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Effects of Lighting Phenomena on Perceived Realism of Rendered Water-rich Virtual Environments

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EFFECTS OF LIGHTING PHENOMENA ON THE PERCEIVED REALISM OF RENDERED WATER-RICH VIRTUAL ENVIRONMENTS

A Thesis

Submitted to the Faculty

of

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by

Micah L. Bojrab

In Partial Fulfillment of the

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of

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To my beautiful wife, Sydney, for providing me everything I needed to excel in life, and to my parents for supporting me all the way through my path.

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ABSTRACT

Bojrab, Micah L. M.S., Purdue University, May, 2010. Effects Of Lighting Phenomena On Perceived Realism Rendered Water-Rich Virtual Environments. Major Professor: Bedřich Beneš.

This study investigates the effects of various common lighting phenomena on human perception found in water-rich virtual environments. The investigation uses a traditional Psychophysical Analysis (PPA) to examine viewer perception of these lighting phenomena as they relate to rendering cost and reveals common trends in perceptual value among the phenomena. The work includes the use of a web-based testing system, proposed for the first time in familiar literature. The system includes five scenes with eight common lighting variables. Every scene depicts a different water scenario, but each shows every lighting phenomenon. The animated videos are rated in order of realism while one lighting variable is changed. The results of this PPA are then compared against the individual cost of each lighting phenomenon and an overall value is derived.

The study shows there is a unique order of importance for lighting phenomena in water-rich virtual environments. The results of the PPA show trends in perceptual quality and that not all lighting phenomena are equal. The testing will also show the cost of each phenomenon is not equal. The study concludes with general guidelines while rendering water-rich scenes.

In future work this “order” can be used to reduce expensive rendering costs associated with these complex scenes with less expense to visual quality. A collective goal to this work and others is real-time interactive water with plausible or ultimately photorealistic results.

CHAPTER 1. INTRODUCTION

This chapter introduces the topic and its significance in the computer graphics community. It presents an unanswered question, for which, the research attempts to provide a theory. The chapter ends with assumptions made while conducting the study and guidelines of exactly what will be accounted and not accounted for within the research.

1.1. Background

Research was started by focusing on computer generated rendering because it continues to be debated topic of research. The body of knowledge is focused on two main conflicting areas which drive the research further. The first is a steady, ever increasing step toward realism in graphics. The second is the increased time needed to render such physically accurate scenes.

Personal interest in the topic started with the examining of various computer-generated rendering platforms for strengths and weaknesses. Research expanded to rendering water simulations created by Purdue University graduate student Nathan Andrysco within the widely academically accepted ray tracer, PovRay. Reducing rendering costs was the main goal of the research, but an underlying goal of maintaining quality existed. The balance between these very negatively associated variables is the area in which this study will attempt to provide a theory. The research will build upon past studies in the area, but diverge in the subject of rendering. The study will focus solely on the complex lighting nature of water.

Water further complicates the balance between reduction in rendering cost and maintained visual quality because of the many global lighting effects that give water its unique appearance. Water is a very important topic because it is a very recognizable substance in our everyday lives and thus is depicted frequently in virtual environments.

The research will adopt similar evaluation techniques to past studies. One featured assessment is of the limitations in the Human Visual System (HVS), which for purposes in this research will include the perceptual quality of synthetic. Many avenues exist for cost reduction based on the HVS, as discussed in Chapter 2. The researchers of this study are examining a viewer's subjective quality, so they may receive generalizable data. This study will extend the perceptual quatlity research to include individual cost of the lighting phenomena so the results may be more complete. Please note, rendering cost will be added to the equation after finding the perceived quality of each element. This is an attempt to receive pure perception data not altered by cost consequently simplifies the testing to a traditional Psychophysical Analysis.

Results of this research can be used to better approximate trends in human perceptual quality and make assumptions based on these findings. Improvements can then be made in the areas of previsualizations (previz), real-time interactive rendering and final (gold) renderings. The researchers are not claiming the study is perfectly accurate, only that it is the best assumption and guidance that can be determined from the testing that was conducted.

1.2. Significance

In recent years, particular focus has been placed on the ability to render scenes with real-time Global Illumination (GI). Current hardware and algorithms are still unable to complete this task outright, so researchers must apply alternative methods to reach GI at interactive rates. One such method has been to focus on the weaknesses of the HVS (Cater, Chalmers & Dalton, 2002; Cater, Chalmers & Ledda, 2003; Chalmers, Debattista & dos Santos, 2006; Dmitriev, 2002; El-Nasr & Yan, 2006). Some cases only focus on the perception of individual lighting effects and the subjective quality of each phenomenon

(Debattista, 2005; Myszkowski, Tawara, Akamine & Seidel, 2001; Stokes, 2004). The research presented will continue in the latter perception-based area and will attempt to find a clear pattern in humans' perceptual value in the rendering of specific lighting effects for various water-rich scenes. One difference between this study and Stokes (2004) is that the testing includes the rendering time or cost of each phenomena and is not based on subjective worth alone. The purpose of previous studies was to reduce render time. It, then creates a stronger study to include render cost and not base assumptions solely on quality. This can then be used to identify differences in the results. The conclusions of this research can be applied to many areas of interest.

The graphical significance of this research can be seen in many different, though ultimately related, fields of computer graphics. The possible areas affected by the results of this research could be previsualizations (previz), photorealistic rendering and real-time interactive rendering. In the context of previz, the theories supported in this paper will be able to be directly applied to maximize quality while still rendering under a predefined time constraint. This works well within the context of previz, because its intent is to have the most information about the final render without the associated cost of rendering all lighting phenomena. It is not economically feasible to render all lighting elements when viewing the result of an animation or simulation, because gold renders can be very costly. Researchers and industry professionals alike can then use these guidelines to determine an optimal combination of lighting effects given the scene and a set of system constraints. This will in turn give scientist and technical animators better insights about the final result, so they may formulate better decisions and ultimately save time and money.

Full rendering is set apart from the other two areas because it is meant to have multiple viewings by the same audience. In these cases, full rendering cannot use approximations or perceptual tricks with its imagery because there is a better chance the audience will notice the discrepancies upon repeated viewings. Gold rendering as it is sometimes called, uses all cases of local and global illumination to receive the best possible visual quality for the style. Only in cases of extreme cost reduction may industry professionals cut high computationally expensive, low importance lighting aspects and maintain a very high level of detail. The research in this study will be dedicated to finding if these special cases exist in the data. An additional area of improvement is shared with interactive rendering and will be covered in the next section.

For interactive real-time environments the goal is an immersive virtual experience with the water. This includes viewing from different angles, physical interaction, or reaction to changes in the surrounding environment. Unlike the other two possible uses for this research, real-time graphics is much more difficult and comes in two parts. The realistic animation of water at interactive rates is the first and will not be covered in this study. This is a whole separate area of extensive research and has very complex problems still yet to be solved with any commonality. Rendering, or rather the reduction of rendering costs while maintaining visual quality, is the second and the focus of this study. Scientists and game programmers will be able to utilize this information more extensively. The added computation of real-time plausible simulation of water combined with visual quality, make this area particularly difficult. Before each frame can be displayed, both the fluid simulation and its rendering must be completed. These are two very complex calculations individually and together they exceed the abilities of current hardware. Real-time programmers are the subset of the computer graphics population which has a goal similar to the one in this study. They want to extract the best algorithms and best graphical quality out of the market's current hardware. This study may show them which visually pleasing lighting elements need more attention because current configuration deem them unfeasible. It may also give insight into which lighting effects hold little importance, or which may be easy substitutes for much more computationally intensive phenomena. The research in this study is best suited for real-time interactive graphics.

1.3. Statement of Purpose

The purpose of this research is to find the order in which the common lighting phenomena have value when associated with water-rich virtual scenes. It is these trends that may be used to reduce render times for previsualizations, real-time interactive rendering and final renders while maintaining an acceptable level of quality. The product of this research is based on the rendering cost and human perception from a combination of various scenes. The results can be generalizable, but are only conformably accurate to the set of data present in this study.

1.4. Research Question

What is the order of importance for lighting phenomena in the human interpretation of subjective visual imagery for virtual fluids?

1.5. Assumptions

The assumptions for this study are as follows:

- Metric
  1. Cohen (1993), Dutre (2003) and Jensen (2001) have stated precisely all of the lighting components needed for accurately rendering materials such as virtual water.
  2. All the lighting elements are able to be accurately rendered.
  3. All hardware and software components used to create rendering data are working properly and consistently over the total production of testing materials.
  4. All render times are relative to the other elements present in the render.
  5. PPA measures the perceptual quality of the lighting phenomena tested.

6. The results of the PPA can be use to accurately find an order of importance of the lighting phenomena tested.
7. Rendering cost of individual elements can be compared to their respective visual quality to find its relative importance to the final image.
8. College of Technology, Engineering and the School of Performing Arts students and faculty will have specialized knowledge that allows them to realize small differences in scene lighting.
9. The types of water tested in the study are ones that are typically seen in animation movies and visual effects.
10. The range of lighting types tested in the study covers the general lighting conditions seen in animation movies and visual effects.
11. Some elements are unable to be rendered into the same scene without multiple types of water present.
12. Elements unable to be rendered in the same scene are not generalizable and will not be covered by the study.

- Research
    1. SMPTE standards can be used to limit extraneous variables due to the environment during the research conducted in this study.
    2. The testing has followed the guidelines of the SMPTE standards accurately.
    3. A controlled environment will improve the accuracy and precision of the data collected.
    4. The computer system is understandable and usable to participants and answers given by the participants are their intended answers.
    5. The participants will answer truthfully.
    6. The participants do not have visual defects with or without corrective lenses.
    7. The students and faculty in the College of Technology, Engineering, and School of Performing Arts are knowledgeable

about how to use and manipulate a web application with mouse input.

8. The results from the specialized group selected for testing will be able to be applied to the general public because the general public will experience less sensitivity to lighting phenomena.
9. Limitations in the Human Visual System are made comparatively to traditional photography. The limitations do not compromise the imagery the participants are viewing or how the participants view them. The limitations only provide avenues, so researchers can capitalize on the insensitive features in the HVS.

1.6. Limitations

The limitations to this study are as follows:

1. The study will only include research on the area of rendering water, and results cannot be applied to all areas in the field of computer graphics.
2. The study will only be focused on perceptual quality and will not focus on any other areas of limitation offered by the Human Visual System.
3. The research conducted will only cover rendering of water, and not the rendering of any other materials similar to water, thus the results will only be applied to water-rich virtual environments.
4. The study will not have involvement in the simulation of water, and results will not be modifiable to suit the animation of water.
5. The study will only cover the important lighting elements for water, and these include:
   a. For materials: diffuse grey, diffuse color, transparency and refraction.
   b. For lighting: caustics, specular reflection, hard shadow and soft shadow.
6. Results must interpret human intellect and may be subject to bias and errors in understanding.

7. All common lighting effects are present in every scene to guarantee generalizable data.
8. Some lighting effects will not be tested in the study directly and they include attenuation, participating media and color bleeding.
9. Qualitative data will be collected in text fields, but this data will not be used to determine quality to the final image. It will only be used to further clarify the data.
10. The research participants will be limited to all College of Technology, Engineering, and School of Performing Arts students and professors willing to volunteer their time without compensation.
11. This study will not be fully generalizable across all water-rich scenes, but will only be a guideline to help reduce rendering cost while maintaining visual quality.

1.7. Delimitations

The delimitations of this study are as follows:

1. Though the testing scenes include animated water, this study will not evaluate the animation of water in any way.
2. This study will only cover broad water types and will not cover specialized cases of water phenomena.
3. The study will not include any other fluid types other than water.
4. No other lighting variables will be tested, other than the ones stated above.
5. The general public will not be included in testing, though the results may be generalizable to satisfy this population.
6. The testing materials will be random, but the same testing materials given to every participant in different orders.
7. Different computer may be used to test participants, but all computers have the same hardware, monitor size and settings, software, and lighting conditions.

8. The environment used in testing will be controlled by the SMPTE standards and no other environments will be used to collect data.
9. Except the SMPTE standards, no other testing parameters will control the environment.

1.8. Terminology

Attenuation – Scattering or absorbing of light due to interaction with participating media or natural dispersion over long distances (Cohen, 1993).

Caustics – "..refer to the illumination of diffuse surfaces by light reflected from a specular surface." (Cohen, 1993) We extend this definition to include light transport and bending through refractive materials and being absorbed by diffuse objects.

Color Bleeding – "diffuse interreflection" referring to the light being reflected off one diffuse surface and being absorbed by another diffuse surface. (Cohen, 1993)

Gold Render – An image rendering containing all of the components needed for a complete render. Gold renders are the final renders, fully composited and ready for the viewing audience.

Hard Shadows – Shadows simulated from distant light sources without dispersion or from a light emanating from an infinitely small source. This creates crisp shadow edges without any bleeding at the shadow boundary.

Occlusion – "due to surfaces positioned between the two differential areas, which block the direct transfer of light" (Cohen, 1993).

Participating Media – Any medium affecting "light transport through absorption, scattering and emission." (Cohen, 1993)

Penumbra – Area created by soft shadow and is characterized by the smooth falloff between full shadow and lit areas.

Previsualization – Visualizations used by artists as tests for viewing animations and timing. They do not generally contain a few, if any of the lighting aspects. These visualizations are generally fast and cheap, and many are produced.

Photorealistic Rendering – “to generate an image that is indistinguishable from a photograph of a real scene.” (Dutre, Bekeart & Bala, 2003)

Realism – Tendency to view or represent things as they really are.

Reflection – Bouncing of light rays off of an object’s surface. Perfect specular reflection is characterized by bouncing of a light ray in only one direction.

Refraction – Bending of light through translucent objects. Perfect specular refraction is characterized by bending of a light ray in only one direction.

Soft Shadows – Shadows simulated from broad lights sources in close proximity to the occluding object. This creates falloff between full shadow and fully lit areas.

Specular – bouncing of light off or bending of light through an object creating lighting bouncing straight into the eye or camera or being absorbed by a diffuse surface. (Dutre, Bekaert & Bala, 2003)

Umbra – Area of shadow that is completely occluded and thus is the darkest section of the shadow. No light is directly falling on this area from a given light source.

1.9. Acronyms

GI – Global Illumination

HVS – Human Visual System (Cater, Chalmers, & Ledda, 2002)

PPA – Psychophysical Analysis

SMPTE – The Society of Motion Picture and Television Engineers

SPH – Smooth Particle Hydrodynamics

1.10. Organization

This thesis has five major chapters. Chapter 2 contains a review of the literature. This section has an advanced study of the work done on the Human Visual System and how it has been applied to reducing render time. The chapter continues with a psychological look into perception and how it relates to HVS, and how testing can be conducted on it. Last, the chapter reviews the Psychophysical Analysis (PPA) and similar studies using this method to collect data.

