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## Tone Reproduction in Virtual Reality

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**Tone Reproduction in  
Virtual Reality**

by

**Antara Mishra**

A Thesis Submitted

in

Partial Fulfillment of the  
Requirements for the Degree of  
Master of Science

in

Computer Science

Supervised by

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Rochester, New York

December 2018

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# **Abstract**

## **Tone Reproduction in Virtual Reality**

**Antara Mishra**

**Supervising Professor: Joe Geigel**

High dynamic range imaging has become very popular over the years in the field of computer graphics and games. The process of tone reproduction compresses the dynamic range of brightness in a scene to the lower range of display devices, thus making it an essential process in the graphics rendering pipeline. Various tone mapping operators have been tested for static viewing conditions. However, perceptual and temporal adaptation may vary for immersive viewing in a Virtual Reality environment. This thesis implements Ward et al. model (1994), Ward et al. model, Histogram Adjustment (1997) and Irawan, Ferwerda and Marschner model (2005) for static and immersive inputs. Faculty and students from the college took part in a personal survey to rate the tone mapped results based on their level of resemblance to real-life outdoor environments as well as the level of visibility in the lighter and darker regions. The proposed hypothesis states that immersion produces a measurable effect on our preference for a suitable tone reproduction model. This hypothesis is tested with the help of null hypothesis testing methods and some regression analysis on the data gathered from the survey.



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# 1 Introduction

In recent years, advancement in Virtual Reality (VR) technologies has led us to believe that VR has great potential in shaping up the future for many fields from Healthcare, Military, Business to Scientific Visualization and Research. We come across numerous solutions provided by VR for applications such as virtual theatres and museums, automobile design and medical diagnosis. Most virtual environments developed for these purposes are a result of one of the Global Illumination techniques, which produces scenes with luminance range in High Dynamic Range (HDR) that cannot be rendered on usual display devices. This creates the need for an appropriate tone reproduction model to map HDR computed scenes into low dynamic range (LDR) for display devices.

Tone reproduction has been extensively studied in the areas of film, animation, and games for rendering 2D environments, however not a lot of research has been done in applying these tone mapping operators to an immersive Virtual Reality environment. When viewing a scene in an immersive space, the surround effect can change our perception of a scene. This might alter the way human eyes adapt to the luminance values in the field of view. Furthermore, the pixels' luminance values change rapidly which may require performing a tone reproduction operation for each frame in real-time. This is usually not a requirement with tone reproduction for still images. Therefore, to find the role of immersion in choosing an appropriate tone mapping model three tone mapping operators are implemented and tested regarding the realism of the rendered scene in VR and rendering performance.

The following section explains the background and terminologies required to understand the tone reproduction process and its necessity in the graphics rendering pipeline along with the related work in this field followed by a description of the tone mapping operators implemented in this paper. Section 3 cites the hypothesis and Section 4 dives into the design and implementation details of the three operators in UNITY. Section 5 describes the survey response received in this study along with the statistical hypothesis testing process employed for data analysis. Section 6 lists down the experimental results and Section 7 provides a detail discussion on the results generated. Section 8 and 9 discuss the conclusions and future work for this study, respectively.

## 2 Background

### 2.1 HDR Imaging and Tone Reproduction

Luminance is defined as the amount of light energy emitted or reflected from a screen in a given direction. It is measured in candelas/m<sup>2</sup> (or nits). High Dynamic Range (HDR) imaging refers to the process of rendering a scene with the help of one of the Global Illumination methods (e.g. ray tracing, radiosity, photon mapping etc.) where luminance value for each pixel is calculated in a high dynamic range. A dynamic range is a ratio of a specified maximum level of a parameter such as power or frequency to the minimum detectable value of that parameter. In our case this parameter is luminance; the absolute scene luminance varies from  $10^{-6}$  –  $10^6$  nits in the real world. The devices used to display the rendering of the scenes have a low dynamic range (LDR) usually 0.1 to a few hundred nits. Therefore, tone reproduction is needed to constrict the HDR luminance values of a scene for it to be displayed on LDR display devices.

