29	21.98	20.43
73	1	2	1	4	0	0	0	0	0	2	3	2.8	18	10	7.76	34.29	9.62	16.09	19.85	38.91	24.12	37.14
74	1	2	2	4	38.16	45.48	55.68	52.36	1	1	3	3.73	22	12	14.86	12.86	14.21	8.89	43.35	49.75	20.58	6.35
75	1	2	2	4	0	15.16	13.92	11.22	1	0	0	2.13	29	10	11.78	22.27	4.14	2.85	21.26	75.07	8.69	15.01
76	1	2	3	4	28.62	30.32	27.84	33.66	6	1	3	5	11	13	29.37	13.08	7.84	10.71	44.36	32.44	12.94	30.29
77	1	2	4	4	0	37.9	0	18.7	0	1	3	4	10	10	11.41	15.59	4.70	20.32	42.13	32.89	18.33	26.69
78	1	2	5	4	0	37.9	41.76	29.92	1	1	2	6.07	16	10	13.51	41.91	10.87	2.97	52.20	44.98	19.25	3.60
79	1	2	1	4	76.32	98.54	97.44	104.72	1	1	2	4.73	20	14	33.36	25.92	2.44	10.19	49.94	53.94	6.35	9.81
80	1	2	3	4	9.54	30.32	55.68	33.66	5	1	3	3.73	21	10	37.23	7.52	5.97	22.72	60.86	17.36	12.28	29.52
81	1	2	4	4	28.62	45.48	55.68	48.62	7	2	3	2.6	28	10	17.16	30.04	13.48	10.32	38.04	49.22	16.29	16.48
82	1	2	5	4	0	15.16	0	7.48	1	1	3	4.33	13	10	12.94	15.03	28.82	13.94	29.00	22.40	10.11	58.52
83	1	2	1	4	0	7.58	0	3.74	4	2	3	2.2	12	10	20.60	14.86	15.28	10.52	41.61	34.94	19.61	23.87
84	1	2	2	4	9.54	30.32	55.68	33.66	6	1	3	4.07	27	10	50.40	5.22	4.07	18.08	66.01	26.03	3.25	24.72
1	1	1	4	5	28.62	45.48	41.76	44.88	7	1	3	2.4	33	12	6.37	24.67	8.17	4.79	31.31	21.10	55.24	12.38
2	1	1	5	5	28.62	75.8	69.6	67.32	1	1	3	3	30	13	6.12	17.65	9.26	8.26	20.33	60.47	27.47	11.75
3	1	1	1	5	28.62	37.9	41.76	41.14	0	1	0	3.4	15	10	18.96	16.21	5.17	12.68	72.10	24.92	12.83	10.16
4	1	1	2	5	19.08	0	13.92	11.22	5	1	3	1.8	27	11	21.64	24.45	5.04	10.96	34.89	44.25	23.70	17.18
5	1	1	3	5	38.16	90.96	111.36	89.76	1	1	3	2.6	18	13	16.95	10.87	10.77	37.86	34.11	29.77	14.39	41.75
6	1	1	1	5	0	15.16	41.76	18.7	3	1	1	2.53	28	10	18.48	40.53	9.42	11.94	60.28	18.93	6.32	34.51
7	1	1	2	5	0	22.74	0	11.22	1	0	1	3.13	17	12	18.86	26.67	4.42	25.98	30.77	39.94	2.62	46.70
8	1	1	3	5	0	7.58	0	3.74	3	2	3	5.87	30	10	16.91	6.04	7.44	13.24	42.83	33.96	21.75	21.50
9	1	1	4	5	19.08	53.06	55.68	48.62	0	0	2	2.4	12	14	19.21	17.56	13.54	18.83	38.11	40.70	23.75	17.46
10	1	1	5	5	0	7.58	0	3.74	0	1	3	4.67	19	10	9.82	35.66	15.20	3.20	29.60	67.05	17.40	5.99
11	1	1	5	5	0	0	0	0	2	1	3	5.6	33	10	19.48	30.00	16.23	4.20	53.82	46.88	1.73	17.60
12	1	1	5	5	57.24	53.06	97.44	74.8	0	0	2	5.53	19	13	10.44	28.61	15.98	7.57	46.12	37.33	25.77	10.82
21	1	1	4	5	9.54	15.16	0	11.22	4	2	3	2.2	31	10	17.83	18.18	16.04	12.71	49.55	37.18	18.58	14.73
22	1	1	5	5	38.16	30.32	55.68	44.88	1	0	1	4.6	15	12	11.01	21.66	9.96	9.99	52.23	29.94	26.94	10.89
23	1	1	1	5	66.78	53.06	55.68	67.32	2	0	2	3.47	15	12	28.22	13.51	19.10	18.54	37.86	22.96	35.91	23.30
24	1	1	2	5	0	7.58	0	3.74	6	1	3	2.87	30	10	13.88	19.51	7.07	9.79	33.22	52.92	21.13	12.73
25	1	1	3	5	9.54	7.58	13.92	11.22	4	1	2	4.4	20	10	32.11	11.14	4.30	20.97	52.00	20.91	2.13	44.98