Chapter 3 contains the methodology used to collect data for this study. It explains in detail the testing methods used and reasons these particular methods were used. It has all of the rendering subjects, an overview of the web-based testing site, the testing parameters and testing environment. The third chapter gives a better explanation of PPA, how this study applies it to conduct research and has the study's hypothesis. The fourth chapter contains the results of data collected during testing and provides graphics and tables to easily identify trends in the data. Chapter 5 reports the suggested order of importance, the lighting guidelines of water-rich scenes, and other conclusions made from the data.

1.11. Summary

This chapter provided an overview of the research conducted in this study. It gave the background of the study, the study's significance and provided strict guidelines that will be followed during this research. The research question and its limitations and delimitations combined to determine these guidelines and set exact boundaries for the study to be conducted within. The chapter ended by exploring general terminology and acronyms used. The following chapter will have a review of past literature on the subject of HVS and its use for rendering, a review of Perception, and a look at PPA as it will be used in testing.

CHAPTER 2. PREVIOUS WORK

2.1. Introduction

The Human Visual System (HVS) is not perfect and research has been dedicated to exploring and exploiting the limitations that occur in human perception. Many different avenues have been explored including inattentional blindness, saliency, change blindness, and perceptual quality. Once the extents of these effects are realized, the researchers conduct different methods of reducing rendering time based on the area being explored.

Three main areas are covered in this chapter and these areas will help define both previous work on reduction of rendering time and better explain the methodology of the study by offering previous work in the area. The Human Visual System will contain many areas of work with determining limitations in the HVS and methods to capitalize on them. A brief review of Perception will better explain the method this paper utilizes in the HVS, and Psychophysical Analysis (PPA) will review the testing method determined for this study.

2.2. Human Visual System

2.2.1. Inattentional Blindness

Inattentional blindness is the inability to see outside of the viewing spectrum and gaze is controlled by the researchers through making the passive viewing experience an active one. This directs gaze specifically towards areas of the render, while others can be rendered at lower quality. The viewing of these images is thus influenced by visual cues created by top-down and bottom-up processing elements.

2.2.1.1. Selective Quality Rendering by Exploiting Human Inattentional Blindness

The 2002 study by Cater et al. addressed the principle of inattentional blindness directly by conducting a series of testing investigating the effects of top-down visual processing when the viewing is task-oriented. They started by reviewing how the Human Visual System digests large sets of data and the anatomy of the viewing angle, so they could later use the data for testing. They suggested the human eye “saccades” important information and it is the process of determining this important information that was used in the top-down processing tested in the study. They finally conclude their preliminary background with two types of selective rendering taking advantage of the flaws in the HVS. Saliency models, which pre-determine important objects in the scene, so any surplus of rendering power will be spent on further development of these areas, and the peripheral vision or visual areas outside of the small visual field. This type of rendering process is use to only render areas in which the human gaze is directly looking, which is done either by predicting gaze or calculating it in real-time. Anticipated peripheral vision was used in the research for this paper to shorten the amount of time to render without diminishing the perceived quality of the render (Cater, 2002).

Researchers selected different quality renders, and pre-rendered them. High quality (HQ), low quality (LQ), and circle quality (CQ), meaning the area of importance (i.e., the mug) was rendered at a high quality standard and the area around it until 4.1 degrees outside of the fovea vision angle, which was then rendered at the lower quality settings. Some were given an objective to do while watching the two differing quality renders; others were just informed to watch. No discernable difference was noted by participants when they watch two differing quality renders consecutively when they had a task. In addition, a considerable amount of people were unable to tell the difference when they viewed the HQ +LQ renders, and nearly all of the participants were unable to identify features within the vision angle when they were not focused on them, let along outside of the fovea angle. These results create substantial arguments for the use of top-down stimuli to selectively render animations in real-time or with high-fidelity. The study itself tested the principle of top-down peripheral selective rendering, not its practice. The study needs to be expanded to include not only actually rendering of this in real-time or high-fidelity, but to account for bottom-up processing and other testable parameters such as sound and types of tasks. This study contributed to the concreteness of one facet in the spectrum of selective rendering, but definitively tested and substantiated the use of peripheral rendering in this context (Cater, 2002).

2.2.1.2. Visual Attention in 3D Video Games

Real-time rendering is a major contributor of selective rendering for a scene's area of interest. The study by El-Nesr and Yan in 2006 researched the eye movement patterns of two different types of video game genres and made assumptions about these types by the types of patterns participants drew with their eyes. They used two established genres, first person shooter and action-adventure. They had six participants wear an eye tracking device while playing each for 10 minutes to determine the gaze of the player. The data was then processed until the researchers could view either the eye tracking over time, or eye tracking position compared to player and important object positions. They analyzed these data sets in an attempt to answer three questions. The first, does bottom-up processing, mainly motion and color, draw attention effectively within the game? Does goal oriented game play make top-down processing more important than bottom-up? And does eye movement differ between differing game genres (ElNasr, 2006)?

Upon analysis of raw data gathered from testing they were able to make assumptions depending on their original questions. Based on the first question, they definitively could state that subconsciously participants were drawn to the bottom-up stimuli of color and motion. They supported this claimed with a data example and graphs. They noted that top-down visual stimuli were very important in goal-oriented gaming, and went further to say developers should use patterns from the top-down approach to effectively guide players in quests. Last, they found a distinct difference between the eye movement patterns between the two different genre types. First person shooters tended to hold eye gaze in the center of the screen only moving outside to check player statistics, but action-adventure player's gaze travel over the screen in a searching pattern (ElNasr, 2006).

The researchers were admittedly under-scaled on scope to make any definitive agreements for or against any claim. They stated they needed more participants, game titles and needed to account for camera movements. Even so, this shows one such study about user perception and how it can be used effectively to improve performance or change interaction with computer graphics (ElNasr, 2006).

2.2.2. Saliency

Saliency, unlike inattentional blindness, has no outside manipulation to guide user attention toward predefined areas. Saliency uses the natural motion of the eyes through a scene and records their movements. Saliency maps are created by understanding the natural movement patterns of the human eye and makes rendering adjustments accordingly. Saliency renderings have multiple areas of importance and the viewing remains passive.

The article by Chalmers et al. in 2006 presented a novel approach to selective rendering call component-based render. Researchers made a claim of the Human Visual System "HVS is good, it is not great" (Chalmers, 2006, p. 1). They took the approach that after the first round of one ray per pixel sampling and the image is displayable, further samples should be conducted by an order of importance based on salient objects in the scene. These salient objects based on human perception are derived from bottom-up and top down processing. The idea behind these further sampling steps is the first pass samples the scene, and records both the renderable pixels and a quality map known as a “q-buffer”, which is stored and analyzed. This “q-buffer” is a gradient map of on-screen distracters (OSD) and can be thought of as a data map masking off the areas that need further sampling. The quality map, similar to an elevation map, holds the amount of samples needed for each renderable pixel, and the computer samples each level of “elevation” consecutively until either the render is complete, or the allotted time is reached. A concurrent system of destructible ray tracing was developed for the quality map. Normal ray tracing systems must finish each ray cast before the image can be complete and displayed. The researcher’s system traced rays in a normal fashion, but rays were able to be forgotten if they were in the process of being sampled and the allotted render time was reached. When the render time was attained, all of the levels of detail that were then complete were displayed (Chalmers, 2006).

A test was conducted to compare render times of full renders against the component-based render. The results of this test were considerable, though the metric of the testing was not supplied. The second test was a psychophysical test comparing a traditional rays-per-pixel approach to the component-based render. This test was a preliminary perception-based study on preference but showed the component-based render only was favored in “lower time constraints since the scheduling and profiling is at a finer grain than that of the traditional” selective render (Chalmers, 2006). The researchers tested their method for parallel processing and scalability. Testing in this section was completed with incrementally more processors, up to 16 2.4GHz processors with 3GB of RAM. The system proved to be completely scalable and showed the biggest gain by achieving almost 41 times faster render speeds with 16 processors on the Cornell Box. The results of this research were substantial but were not replicable because the testing parameters were not reported.

2.2.3. Change Blindness

The HVS system has difficulty in perceiving change within an image. These studies do not directly affect the ability to render global illumination faster, though they do clearly define and manipulate the abilities of change blindness.

The study by Cater et al. in 2003 was a selective rendering test of the human vision defect change blindness. This effect, caused by the shocking of the natural automatic detection system by blinking or some other visual disruption, will allow changes in the scene or environment to go unnoticed by the perceiver. In this regard the researchers are testing its effects as they translate to computer graphics. The testing of change blindness is conducted through a study on perception and individuals' ability to identify change. Twenty-four images were assembled and shown to participants. The images were first evaluated for the "central" and "marginal" objects present in the scene (Cater, 2003).

Once the scene had a natural cognitive hierarchy assigned to it, the full rendered images were shown to the participants and a short while later a vision discontinuity was introduced. With the introduction of either a flicker or a mud splash, the scene was altered slightly or an object was removed. When the vision discontinuity was removed the altered scene was shown as if it were the original. This testing resulted in definitive proof that real-world proven change blindness is also viable as a selective rendering tool in computer graphics. In all cases the marginal objects went unnoticed longer than the central objects. This fact along with inattentional blindness shows that important objects are harder to alter and a need for proper distractions must be used. In this regard, bottom-up processing could be utilized to direct attention away from altered or less renderable areas, thus creating a greater chance the alteration will go unnoticed by the viewer (Cater, 2003).

2.2.4. Perception Quality

Perception quality is the most common form of perception-based rendering, because it deals with the frequent researched field of component-based rendering, which renders the most important lighting effects first and then, if available, computes additional lighting. This form caters directly to this paper and is the style in which this paper is researched. This form, for the purposes of this paper, also deals directly with the inability of the HVS to notice quality of an image after a certain degree. The concept similar to the image format jpeg, in that the human eye can only see a defined amount of quality, after which the benefits are minimal. Researchers in this category cater rendering the image or components of the image to a certain quality where humans are unable to see discrepancies.

2.2.4.1. Perceptual Illumination Components: A New Approach to Efficient, High Quality Global Illumination Rendering

The study by Stokes et al. is very similar to the study being conducted in this paper, and thus will serve as a reference for our research. Psychophysical experiments were performed among ten volunteers to find the perceptual important and visual quality of the direct and indirect lighting components present in common scene rendering. These elements were broken fundamentally into separate components and the participants were asked to rank them depending on their perceived visual quality. The experiment found the direct lighting only scenes were the lowest importance, where the highest belonged to indirect diffuse. Indirect specular and glossy were roughly equal, though less than the indirect diffuse and finally there were enough variation in different views of the same scene to suggest components should be determined depending on the viewport, and not by the scene alone (Stokes, 2004).

They next created a metric able to predict the necessary component for rendering any view with 70% accuracy. This accuracy was determined by comparing the original testing against the formulated metric. One exclusive benefit from metric is the ability to qualify the results, where the psychophysical testing could not. This informed the researchers not only the order of importance, but the perceived quality benefit from including and excluding variables in rendering. The study is fundamentally similar to the study we are conducting, except for the exclusion of rendering time in the psychophysical experimentation. In the context of rendering local and global illumination with respect to decreasing the render time, the render time should undoubtedly be factored into the testing metric. In this way, the study fell short in predicting the best parameters to render for any scene. Furthermore, the psychophysical study was limited in scope and did not include animation, or a wide range of scenes for testing (Stokes, 2004).

2.2.4.2. Selective Component-based Rendering

Selective component-based rendering gives the ability to effect each aspect of rendering, from top-down and bottom-up processing to progressive global illumination. The system by Debattista et al. gives full control to the user at the component level, and can be set to render in many different fashions with many different rendering conditions. At the heart of the system is “crex” or component regular expression. It gives the ability to select components to render and in what order. The component type (i.e., diffuse, reflection, and dielectrics) can be set and in what order, the number of radiant bounces into the scene, and even the areas or objects themselves via saliency maps. The process may be set to render a target time, and utilized a smart destructible ray tracer that samples and continues to sample as long as the target time has not been reached. This monitor will project out the time it will take to finish the current round of sampling and discontinue the process if the projected time exceeds the allotment. This projection is done in microseconds (Debattista, 2006).

Testing of this system was done similar to Cater (2002) by showing the participants the same section of animation twice, once at different levels of detail, and asks them details about the scene. Results from this study shows that when participants watched the scene actively, there was no significance between participant being showed the high quality twice and participants being showed the high quality then the component-based render. This means subjects were unable to tell the difference between the two render qualities. Further testing of the rendering at the component level revealed some significant errors in the components and the original. Also, if the primary rays have not finished casting, the progressive render would not be able to be stopped (Debattista, 2006).

2.2.4.3. Interactive Global Illumination Using Selective Photon Tracing

Interactive global illumination using selective photon tracing introduced a novel solution to photon mapping by allowing the scene to achieve a much higher photon density than concurrent systems, and thus was able to effectively show global lighting. The researchers utilized the lack of a need to resample an area if no changes to that area have been introduced. The constant monitoring of the relevant and expired scene photons is done via the Halton sequence, which stores and examines photons for changes in the environment. When a change was detected the quasi-Monte Carlo ray tracer resamples the area, limiting itself to a predefined amount of photons per frame. This incrementally builds the Global Illumination back up to the acceptable level while maintaining the near interactive rates. Density Estimation Photon Tracing (DEPT) was used as the framework for calculating the global lighting from the photons, though an extension was made to process the dynamic environments.

The system was tested on two scenes of varying mesh and lighting complexity. An average frame rate was found to be eight and 1.1 for the simpler and more complex scenes respectively. The results are significant but the frame rates are not smoothly interactive (Dmitriev, 2002).

2.2.4.4. Perception-guided Global Illumination Solution for Animation Rendering

The study by Myszkowski et al. researched on Yee's assumptions that others perception-based global illumination techniques break down if seen by multiple people or more than once by the same person (Yee, 2000). They went further by understanding direct light greatly effects the perceptual change in a scene. Conversely, the indirect lighting, although closely tied to quality, does not have to be as accurate as direct lighting. They achieve a system of "key framing" the indirect lighting of the scene, and interpolating the between frames. They save precious rendering time by working just under the level of perception, which is an error in the HVS. The distance between key frames is set at the beginning and reevaluated many times during the animation rendering. If the pixel change is greater than the perception, the key frame distance is shortened and then reevaluated. The key frame system is limited by the user's ability to approximate an amble key frame distance. If unable, the system is essentially under-sampling or oversampling while it is calibrating (Myszkowski, 2001).

Though the study was based on human perception, no tests were conducted on the outcomes of the system to prove their claims. This system was not tested at least in this paper, and accuracy remains in question (Myszkowski, 2001).

2.3. Study on Perception

The field of perception, or how humans not only experiences the world but understands it, is a saturated topic. It is one of the oldest topics in Psychology and countless journals, technical papers and books have been published describing it fully. For the purposes of this study, it will only be covered in short along with a study on Visual Perception.

Perception is the interaction of the five senses with the physical world and the interpretation of those signals by the brain to be able to identify the results. The brain is the most complex organ in the human body and it is this interpretation by the brain that is the most important part of the process. Barry Maund (2003) described perception as:

> The most natural view to take of perception is that it is a process by which we acquire knowledge of an objective world. We take this world to consist of physical objects and happenings, which exist independently of us and our acts of perceiving, and which are the things we commonly perceive. (p. 1)

He is describing this process by using the word “commonly,” because the brain tries to understand stimuli by matching them with past stimuli it has experienced. The brain is unable to experience and interpret the full range of stimuli by every sense. Even the brain is incapable of decoding and understanding the full range of information from all five sources. It is entirely too much data to sort and interpret for one entity. The brain in turn only takes a subset or range from each sense and each of the sensory organs is tuned to its respective range (Maund, 1995). Some scientists believe this severely disconnects humans from the reality of the outside world. They believe it buffers the human experience and that the outside world is entirely different from the “mental constructions” the brain assembles (Maund, 2003).

Others feel this suitable for faster processing of the important information and it allows the brain to facilitate rapid development of the critical outside world. With the adequate stream of information, the brain is then able to departmentalize this data and perform memory lookups with ease and higher accuracy (Maund, 2003). The brain is specialized for this departmentalizing and categorizing process, so it can comfortably retrieve data. If the brain were a computer it would have the greatest Google® search algorithm ever. Walter Freeman (1991) described this recovery process as:

> Much is known about the way the cerebral cortex, the outer rind of the brain, initially analyzes sensory messages. Yet investigations are only now beginning to suggest how the brain moves beyond the mere extraction of features-how it combines sensory messages with past experience and with expectation to identify both the stimulus and its particular meaning to the individual. (p. 78)

The current study only accounts for optical stimuli generated by digital imagery. Visual Perception is a subset of the larger Perception that only deals in the ocular realm of stimuli. Visual Perception is debatably the most important area dealing with the five senses because humans gain a majority of their information about the outside world by sight (Zoltan, 2007). The Human Visual System (HVS) is limited to accessing data in the electromagnetic spectrum between 400-790 terahertz (Maund, 2003). The entire electromagnetic spectrum is much larger and this is one such limitation of the HVS. This reduced range is one of many limitations by the ocular system in an attempt to reduce the amount of information needed to be processed by the brain. Other important properties of the HVS are covered in Section 2.2. Each of these examples offer reductions in rendering cost made possible because the various limitations in the HVS. All of these studies also attempt to sustain a high level of visual quality in the imagery by reducing cost in areas not in mainstream focus of the ocular system. The current study extends this previous research by analyzing trends in subjective data and compares pure psychophysical analysis to the cost of production of each stimulus.

2.4. Psychophysics

2.4.1. Psychophysical Analysis

The testing method is described in this study as a traditional psychophysical analysis, which it only partially accurate, but used for the ease of identifying it. This section will fully define the method used in this study as it is defined in previous literature and psychology journals.

Psychophysical Analysis is the process by which humans correlate stimuli with their percepts. Percepts are how humans perceive a particular stimulus or set of stimuli and the sensations of emotions those stimuli generate. A great deal of focus in the field of psychophysics is the sensitivity of a subject to a stimulus, or the threshold at which a sensory organ can report a change (Gescheider, 1997). Many theories and methods have been created to measure the sensitivity threshold, and two main theories are prevalent. Absolute and Differential Sensitivity differ in the way measurements are controlled and collected. Absolute Sensitivity measures the “transition between sensation and no sensation” and Differential Sensitivity is “measured by determining the smallest changes in energy required” report changes (Gescheider, 1997). The theory relative to the current study is closer to an Absolute style, in that the lighting phenomena included or absent in the scene will have an overall effect on subjective experience. This effect will be recorded but traditional psychophysical analysis only accounts for singular variables. Multiple stimuli are not compared directly, but only quantitatively with the degree of sensation due to the stimulus.

2.4.2. The Law of Comparative Judgment (Thurstone, 1927)

In 1927, Louis L. Thurstone published a cornerstone review featuring a new way to interpret perceptive data by obtaining measurements from the comparison of two or more physical stimuli. Until then, scientists were attempting to quantify amounts or degrees by which a subject would experience a stimulus on a continuum. These measurements were generally unreliable due to participants being unable to accurately quantify their experiences and that subjects experience and interpret stimuli uniquely and to different degrees. Even the repeated exposure of the same stimuli to the single subject created variations in “Discriminal Process” (Thurstone, 1927). Each human is distinct and are equipped with his or her own personal experiences that shaped his or her “Discriminal Process.” This process is the reasoning behind how a human comes to intuitive conclusions based on a particular set of stimuli (Thurstone, 1927). Thurstone proposed humans were much more capable of quantifying comparisons and the process by which a subject came to a conclusion about two or more stimuli is not important as long as the subject came to different “comparative judgments from one occasion to the next” (Thurston, 1927). This means that a long as a subject experiences two separate stimuli differently, those stimuli may be compared and the degree to which those separate stimuli were experienced can be quantified. Louis L. Thurstone (1927) identified his fundamental law as:

> The law of comparative judgment is applicable not only to the comparison of physical stimulus intensities but also to qualitative comparative judgments such as those of excellence of specimens in an educational scale and it has been applied in the measurement of such psychological values as a series of opinions on disputed public issues (p. 273).

This is an important difference between the Law of Comparative Judgment and pre-existing laws, in that the testing no long needs to be limited to physical stimuli, only to stimuli that elicit psychological responses. This completely expands the range of possibilities to ideas, feelings, thoughts and opinions. The research in this study, though does start with a physical stimuli, the optical response to imagery, but it is the emotional response to that stimuli that is more interesting. The study attempts to find how important a particular lighting element is to the realism of virtual water. It uses the Law of Comparative Judgment in a traditional psychophysical experiment to make comparisons between lighting stimuli and elicit emotional responses to find their subjective visual quality.

2.5. Summary

This chapter contained a review of previous work in the field of HVS and its application to rendering. Many articles used the limitations of the HVS to reduce rendering cost in a number of ways. Inattentional blindness and saliency said rendering quality could be focused in areas of interest instead of all areas, change blindness stated the humans usually will notice changes at the end of discontinuities, and perceptual quality lets researchers spend available render cost only towards the lighting effects of the best visual quality.

The chapter also gave insight into Perception, sharing common reasoning for these limitations in the HVS and their purpose. It made connections between the optical system and the brain, and showed the brain as a decryption and interpretation expert.

The chapter ended with a review of psychophysical analysis and one particular theory developed by L.L Thurstone in 1927 called the Law of Comparative Judgment. This theory made comparisons between two or more stimuli instead of making absolute judgments about individual stimuli. This allowed subjects to indentify differences between the emotion effect of stimuli instead of quantifying physical properties on a continuum. The next chapter will contain the methodology used during testing, and a review of the parameters for the study and how they were measured and controlled.

CHAPTER 3. METHODOLOGY

3.1. Introduction

In this chapter, perceptual quality will be explained in greater detail with its uses in the context of rendering. Perceptual quality is the psychophysical approach the study takes to reduce rendering cost, so the chapter will begin with an overview. The research improves pre-existing Psychophysical Analysis (PPA) method in many critical ways including advancements in the testing system, more advanced techniques for controlling the testing environment and by identifying the testing variables properly. In addition, the study expands previous literature to include rendering time as a comparison, because it is a critical component in identifying not only the overall importance but its relative value. This section will explain the methodology in detail, so future researchers may be able to recreate or extend the study.

3.2. Perceptual Quality

Perceptual quality is a measurement of subjective value. Perceptual quality can be expanded to say that it is a measurement of the emotional or psychological response to any stimulus or group of stimuli (Wang, Bovik, Sheikh & Simoncelli, 2004). This study will focus on the effective response to a series of visual stimuli, in particular a grouping of animations depicting virtual water in various environments. The researchers will compare the emotional response of imagery while individual stimuli are absent and compare the results against the entire group. This separation of the collective lighting phenomena into components gives clear judgments into how a lighting element in perceived and value it provides to the scene.

Component-based rendering gives the ability to render at the component level and use available resources towards selected lighting phenomena. This method of specialize rendering paired with perceptual quality will allow researchers to identify the important lighting components and spend resources on these effects first and continue to spend available resources on other effects until no components are left or the resources are no longer available. The method will retain higher levels of visual quality while reducing rendering cost at all levels. The order of importance proposed in this study will optimize these reductions to obtain ideal visual quality.

The methodology used in previous studies to reduce render cost is a combination of component-based rendering and a traditional approach to psychophysical analysis. It was not found that the literature provided any previous studies including rendering cost of the components while testing the perceptual quality. Rendering cost is the reason for finding the perceptual quality and should be included for accuracy. We will compare the component-wise cost with a traditional psychophysical analysis with the Law of Comparative Judgment. Comparing the results from the two tests will gives a better argument for order of importance in water scenes and a richer understanding for future research in component-based rendering.

3.3. Updating Psychophysical

The proposed study is a psychophysical study conducted on the same basis as the previous 2004 study proposed by Stokes et al. In Stokes (2004), the participants were asked to make subjective quality identifications for a series of printed images and rank the quality in order of personal preference. This research extends the study in a number of ways. The research uses animated videos in a PHP-based digital testing system. It controls the testing environment through a broadcasting standard and participants are specialized in computer graphics. It also includes the render time or cost of each lighting phenomena, which is a novel approach determined from the literature. This method is paramount in the research, because the connection between rendering cost and the quality of lighting phenomena will make much stronger arguments for its value.

The proposed study further strengthens the literature by Stokes by changing the printed testing materials to an interactive website, so phenomenon can be viewed more naturally. The digital testing system allows for imagery to be animated and the quality of the monitor is near an exact match of the end application. The testing environment use to collect data is well controlled by broadcasting standards for testing (SMPTE, 2003).

Previously known literature only tested scenes in which the results were immediately applied and this limits itself to ad hoc solutions that were unable to be generalizable. This study will test a range of common scenes so results can be generalized over all possible scenes and lighting conditions. This research will also be restricted to testing water scenes where there may be a unique order of importance. The following sections will explain these differences completely.

3.4. Methodology

3.4.1. Testing Materials

The selected scenes are of various common types of water. The scenes will also contain different lighting schemes, which will generalize the results further. All of the scenes tested will be animated, because the intended use is to reduce the cost of animations and static water will still reflect and refract dynamic environments.

3.4.1.1. Design

The current study created an interactive web-based application to view animated scene on a video monitor. The intended use of the outcome is nearly an exact match to the testing method. This will offer better testing results due to more accurate stimuli and subjective emotional responses to those stimuli. In a similar fashion to Stokes' study, all lighting elements are viewing simultaneously for optimal comparisons.

3.4.1.2. Subjects and Scenes

Five scenes in all were created for the study. A glass of water, see Figure 3.1, is common water with no participating media or attenuation. This is a great basis for testing, because it is identifiable to all participants, is easily understood and all phenomena are easy observed. A simple background was chosen to not distract the viewer's focus.

Figure 3.1 Glass Pour Scene: Final Rendering

The invisible box scene (Figure 3.2) shows rapid motion, high velocity water. It is in a similar environment and lighting to the glass of water, but offers very dynamic and separated water for complex caustics and shadow in lighting. This scene also introduces rigid-fluid interaction or the interaction of water with objects. The objects were chosen to be reflective to amplify the effects of specular reflection and offer more complex lighting into the environment.

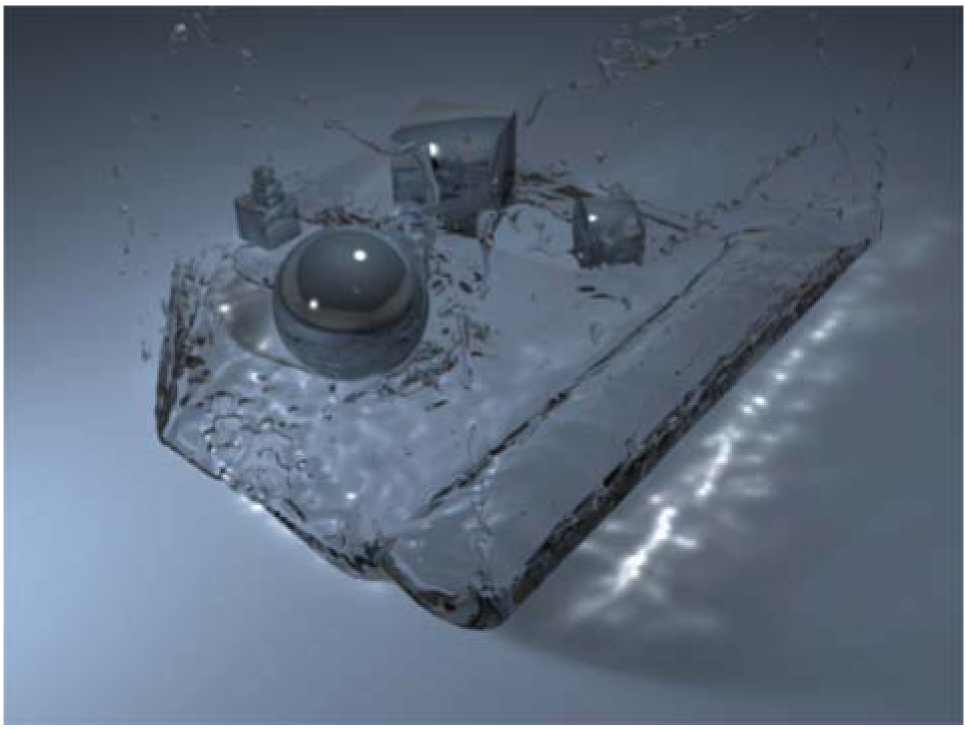

Figure 3.2 Invisible Box Scene: Final Rendering

The rest of the scenes were selected to be real world scenes to show water in its natural surroundings. The ocean buoy scenes were selected to show common deep water in various lighting conditions. The first is an ocean buoy moving in the waves on a sunny day. Attenuation and participating media are not directly tested due to their lack of necessity in previous scenes, but they do get shown within this scene. Every scene in this study needs an alternative diffuse object to collect caustics. An open ocean by itself does not exhibit caustics, because by definition caustics are only absorbed by diffuse surfaces and the ocean has no diffuse property. The ocean buoy otherwise has no significance other than being a common object found in the ocean to collect caustics.