26	1	1	1	5	9.54	0	0	3.74	6	2	3	3.33	26	10	8.41	12.52	7.65	7.31	37.38	49.89	15.91	16.85
27	1	1	2	5	47.7	45.48	27.84	48.62	1	2	3	3.27	15	11	18.95	12.42	23.49	13.02	57.22	18.45	24.57	19.78
28	1	1	3	5	0	15.16	0	7.48	4	2	3	3.07	29	10	23.61	4.39	23.90	18.30	61.11	7.04	25.38	26.50
29	1	1	4	5	9.54	22.74	13.92	18.7	0	1	2	3.67	13	10	11.64	19.61	5.54	4.00	3.50	106.82	3.45	6.25
30	1	1	5	5	19.08	15.16	55.68	29.92	5	2	3	5	14	12	15.43	34.89	26.47	4.64	30.73	36.41	38.64	14.25
31	1	1	4	5	0	15.16	0	7.48	5	1	0	3.67	12	10	17.96	42.34	14.71	2.75	37.18	50.75	14.81	17.30
32	1	1	5	5	0	30.32	27.84	22.44	4	2	2	3.67	31	10	12.59	19.72	1.97	1.90	37.47	71.98	8.47	2.10
33	1	1	1	5	0	53.06	13.92	29.92	7	2	3	3.73	16	10	19.35	16.71	12.44	12.89	36.36	33.92	25.33	24.40
34	1	1	2	5	0	0	0	0	4	1	3	2.33	25	10	46.80	17.80	5.34	1.03	61.01	37.31	11.49	10.23
35	1	1	3	5	38.16	53.06	41.76	52.36	3	0	0	4.13	29	18	34.31	11.66	23.87	16.92	10.99	13.66	21.65	73.72
36	1	1	1	5	28.62	60.64	55.68	56.1	2	1	3	3.47	16	11	12.27	23.98	13.93	1.68	49.15	40.96	29.89	0.02
50	1	2	4	5	9.54	22.74	13.92	18.7	2	0	2	3.67	16	10	6.00	16.21	7.96	9.42	29.09	44.93	38.98	7.04
51	1	2	5	5	9.54	15.16	13.92	14.96	7	2	3	4.6	22	10	6.55	42.25	29.14	4.05	14.91	63.69	38.14	3.29
52	0	2	1	5	47.7	37.9	180.96	86.02	6	2	3	2.4	37	17	3.90	28.87	3.22	6.12	76.30	79.36	27.92	7.60
53	1	2	2	5	19.08	53.06	69.6	52.36	5	1	3	3	13	11	16.19	16.14	19.98	11.80	49.97	23.72	34.17	12.16
54	1	2	3	5	0	15.16	0	7.48	4	1	1	5.33	22	13	38.33	20.10	7.84	18.17	42.74	38.10	14.18	25.00
55	1	2	1	5	0	7.58	13.92	7.48	7	2	3	3.33	37	11	23.47	27.25	11.61	21.07	11.27	58.27	35.11	15.36
56	1	2	2	5	47.7	98.54	139.2	104.72	1	1	0	3.53	13	14	16.51	21.52	3.12	21.28	23.63	61.08	3.35	31.97
57	1	2	3	5	9.54	37.9	41.76	33.66	5	2	3	3.6	19	11	45.55	3.62	1.45	39.43	70.05	4.22	0.43	45.31
58	1	2	4	5	19.08	22.74	13.92	22.44	0	1	3	2.87	17	11	26.87	18.51	12.58	9.16	48.08	45.55	15.98	10.41
59	1	2	5	5	0	7.58	0	3.74	0	0	2	5.6	27	10	16.98	18.71	15.18	5.47	66.91	7.40	37.39	8.31
60	1	2	4	5	47.7	37.9	13.92	41.14	0	1	3	3.8	14	22	13.74	12.81	8.06	9.42	58.82	27.55	16.65	16.99
61	1	2	5	5	0	7.58	0	3.74	1	1	2	5.13	13	11	28.63	32.29	4.84	2.25	11.44	89.48	16.73	2.37
62	1	2	1	5	19.08	22.74	97.44	44.88	0	1	3	2.8	13	10	19.40	0.00	19.75	17.20	59.54	8.26	34.14	18.08