Figure 3.3 Sunny Buoy Scene: Final Rendering

The second ocean buoy scene is the same in every way as the sunny day, but is shown at sunset. This is a low light environment, which will display completely different lighting conditions, and was chosen to compare against the sunny day to find differences when only the lighting was altered. Sunset was used instead of night because the scene still needs enough lighting to properly show variation in the material elements. Though night is a common lighting environment for water, no lighting scene will be tested in the study because not enough information will be conveyed to make steady judgments.

Figure 3.4 Sunset Buoy Scene: Final Rendering

The fifth scene is a diffuse lighting environment with deep water. The rain on a lake shows complex animation on the surface not present in the ocean scenes, and the diffuse lighting will reduce the effects of caustics on the scene. To keep with tradition, a buoy was selected to be the object to collect caustics.

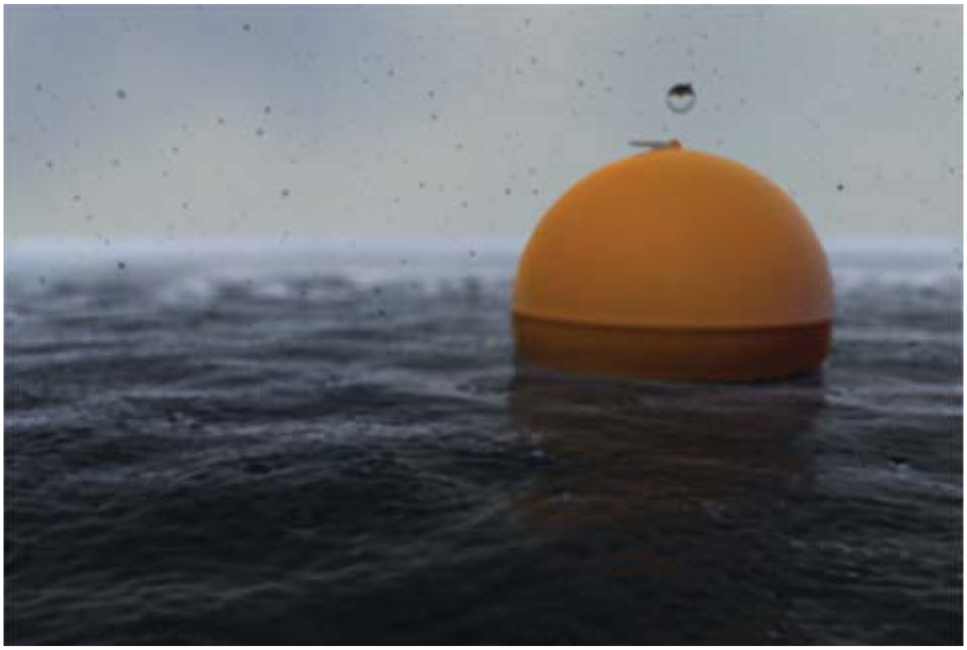

Figure 3.5 Rainy Lake Scene: Final Rendering

3.4.1.3. Lighting Variables

There are many variables present for this study. Dependent variables include all of the material conditions: diffuse grey, diffuse color, transparency and refraction and lighting conditions: caustics, specular reflection, hard shadow and soft shadow (Cohen, 1993; Dutre, 2003; Jensen, 2001). The videos are constructed using a component-based rendering technique where all of the elements are rendered into separate images and then the images are reconstructed to create the final testing videos. Each video has one of the above elements removed or in the case of materials, replaced and the final rendering is among the tested videos. Some elements, such as refraction and soft shadow are selected as default elements, because they are present in the final rendering and are used in every scene that does not directly affect them. The remaining elements change or replace these elements to compose the modified animations. Every scene is rendered and constructed in the same way to promote continuity over the entire testing materials. The videos include: Diffuse Grey, Diffuse Color, Transparency, No Caustics, No Specular Reflection, Hard Shadow, No Shadow and the Final Rendering.

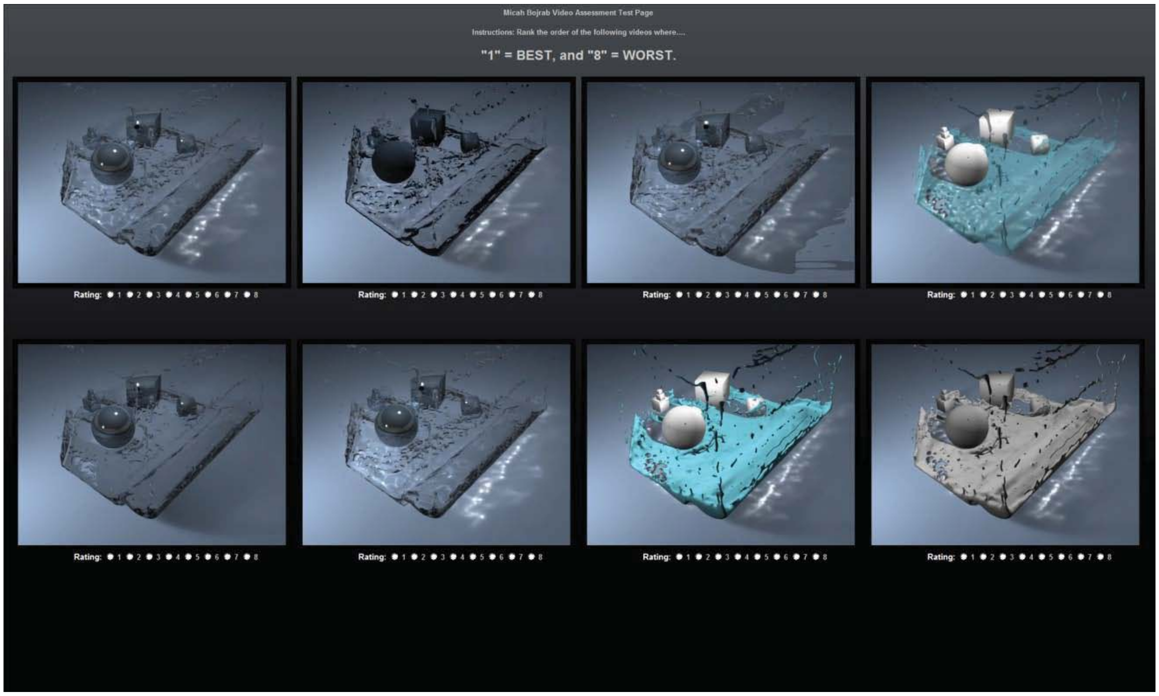

Figure 3.6 Testing Layout:
Videos are 480x360 resolution arranged in a 4x2 grid

3.4.1.4. <u>Rendering Time</u>

Rendering times for each of the lighting variables was recorded for every scene. Thirty frames of the video sequence are selected to specify the total render time of the relative rendering cost. Stipulations for selecting thirty frames are that every frame must contain all of the lighting elements, the scene will be rendered eight times to make element cost comparisons and all frames sets are consecutive. These times are then made percentages of the total rendering time to find the cost per element. These times then are compared to the results of the traditional Psychophysical Analysis (Thurstone, 1927) to find a lighting element's relative value to the scene.

3.5. Testing System

3.5.1. Testing Platform

The testing is conducted on a lab computer within a controlled environment. The 30" computer monitors are calibrated for viewing animations of 480x360 resolutions and are arranged on the testing site in a 4x2 format so every video is view simultaneously and compared directly. See Appendix A for a complete listing of testing forms.

The computer system is PHP-based site for recording and sending data. The pages have eight Flash players embedded to play the videos and basic radio boxes for receiving data. The site was intentionally designed simple to increase the usability and decrease errors caused by the functionality of the site. Even the layout and aesthetics of the site are focused to draw attention toward the videos.

3.5.1.1. Opening Instruction

The researchers gave the same verbal tutorial to all of the participants of the study. This instruction familiarized the participants with the system they would encounter and gave them a quick overview of what the subject should expect. The instruction was as follows:

> "You will see a series of eights videos displayed in parallel. You will be rating these videos in order of what is most realistic to what is least realistic, with number 1 being the most realistic. Each page has a 75 second timer and will give you a 15 second warning. There are five

scenes in all and when you come back to the opening questionnaire the test will be complete. Do you have any questions?

To further aide in the instructions portion of the web-based application an additional page of information was created. This page displayed in Figure 3.7 and is read as follows:

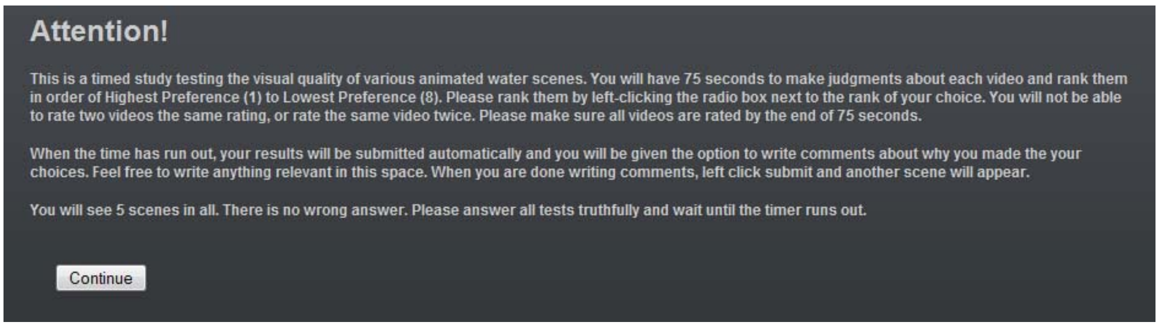

Figure 3.7 Instruction Page

3.5.1.2. <u>Demographic Survey</u>

Each participant, upon volunteering for testing, receives a unique randomized identification number. This number is used to classify participants while processing the data because no other identifying information was collected during the study. The identification number is displayed to the participant, but is not tied to the participant in any way.

The participants start the study by answering an opening survey to gauge their competency. The survey finds the level of experience for the individuals tested, and verifies they are in the specialized group that are knowledgeable of computer graphics and are comfortable with the use of a computer. It also identifies any visual defects that may invalidate the results for the participant. These visual defects include: Partial Blindness, Color Blindness, Low Blindness, Glaucoma and Cataracts. All of these visual defects could potentially compromise the validation of the study and thus participants with visual disabilities were not included in the final results.

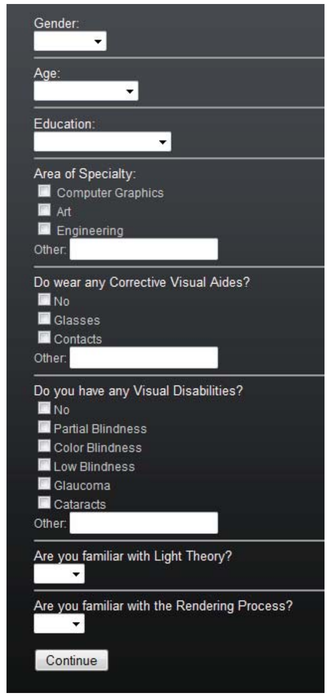

Figure 3.8 Introductory Survey Layout

3.5.1.3. <u>Testing Scenes</u>

Once the demographic survey is complete, the participants are guided to the first of five pages. A random generation algorithm was used to randomize the loading of each of the five testing scenes. Every scene is viewed by each participant, but the order of viewing is randomized. When a page is loaded, the participant is prompted that he or she will have 75 seconds to specify the ordering of visual importance for each video.

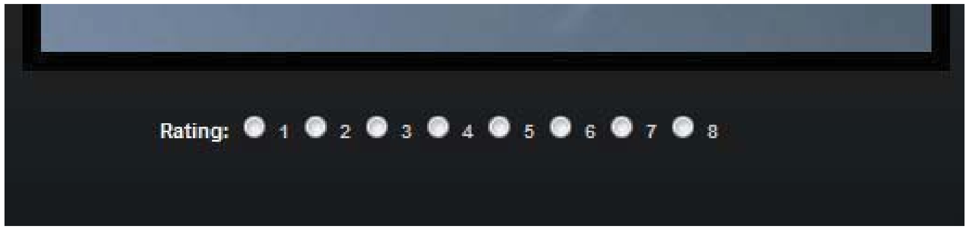

Figure 3.9 Radio Layout

Subjects select radio boxes (Figure 3.9) below each video to rate the video from one (“most realistic) to eight (“least realistic). Due to proper error checking, two videos cannot be rated the same and the same video cannot be rated twice. If any conflicts arise, the previous rating of the conflicting value is overwritten or discarded.

Once a video is selected a larger reference number is displayed next to the video (Figure 3.10). This feature was added during iterative testing to make quick visual references between rated videos. The effect reduced comparative time considerably, though no official calculation was recorded and testing participants reported the feature to be very beneficial.

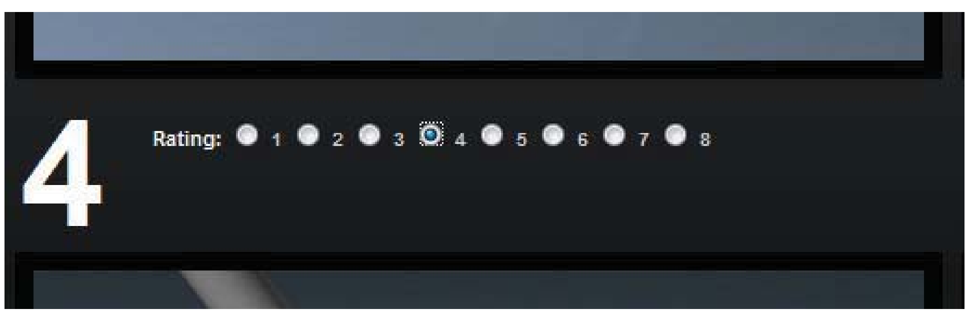

Figure 3.10 Reference Number

At the end of 75 seconds, the testing results for the scenes are automatically submitted and the testing allows participants to leave comments about the decisions he or she has made. The text fields (Figure 3.11) are optional and any data held in these fields are connected to the results of the quantitative part of the testing. This qualitative study is present to gain insight into “why” participants made the decision they did, though the results of this study are not factored directly into the quantitative analysis in any way.

Figure 3.11 Text Field

The pages, displaying one of the five testing scenes, have eight videos displaying all of the major elements with one element removed. This concept was explained further in Section 3.4 and was displayed properly in Figure 3.6. The pages are calibrated to be displayed on a 30” widescreen LCD monitor with a resolution of 2560x1600. The large format allows for better crisper viewing of the videos in a two rows by four columns scheme, while still maintaining a high resolution for each video (480x360).

Once all of the testing requirements for a page are completed, the participant will continue to new pages, and they will be randomly generated until all testing scenes have been seen. Each scene is displayed fully in Appendix A for reference. Lastly the participant will be taken to a resolution page thanking them for their time in volunteering.

3.5.1.4. Timed-Based Study

The 75 second timer was added to the study to satisfy criticisms to unlimited testing. It was determined the testing parameters are better controlled if the time was limited. Preliminary suggestions were to have a rapid timer and videos were hidden at the end of a thirty second timer. This would mimic the traditional rapid viewing by audiences of digital scenes. Rarely do audiences view elements statically for more than a short time, so this method was proposed to recreate this topic. Decisions in this timing scheme would be determined without directly viewing the videos.

This preliminary assessment contained a fundamental flaw. With the traditional psychophysical analysis as reviewed in Chapter 2, is assessment of emotional response to a set of stimuli (Gescheider, 1997). Without the stimuli present in the study (i.e. the videos are hidden at the end of thirty seconds) the entire study open to becoming invalid.

In response, a longer 75 second timer was determined by testing the average time preliminary testing subjects took to complete the survey. To limit the time to this allotment without extending the viewing or changing the testing fundamentals, the testing results are automatically submitted at the timer's completion. This offers the ability to submit results without having all parameters selected. It was determined that a scenario where no results were recorded is acceptable across a large range of testing subjects and these occurrences would not be calculated into the final results.

A fifteen second reminder is visually prompted before the results are submitted to pad the incidence of no submittals. This addition was made during preliminary testing and was determined to be helpful. .

3.5.2. Testing Environment

This study has many variables and is based on perception. Consequently, there is a need to control as many extraneous variables as possible allowing the participants to focus on perceiving the image quality itself. The testing system was constrained by making it intuitive and easy to navigate. Likewise, many variables in the environment will be controlled by the standards of the Society of Motion Picture and Television Engineers (SMTPE). These standards are used in testing of new digital file formats and other broadcasting system, so they may have recognizable and generalizable results (SMPTE, 2003). This study selected SMPTE 196M-2003 as the closest standard to the testing conditions to give optimal control over the environment. This standard is the SMPTE Standard for Motion-Picture Film Indoor Theater and Review Room Projection Screen Luminance and Viewing Conditions (SMPTE, 2003). These guidelines will control the studies viewing conditions and overall environment but will differ in the screen conditions and playback rates.

3.6. Population and Samples

Only students and professors in the College of Technology, Engineering and the School of Performing Arts at Purdue University are tested in this study. These individuals are comfortable with technology such as that used by the testing system, and will be able to use it properly with low instances of error. These individuals are educated in lighting and will have a basic understanding of color theory. This population is associated with technology or imagery and typically has a better understanding for the fine nuances in lighting and thus will have a better judgment in quality. The results found from this sample should be expandable to the general population, but testing of this reliability is outside of the scope of this study.

3.7. Summary

This chapter has provided an explanation of methodology used in during testing. The chapter started by giving an explanation of Perceptual Quality and how it pertains to testing. It gave a brief explanation of a similar previous study conducted through Psychophysical Analysis and how this study differs. The chapter then thoroughly explains the four parts of the Methodology: the testing scenes, variables, system and environment. The next section will provide testing results.

CHAPTER 4. RESULTS

4.1. Psychophysical Analysis

4.1.1. Processing for Data

Before the results of testing could be interpreted, a common form of processing was established to develop each set uniformly. This increases validity of the results by making each set comparable and the overall study generalizable. Most importantly, the data processing needs to provide useful insights into common trends. The lighting effects are somewhat disconnected from one another due to the testing of both material and lighting properties and the processing related to them.

It was first determined that the final render would be among the testing data. This provided a solid anchor to compare results against and gave insight into how important all the lighting effects are. This scene in all cases should be determined as the most realistic, because it contains all of the lighting phenomena. After the final render, the lighting materials were added to the scene to replace the default refraction of natural water. When creating these scenes, all other lighting elements were included in full, so only the material would be altered. Addition of materials in this manner means decisions are solely based on significant changes, so the overall quality would be recorded directly. To explain this further, a material that scores highly on a scale of one to eight, with one being very visually accurate, would directly mean that the effect was not realistic. A lower score, closer to one, would mean the element was very important to the scene.

In direct opposition, the lighting elements were subtracted from the scene to show their influence. In this fact, the lighting elements are all present in a real world scene, where the material properties are not. These lighting effects must then be deducted from the scene to show their individual significance. In this fact, a higher score for a lighting effect means it was more important to the overall scene because the scene was not nearly as visually accurate without the presence of the element. A score closer to one will show the scene is unaltered without the lighting phenomena and will deem this an element of less importance. These two processes are contradictory, but an importance of each element can be determined with a single test.

The researchers of the study took advantage of the Statistical Department Consulting Service of Purdue University to both confirm the experiment methodology and give clear insight into the statistical analysis of data. It was determined, due to the simplified nature of the testing, that a standard mean and standard deviation of the data would be sufficient to view the results in a form that preserves the order of importance.

4.1.2. Demographic Results

Data collection was conducted over five consecutive days and 101 participants were tested from all of the major population areas. No participant was tested twice and no compensation was given to volunteers. 77.2% of the subjects were male. More female participants would have been preferred, but testing did not show conflicting trends between the genders.

Age ranges had a distinct majority in the 20-30 category. Also, due to the geographical location, 71.3% of volunteers had some form of higher education and 80.2% had a background in computer graphics. This is a model population for a study of this type, because a large majority is specialized in the area of the study and thus will realize small changes in lighting more easily than the general population.

A majority of participants had corrective visual aids during the testing. Surprisingly, 94% of individuals had no visual defects, and thus could easily be included in the study. The other 6% had minor visual problems ranging from color blindness to being legally blind without the use of visual aids.

Most importantly, 57% and 67% percent of participants had at least basic a knowledge of Light Theory and the Rendering Process respectively. Along with having an overwhelming majority in the field of computer graphics, this shows that the population tested was favorable for receiving well educated and experienced results.

4.1.3. Study Results

Each of the scenes will be presented separately and individually scrutinized for small differences. At the end of the chapter all of the results will be combined to form a comprehensive study across all scenes to receive the best generalizeable data. Each of the scenes offer some small differences in the subject of water and how it is commonly displayed within its environment, but the end of the chapter will provide a complete look at the results.

4.1.3.1. Glass Pour Scene

The Glass Pour scene showed a much larger effect on the absence of caustics within the scene. Compared to the natural environment scenes the caustics were much more important to the viewing audience. Specularity, though important to every scene, showed it was least important in the Glass Pour scene. Surprisingly, shadowing was nearly as unimportant to the scene as the absence of shadow and the substitution of hard shadowing made a very small effect on visual realism to the viewing audience. No shadow was said to be more realistic than hard shadow, and both scored nearly equal to the accuracy of the final render.

The Glass Pour scene was the most consistent in selection. The average standard deviation across all videos in the scene showed it was much easier for participants to view the lighting effects properly and make judgments about these lighting effects. The participants also suggested in the qualitative portion of the testing that this scene was the easiest to find differences, and suggestions were also made to start the testing with this scene first. The researchers noted the considerations, but retained the randomizing scene order for better reliability.

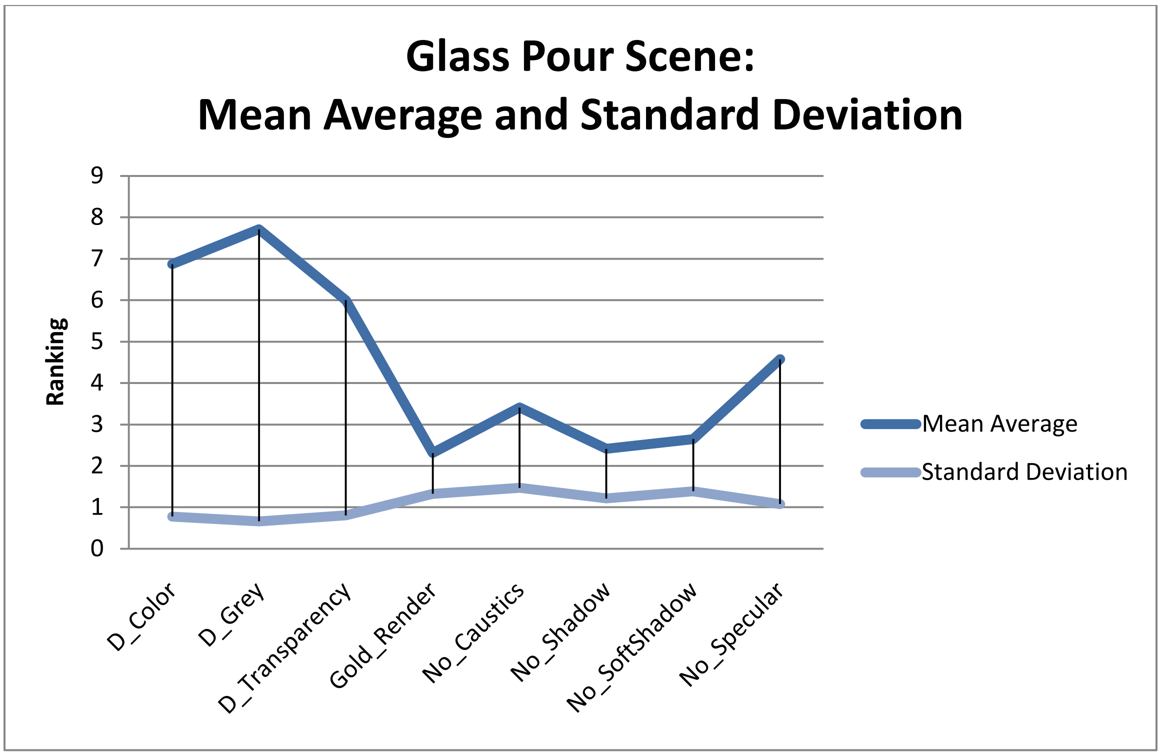

Figure 4.1 Glass Pour: Average and Standard Deviation

The most important finding of the study was in the Glass Pour scene. This scene was one of only two scenes where the “gold” or final render was voted the most realistic. The scene that contained all of the real world lighting phenomena was selected as the most realistic in less than half of the study. In both scenes where the final rendering won as being the most accurate, it was only selected best by an average margin of .065 which is greatly outweighed by a standard deviation of 1.29. This scene contained the most votes for the Final Render being the most realistic with 39% of participants. To put this in perspective, the Default Grey rendering was selected as the worst render 81% of the time for the same scene.

4.1.3.2. Invisible Box Scene

The Invisible box scene had the largest deviation of any scene. On average the participants deviated from an average score by more than 1.3 and this scene also had the largest single deviation of 1.58 for the absence of specular reflections. From Figure 4.2, it can be seen that specular reflections and then caustics were very important to the scene. Shadows of any kind were of low importance.

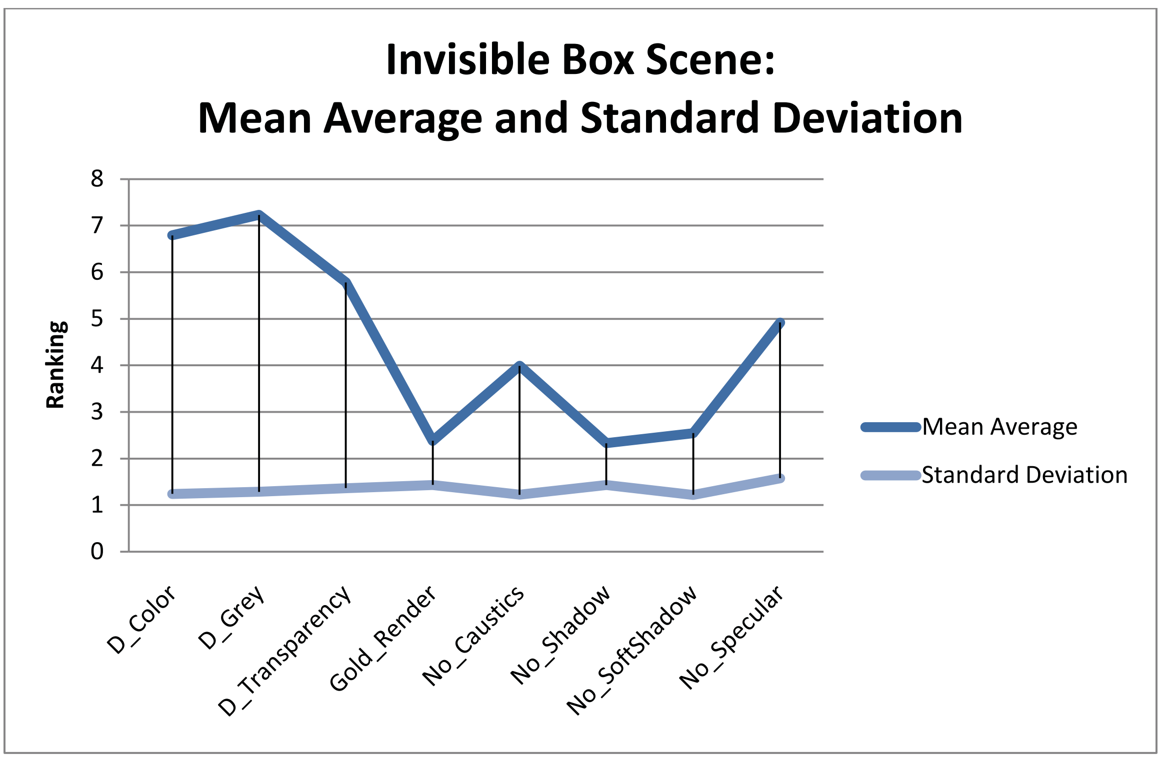

Figure 4.2 Invisible Box: Average and Standard Deviation

4.1.3.3. Sunny Buoy Scene

The Sunny Buoy scene had the smallest deviation between Gold Render, No Caustics, No Shadow, and Hard Shadows. This means that these four lighting elements present in the top rankings of every scene were nearly identical in visual quality to the final rendering. The scene was viewed virtually the same without caustics and without shadows. Two major lighting elements can be ignored in similar scenes with minimal consequences.