63	1	2	2	5	28.62	90.96	83.52	78.54	1	0	3	1.53	11	10	6.32	7.74	5.20	18.11	53.65	26.67	16.83	22.87
64	1	2	3	5	66.78	68.22	180.96	108.46	1	0	2	4.4	24	15	16.78	13.29	8.51	9.21	46.58	32.82	15.58	25.03
65	1	2	1	5	0	0	0	0	6	2	3	1.8	40	10	13.99	16.82	12.59	20.48	56.52	15.31	25.60	22.58
66	1	2	2	5	28.62	37.9	27.84	37.4	7	2	3	3.47	38	14	22.68	20.30	4.84	18.00	32.59	41.36	4.40	41.66
67	1	2	3	5	0	0	0	0	1	1	3	5.2	21	10	26.59	11.27	4.50	24.92	43.46	32.49	2.77	41.30
68	1	2	4	5	9.54	37.9	13.92	26.18	7	2	3	2.2	31	11	17.75	27.14	11.71	13.54	33.17	52.72	15.39	18.73
69	1	2	5	5	19.08	75.8	97.44	71.06	0	1	2	4	11	12	15.41	20.28	6.14	6.56	18.65	50.84	33.21	17.35
70	1	2	4	5	0	22.74	13.92	14.96	7	2	3	2.53	14	10	8.97	13.13	15.01	9.32	33.12	43.21	26.22	17.48
71	1	2	5	5	0	0	0	0	3	1	3	3.87	17	10	15.79	39.83	12.21	16.53	34.94	44.25	21.18	19.65
72	1	2	1	5	0	7.58	0	3.74	6	2	3	1.93	31	10	20.50	9.55	12.01	17.13	36.04	35.06	19.68	29.24
73	1	2	2	5	0	0	0	0	0	2	3	2.47	15	11	31.19	36.69	6.05	2.47	54.02	48.68	8.66	8.67
74	1	2	3	5	38.16	45.48	41.76	48.62	6	2	3	4.4	31	11	33.09	16.91	0.93	2.55	85.89	34.12	0.00	0.02
75	1	2	1	5	0	15.16	13.92	11.22	2	1	2	2.07	29	10	4.69	12.11	3.22	12.18	61.98	37.71	7.37	12.96
76	1	2	2	5	19.08	30.32	13.92	26.18	6	2	3	2.87	11	11	20.70	14.68	15.06	12.84	53.22	30.89	23.37	12.54
77	1	2	3	5	0	37.9	0	18.7	0	0	3	4.07	10	10	49.94	3.30	0.83	17.21	75.09	5.60	13.11	26.24
78	1	2	4	5	19.08	53.06	41.76	44.88	6	1	3	2.2	17	10	18.65	25.12	10.14	17.20	26.59	53.97	12.39	27.07
79	1	2	5	5	66.78	98.54	125.28	108.46	3	1	2	5.53	10	12	21.30	22.13	18.41	2.03	27.74	49.60	37.96	4.72
80	1	2	4	5	0	0	13.92	3.74	7	2	3	2.07	27	10	11.05	25.18	16.33	7.82	27.24	45.01	36.39	11.37
81	1	2	5	5	38.16	68.22	69.6	67.32	6	2	2	5.27	29	11	18.50	15.08	12.51	9.91	56.07	27.12	16.98	19.86
82	1	2	1	5	0	15.16	13.92	11.22	1	1	3	2.8	15	10	24.12	27.49	3.64	18.75	34.17	59.62	11.12	15.10
83	1	2	2	5	0	0	0	0	4	2	3	2.8	11	10	21.97	10.02	11.80	16.75	42.00	30.34	26.92	20.76
84	1	2	3	5	9.54	15.16	27.84	18.7	6	1	3	3.73	25	10	38.93	9.67	1.83	44.76	47.73	18.05	20.40	33.86

Table F.4: Gallery Experiment Data.

F.5 The Knot Experiment

Since there is a large amount of data (26 trials for 101 participants), the data is presented at:

http://www.cs.unc.edu/~zimmons/diss/knotdata.html

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