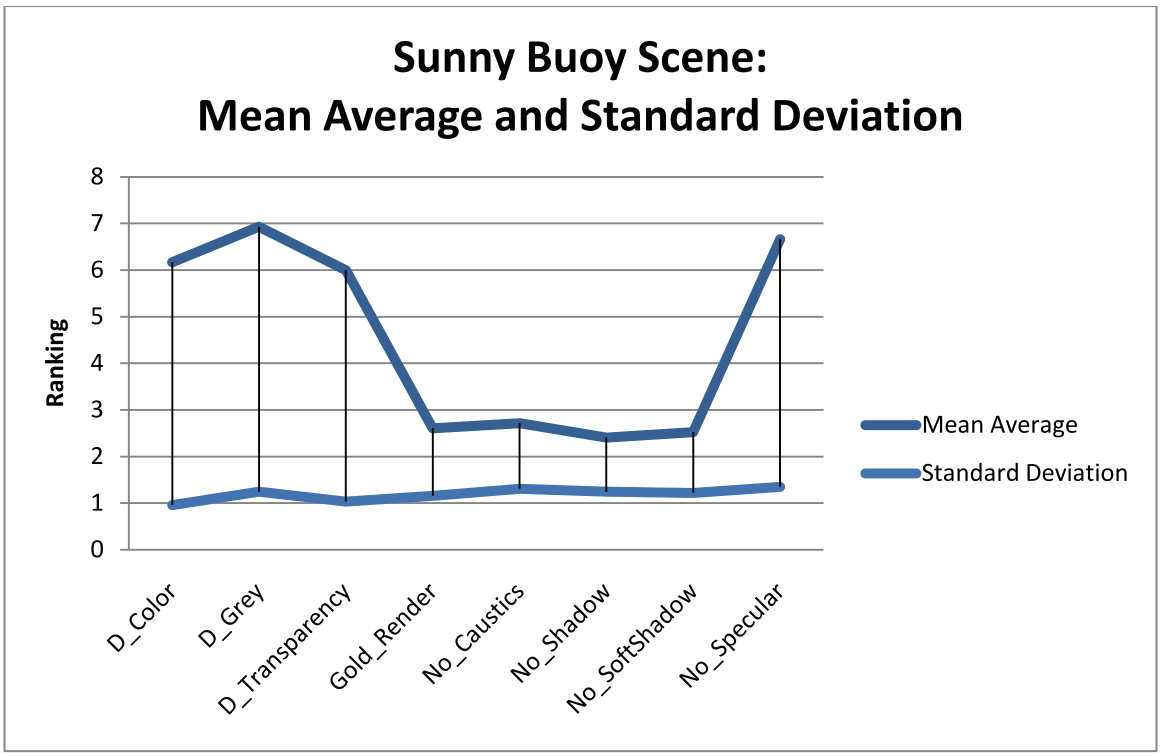

Figure 4.3 Sunny Buoy: Average and Standard Deviation

Having no specular reflection in all of the deeper water scenes had a much larger effect on the scene's appearance and in these scenes No Specular was nearly ranked as poorly as Default Grey which was the feature that constantly came in last. In deep water scenes, reflection is very important, because the sea bed cannot be seen. As there are no reflections of the sky in the water, the water appears black as all lighting is absorbed into its depths before it properly illuminates the bottom. In conclusion, specular reflections are one of the most important features in any deep water scene.

4.1.3.4. Sunset Buoy Scene

The Sunset Buoy scene was similar to the Sunny Buoy but results were not as consistent. In both scenes specular reflection was very important, though not as crucial as in the Sunny scene. This may be due to the effect of black water not being as recognizable in a low lighting environment and so material effects such as Default Color and Default Transparency were degraded the image quality more.

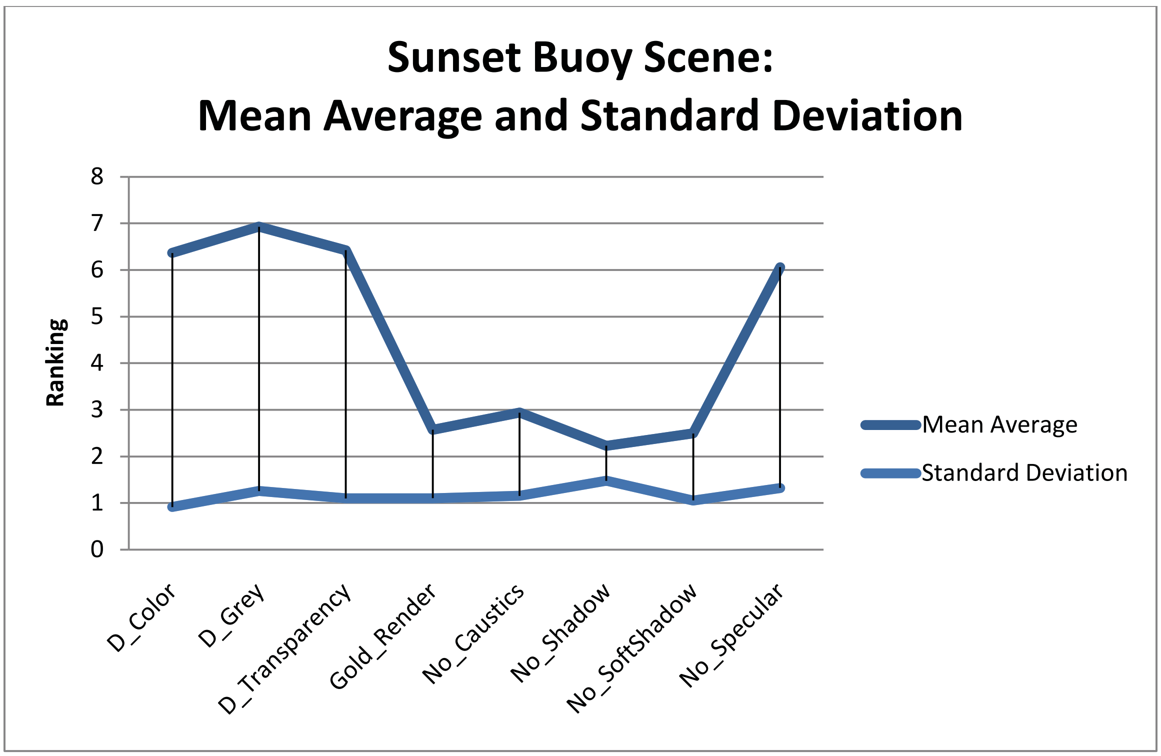

Figure 4.4 Sunset Buoy: Average and Standard Deviation

Sunset buoy contained a very important trend in the data. As viewed by the participants, it contained the consistently most visually realistic video of all of the scenes or the video with the lowest average score. That scene was No Shadow, which further solidifies the idea that shadows are unimportant to water-rich scenes. Some criticisms may arise to show the scene is dominated by materials that cannot collect shadows or caustics, but the rebuttal would be that the buoy is a focal point of the scene, and it is capable of displaying both.

4.1.3.5. Rainy Lake Scene

The diffuse lighting of the Rainy Lake scene differs from other scenes, because most of the common lighting features are lost during diffuse lighting environments. This was displayed in the close grouping between the four videos ranked most visually realistic. During the qualitative portion of the study, an overwhelming 31 participants noted the videos were either very similar or they guessed on numbering, because they could not tell the difference between Final Render, No Caustics, No Shadow and No Soft Shadow. These videos also had a high standard deviation showing the wavering nature of their rankings.

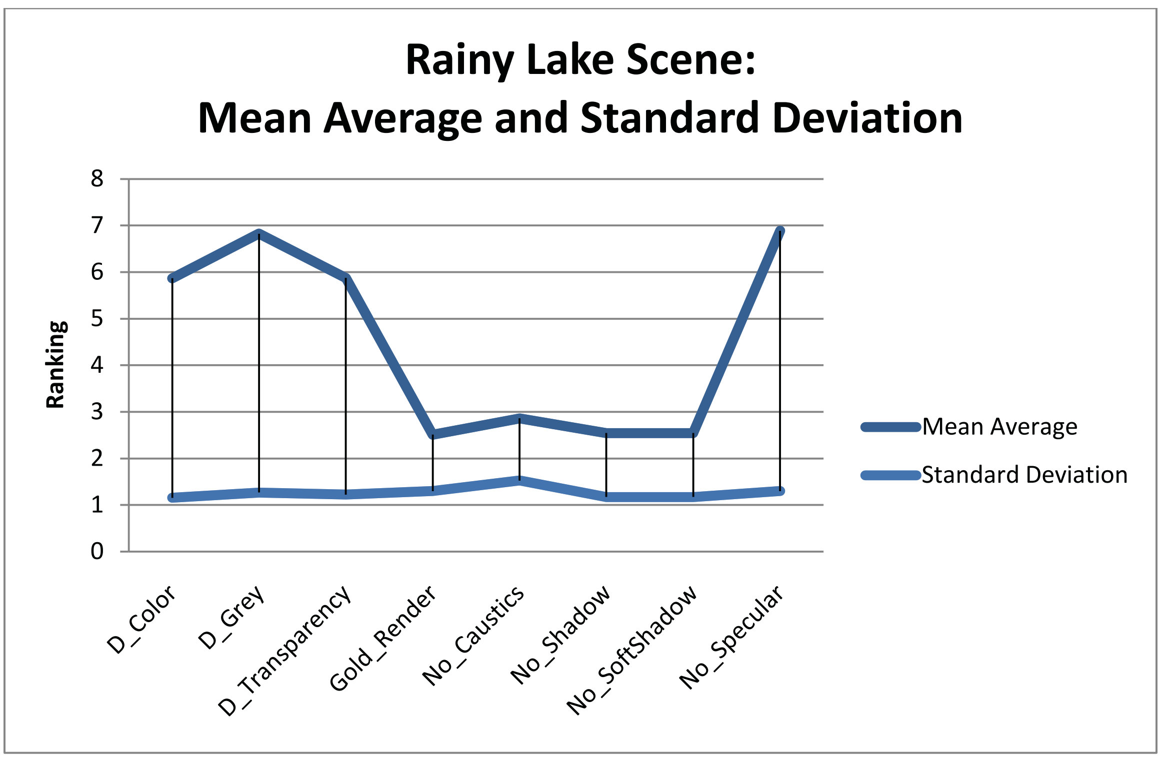

Figure 4.5 Rainy Lake: Average and Standard Deviation

The Rainy Lake scene was the only scene where a lighting phenomenon other than Diffuse Grey came in last place. Specularity was very important to the look of this scene, and without it, the video was said to be the least realistic. The effect may have been amplified by the diffuse lighting and the other lighting elements not being displayed as prominently. In this way, more importance was placed on specularity to maintain the appearance of water, and without it the scene failed.

The total influence of all elements is included below. No Shadow on average was deemed higher visual quality against the Gold Render. This is an alarming discovery from the perceptual testing. No Caustics was important to the scenes because the subjects noticed its absence. Likewise there was a large jump in visual quality when specular reflection was disabled. This lighting phenomenon approached the consistently low ranking of the material phenomena.

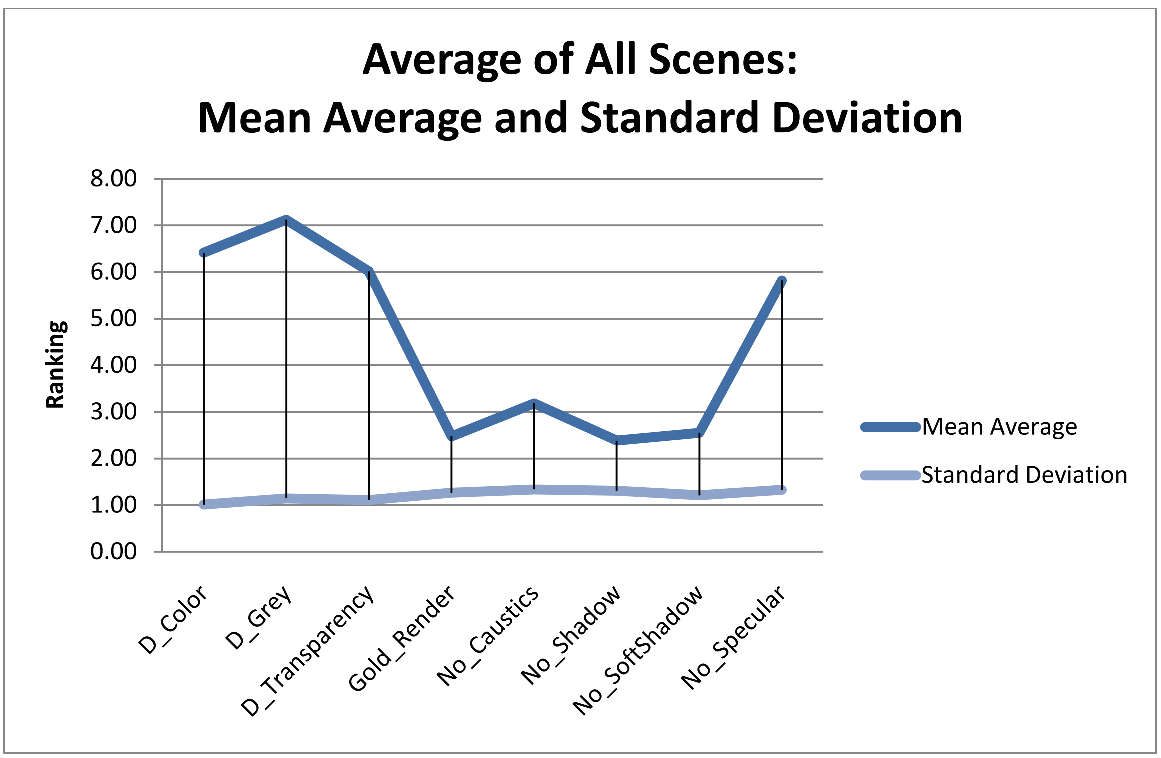

Figure 4.6 Total Average: Average and Standard Deviation

4.2. Rendering Cost

4.2.1. Processing for Data

A test segment of the entire scene was rendered eight times with one change in the elements. The singular differences between each scene gave the researchers a reference of comparison. Only one lighting element was changed between scenes so any change in cost would be a direct result of the lighting element being applied. Researchers could then isolate a component to find the render time of every element. It was determined that Diffuse Grey would have a relative cost of 0.0 seconds, because it was the least costly. It may also be said that a minimum of diffuse grey with no lighting effects must be established to render a scene. All other costs associated with rendering the scene would be considered equal throughout the testing. This will create a relative cost of Diffuse Grey to be 0.0 seconds.

4.2.2. Timing Results

Each scene had eight, 30 frame series that needed to be rendered to record data. Each scene was rendered three times each to verify the results of rendering and to ensure no computational error had occurred.

The scene is in the top left corner of the table and it tops a list of all lighting elements tested in the study. The next column is the scene in which the current lighting phenomena will be compared against to view the relative rendering cost. The third column is the observed rendering time of the total scene, which is the number of seconds per frame. The fourth column shows the relative cost per frame with the difference between the current cell and its reference scene. The last column contains the relative cost percentage of the individual elements.

The Glass Pour scene reported nearly eighty percent of the total computational cost coming from caustics and soft shadows. These variables are very costly in the scene and should be avoided if either is not needed.

Table 4.1 Glass Pour: Component Cost

GLASS POUR SCENE	Reference Scene	Total Time /frame (s)	Relative Time /frame (s)	Cost %
Diffuse Grey	None	2.07	0	0.00
Diffuse Color	Grey	2.07	0	0.00
Transparency	Grey	6.21	4.14	3.64
Refraction	Grey	22.76	18.62	16.36
Soft_Shadow	Refract	55.86	33.10	29.09
Hard_Shadow	Refract	24.83	2.07	1.82
Caustics	Refract	76.55	53.79	47.27
No_Specular	Refract	20.69	2.07	1.82
		Total Time (s)	113.72	

The Invisible Box had a similar distribution to the Glass Pour scene but had more overall cost dedicated to the rendering of refraction. This is more than likely due to the multiple refractive tracings through the broken fluid. In the Glass Pour scene the water was all one body, so the computer traced a bend in and then a bend out. The Invisible Box scene had many fluid boundaries, so the bending of light must be traced through complex surfaces.

Table 4.2 Invisible Box: Component Cost

INVISIBLE BOX SCENE	Reference Scene	Total Time /frame (s)	Relative Time /frame (s)	Cost %
Diffuse Grey	None	18.62	0.00	0.00
Diffuse Color	Grey	18.62	0.00	0.00
Transparency	Grey	22.76	4.14	5.13
Refraction	Grey	57.93	37.24	46.15
Soft_Shadow	Refract	66.21	8.28	10.26
Hard_Shadow	Refract	60.00	2.07	2.56
Caustics	Refract	84.83	26.90	33.33
No_Specular	Refract	55.86	2.07	2.56
		Total Time (s)	80.69	

The Sunny and Sunset Buoy scenes had unusually high render times, which lead the researchers to run more testing. Ultimately the test was run three times with very similar results in each. In the same fashion as the refraction in Invisible Box, the multiple trace depth encountered while rendering the ocean was determined to be the culprit. This tracing through multiple surfaces increased the rendering time more than adding more lighting effects in certain scenes. This occurrence will be included in the Chapter 5.

Table 4.3 Sunny Buoy: Component Cost

SUNNY BUOY SCENE	Reference Scene	Total Time /frame (s)	Relative Time /frame (s)	Cost %
Diffuse Grey	None	18.62	0.00	0.00
Diffuse Color	Grey	20.69	0.00	0.00
Transparency	Grey	163.45	144.83	46.98
Refraction	Grey	80.69	62.07	20.13
Soft_Shadow	Refract	124.14	43.45	14.09
Hard_Shadow	Refract	84.83	4.14	1.34
Caustics	Refract	134.48	53.79	17.45
No_Specular	Refract	80.69	0.00	0.00
		Total Time (s)	308.28	

The ocean buoy scenes were the longest to render overall for all lighting elements. Between the two scenes, the Sunny Buoy scene was the more expensive by almost double. The different lighting set needed to achieve the time of day was to blame. Other than the lighting; the animations, the scenes and the rendering information was the same between these two scenes. Less digital lights were needed to light the dim Sunset scene. None of the scenes used Global Illumination so more lightings were added to achieve the effect of bouncing rays.

Table 4.4 Sunset Buoy: Component Cost

SUNSET BUOY SCENE	Reference Scene	Total Time /frame (s)	Relative Time /frame (s)	Cost %
Diffuse Grey	None	18.62	0.00	0.00
Diffuse Color	Grey	18.62	0.00	0.00
Transparency	Grey	97.24	78.62	40.43
Refraction	Grey	74.48	43.48	22.36
Soft_Shadow	Refract	97.24	22.76	11.70
Hard_Shadow	Refract	80.69	6.21	3.19
Caustics	Refract	105.52	31.03	15.96
No_Specular	Refract	62.10	12.38	6.37
		Total Time (s)	194.48	

The Rainy Lake scene had a majority of the cost in the shadows and caustics phenomena. This scene also proved these same lighting elements were unimportant to the realism of the scene. This occurrence has allowed from gains in rendering cost in similar scenes as detailed in Chapter 5.

Table 4.5 Rainy Lake: Component Cost

RAINY LAKE SCENE	Reference Scene	Total Time /frame (s)	Relative Time /frame (s)	Cost %
Diffuse Grey	None	14.48	0.00	0.00
Diffuse Color	Grey	14.48	0.00	0.00
Transparency	Grey	22.76	8.28	8.89
Refraction	Grey	26.90	12.41	13.33
Soft_Shadow	Refract	55.86	28.97	31.11
Hard_Shadow	Refract	39.31	12.41	13.33
Caustics	Refract	57.93	31.03	33.33
No_Specular	Refract	26.90	0.00	0.00
		Total Time (s)	93.10	

The average total cost of each lighting phenomena is displayed below. The results of this table are displayed differently than the individual scenes. The

Specular component is the only feature subtracted from the scene during the testing. In the Total Cost table below, all elements are adjusted to show total cost per component instead of the relative cost like in the previous sections. This shows a more complete view of the results and the object of testing used to find each component value.

In this table, transparency has the highest cost associated of any lighting phenomena. Though this is a special case in the use of transparency, it will happen. The results will show that it will happen quite frequently in the rendering of water, where there are many depth traces through boundaries. As the number of overlapping surfaces increase, so too will the cost associated toward Transparency.

Low average costs were associated with Diffuse Grey, Diffuse Color, Hard Shadow, and Specularity. Higher costs were associated with Refraction, Soft Shadows, and Caustics.

Table 4.6 Total Average: Component Cost

TOTAL COST	Reference Scene	Total Time /frame (s)	Relative Time /frame (s)	Cost %
Diffuse Grey	None	14.48	0.00	0.00
Diffuse Color	Grey	14.90	0.42	0.00
Transparency	Grey	62.48	48.00	30.37
Refraction	Grey	52.55	34.77	22.00
Soft_Shadow	Refract	79.86	27.31	17.28
Hard_Shadow	Refract	57.93	5.38	3.40
Caustics	Refract	91.86	39.31	24.87
No_Specular	Refract	49.25	3.30	2.09
		Total Time (s)	158.07	

4.2.3. Summary

This chapter showed the results from the PPA and the rendering time trials. It first discussed specifics about how these data were collected and processed, and then displayed the data in a form that made it easier to formulate quick judgments. Between each section a brief overview of what the data had shown was detailed and insights into rendering practices were shared. In the next chapter, the conclusions of the study will be outlined. The chapter includes a breakdown of the major data points and offers insight into what the data suggests about rendering practices. Har

CHAPTER 5. CONCLUSIONS

5.1. Introduction

The psychophysical analysis (PPA) showed many interesting trends in the data. This chapter provides a general discussion and outcomes from these trends. PPA data combined with the rendering cost will show an element's individual value to a scene. This section will include a brief discussion on findings from each scene and form judgments about the differences displayed between scenes.

5.2. General Findings

5.2.1. Refraction

First and foremost the data suggested primarily that refraction is important to the rendering of water. In all cases, the realism was increased while refraction was applied except for No Specular in the Rainy Lake scene. Refraction could be said to provide the most realism to water and its influence was nearly unanimous. Refraction should be used in every case that is capable of the extended cost of the element. Diffuse Grey, Diffuse Color and Transparency were continually dubbed the least realistic, though still could be used as alternatives when refraction is too costly for a scene. Previsualizations are a great example of when Default Color may be used to replace Refraction and still keep an acceptable level of visual quality.

5.2.2. Specular Reflection

Specular Reflection is suggested to be the second most important to the water scene, but was definitely more important in deep water scenes. The low cost associated with specular reflection makes it an ideal candidate for improving a scene's realism in all uses. Even real-time applications, the most strenuous of all uses, would be capable of displaying this element properly. Though not as important as Caustics in brightly lit, shallow water scenes, the specular reflection becomes extremely important in deep water scenes where the bottom cannot be seen. In these scenes, the caustics are not shown as the prominent lighting entity for moving of water, so specularity was second important. In all cases, Specular Reflection should be included for realism.

5.2.3. Caustics

Caustics were third important due to the extremely high cost of the extra photon casting. This additional step in rendering causes caustics to almost add a one fifth of the total rendering time. In the real world there are infinite samples of light to give caustics their proper appearance, and there can only be a small fraction of this in a virtual scene. Caustics, in the current study were capped to a reasonable 100,000 photons per frame, so the possible effects on rendering time were not displayed in a sobering manner. Caustics are definitely a slippery slope during rendering, but can be used sparingly with high benefit to visual quality. This element should only be used in quality renders where the high cost is beneficial. When possible this lighting phenomenon should be under-sampled to reduce the rendering cost.

5.2.4. Soft Shadow

Soft shadow, shown in the final render, was next important lighting feature. It was designated more important than hard shadow, but no shadowing was surprisingly the most important video of the entire study. This does not explain that shadows are unimportant and they cause decreases in the image quality, but it does substantiate the previous claims that Refraction, Speculartiy and Caustics are more important.

In a side point to this argument, no shadows were unable to be distinguished from soft shadow in most cases. To illustrate this point, if soft shadows were important to the scene, the Gold Render video would have been distinguished as the video displaying the most realism in 100% of the tests. After all, this video displayed all of the lighting elements. All other videos subtracted lighting elements and subsequently should have decreased quality. In reality, the final render was only selected as the most realistic in one out of four tests and No Shadow video scored higher on the Psychophysical Analysis (PPA), meaning a majority of subjects could not tell the difference when shadows weren't present. The researchers present the finding in this manner, because the Hard Shadow video had a distinct decrease in visual quality in all cases. Restated for clarity; participants knew they did not like hard shadows, but were inconclusive in the difference between no shadow and soft shadow.

5.2.5. Hard Shadow

Following this is hard shadows as the last lighting element of importance in the study. This lighting element is rendered with low cost in most cases, much more so than soft shadow, and can be used as a substitute when shadows are needed and soft shadows are too expensive. With this said, no shadow is suggested to be the best alternative to soft shadow, because there is no cost associated with it.

5.2.6. Diffuse Color, Transparency and Diffuse Grey

In the last three spots are the three diffuse material elements. These elements came almost unanimously in the final spots with little variation in their rankings. Diffuse color is selected as the next important element in order not because it scored higher in the PPA, but because the rendering cost of Transparency in water-rich scene was astonishingly high. Transparency was the single most expensive element in the study and it even outweighed the global lighting elements. This can be explained simply with a small background into how each element is calculated.

With Transparency, a ray is casted into the scene and collects data on which elements it hits and how transparent those elements are. It then adds these transparent values together to find the total color value for each pixel. A material such as refraction on the other hand at first glance would be considered to be more expensive, but that can be deceiving. With Refraction, a ray is casted into the scene and it gets bent as it enters and exits a surface until it finally collides with an opaque object. This means it only reports the first hit on an opaque object instead of remembering all of the materials and surfaces it passed through and adds them together. There is the answer to the mystery. In water objects, there is a great possibility of multiple transparent objects in order because of the very complex boundary surface. This may not be the case in non-water scenes, but it is suggested not to use a transparent material for water.

Lastly, the study includes Diffuse Grey as least important. It is reported last instead of Transparency, because it was designated the least realistic video more than 90% of the time. Transparency is still more costly, but Diffuse Grey was decidedly elected least important by the participants.

5.3. Order of Importance

The generalized order of importance of importance of lighting phenomena specific to water-rich virtual environments is as follows:

1. Refraction
2. Specular Reflection
3. Caustics
4. Soft Shadow
5. Hard Shadow
6. Diffuse Color
7. Transparency
8. Diffuse Grey

The order of importance will suggest all shadows may be deleted from the scene with an average drop in 20% of rendering time with virtually no drop in visual quality. Using refraction instead of transparency in some scenes will provide an 8% reduction in rendering time with a considerable increase in realism. Caustics may not be used in some scenes with an 8% decrease in visual quality, but a 25% drop in rendering cost. Finally, refraction can be substituted by a diffuse material for an increase of 30% of the rendering time, but that also shows a 53% decrease in visual quality. This sacrifice is substantial and should only be used in low rendering cost scenarios.

5.4. Ten General Guidelines

This section contains quick reference guidelines when rendering water. These principals are based on all scenes so they can become more generalizable. Every scene can offer unique problems and solutions, so these guidelines are only suggestions or a solid starting point in research.

The rendering guidelines are as follows:

1. Refraction is the most important in materials creating realism in water. Use it whenever the render cost allows.
2. Specular Reflection is the most important lighting phenomena when rendering water. Reflection also is very light to implement.
3. Specular Reflection becomes more important in deep water scenes in every lighting possibility. Always use it no matter the cost.
4. Caustics are very important, but expensive. Use sparingly and the benefits will outweigh the costs.
5. Low and diffuse lighting environments do not need expensive lighting effects such as shadows and caustics. As lighting gets dimmer or more diffuse, the time spent on these features can decrease.
6. Lighting effects become more important in shallow water scenes with bright lighting. Caustics, shadows and refraction can be more visible in these scenes and should be handled with more care.
7. Soft shadows should be used only after basic implementations of refraction, specular reflection and caustics. If cost does not permit the use of shadows, include no shadows instead of hard shadows.

8. Diffuse material replacements should be only used for Previsualizations, and not at all in production. They are fast solutions that when colored resemble water.
9. Transparency is expensive and of low importance. Use diffuse colors before ever using transparency for the material of water.
10. Water is a complex material distinguished by the world around it. Reducing computational cost of the lighting phenomena, such as refraction, specular reflection and caustics, is a better solution than not including the elements.

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APPENDIX

APPENDIX

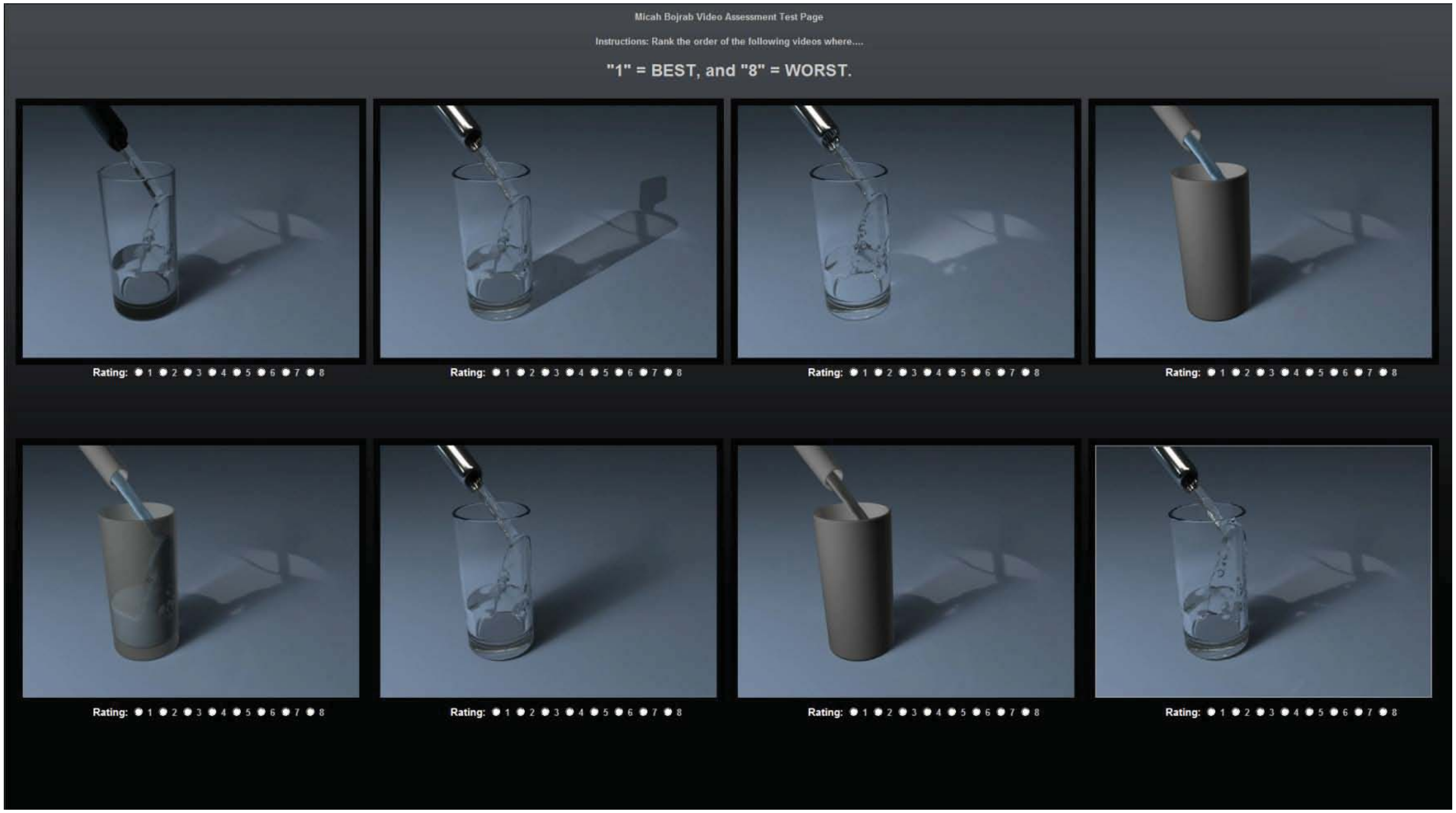

Figure A.1 Glass Pour Scene: Layout

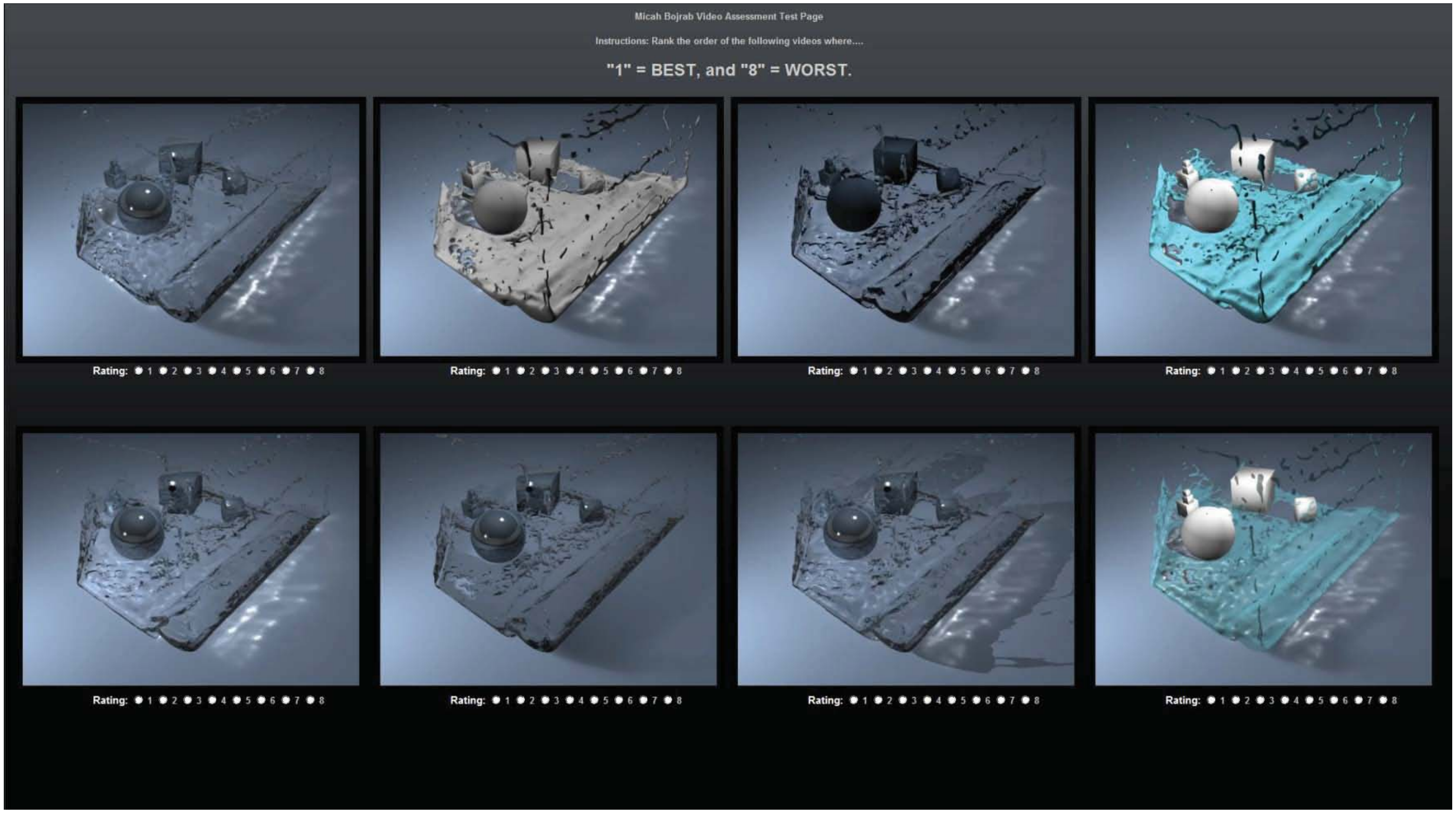

Figure A.2 Invisible Box Scene: Layout

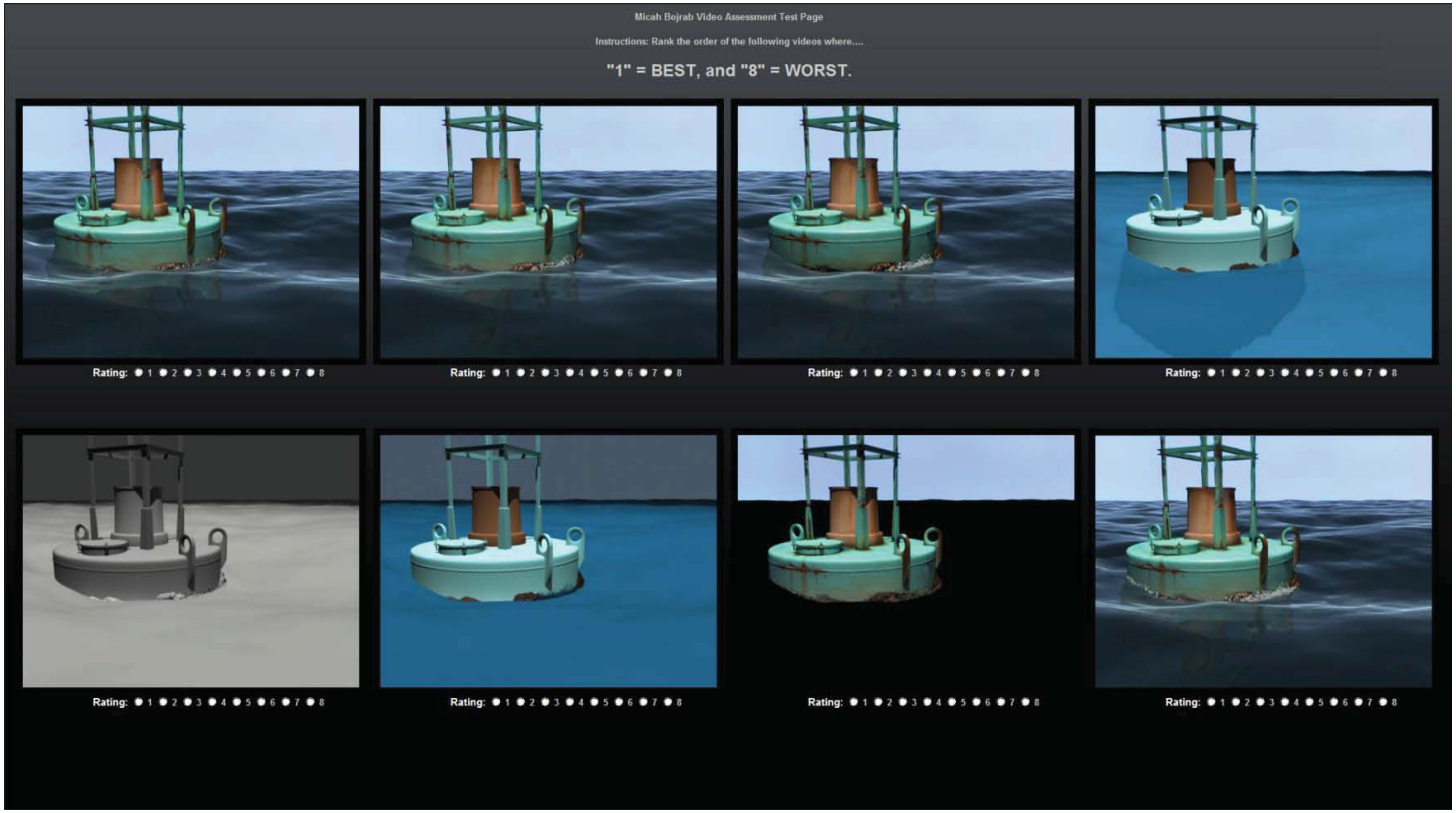

Figure A.3 Sunny Buoy Scene: Layout

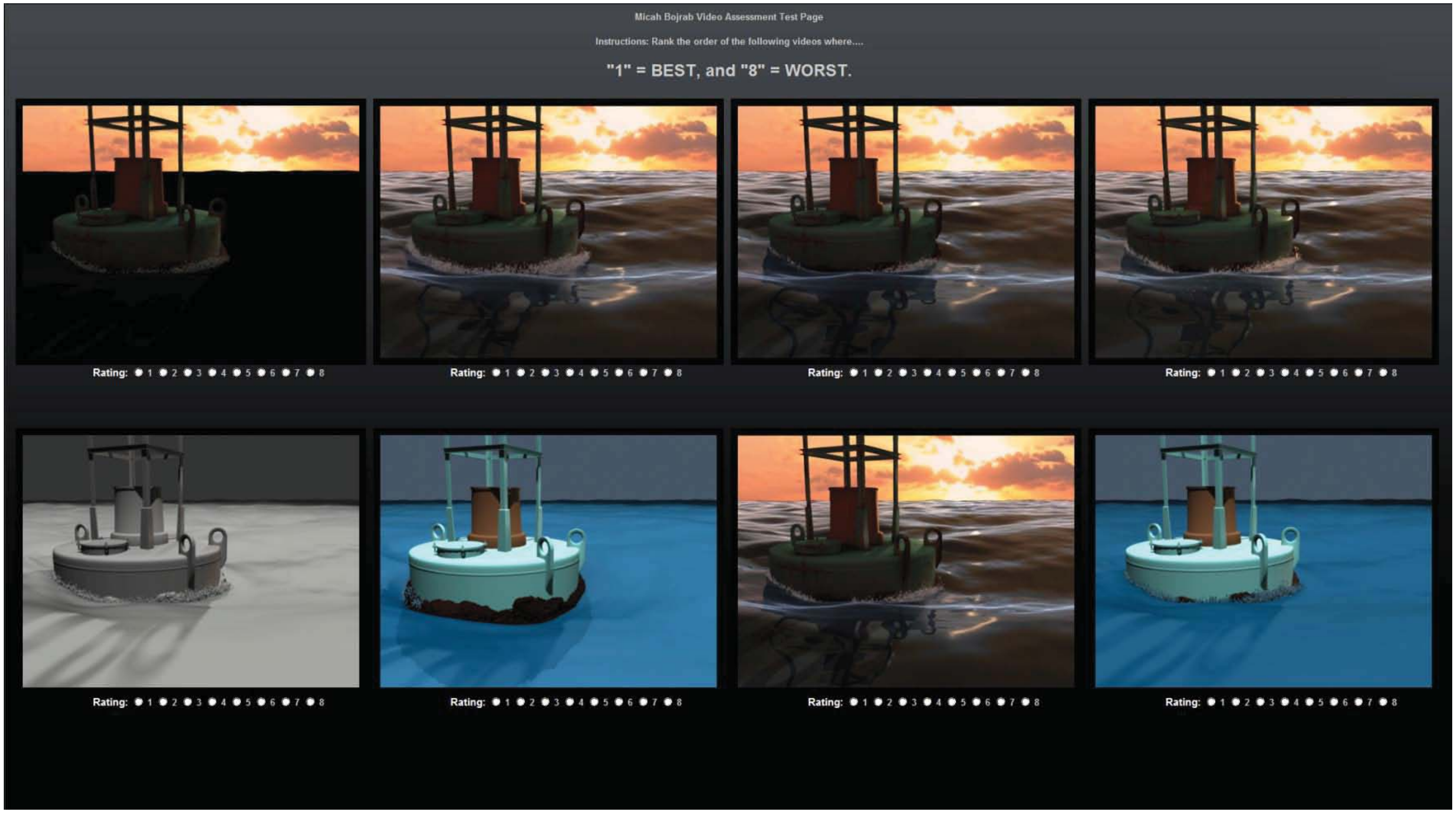

Figure A.4 Sunset Buoy Scene: Layout

Figure A.5 Rainy Lake Scene: Layout