Tone reproduction is described as the process of compressing the dynamic range of a scene's luminance values so that it can be displayed on a given device in a such a way that minimizes the perceptual difference between viewing the scene and viewing the rendering of the scene. Tone Mapping Operators (TMOs) are used to perform the tone reproduction process. They try to map the large dynamic range of luminance values in the real world to a very small and restricted dynamic range of output display devices. Figure 2.1 provides an estimate of the degree of compression required to display HDR scenes on low range devices. The tone reproduction process occurs as a post-processing step in rendering a scene. A linear tone mapping of the luminance values will not suffice as the human response to light is neither simple nor linear. Furthermore, the response models of output display devices are not linear and improper response modeling might lead to an incorrect perception of results.

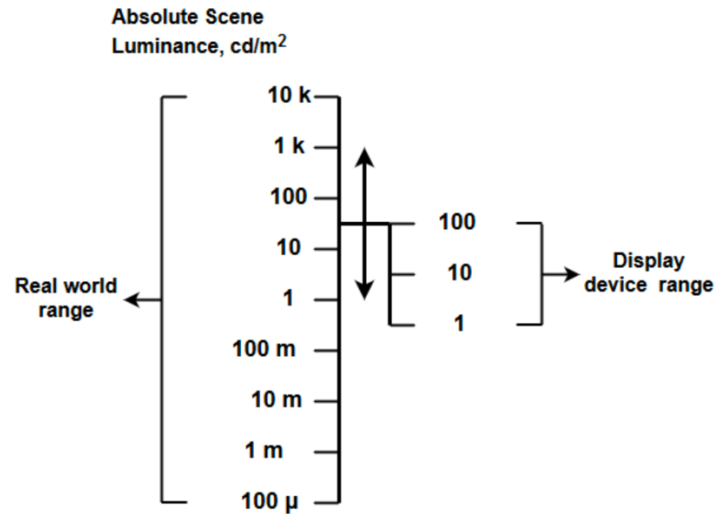


Figure 2.1 Order of luminous range of real world vs. display devices

## 2.2 Tone Reproduction for HDR scenes in VR

With the recent increase in the number of VR applications ranging from medical diagnosis to building real estate models, realistic rendering of the virtual environments has become essential. An appropriate tone reproduction model can help simulate human adaptation to the scene minimizing the perceptual difference between the real and created/virtual scene. The requirements for a suitable tone mapping operator for an immersive VR space can be different from non-immersive, static images. As discussed earlier, immersive viewing can lead to tone mapping operations for every frame which requires the computations to be in real-time [1]. In case of VR, the viewer is completely immersed in the space, blocking any light from the real world whereas in case of still images we have a real viewing environment which can affect our image perception. In case of non-immersive viewing, factors such as the surround effect where the surrounding colors of an area can lead to a different color perception and chromatic adaptation (when receptors adjust to stimulation levels) can cause variation in color appearance. For immersive inputs, temporal tone mapping becomes very essential. A good temporal adaptation model should produce smooth rendering per frame along with being consistent in terms of quality and performance.

## 2.3 Head-Mounted Display Devices

The result of the tone reproduction models in VR is tested on a Head-mounted display (HMD) device. They are often referred as VR headsets, their goal is to provide a stereoscopic vision using two small screens which provides an illusion of

a 3D world, large horizontal and vertical fields of vision corresponding to the visual field of the user and an immersion of the eyes [2]. It becomes very important to capture the movements in the peripheral vision accurately to ensure smooth immersive experience. The screens of the VR headsets can be of two types: LCDs (Liquid crystal display) or AMOLED/OLEDs (Active-matrix organic light-emitting diode and organic light-emitting diode respectively). They have a display luminance range of 0 to approximately 600 nits. Figure 2.2 displays the Oculus Rift DK2 headset and sensor used for this study.



Figure 2.2 Oculus Rift DK2 headset and sensor

## 2.4 Related Work

Many tone mapping operators have been developed and tested over the years for static images. They can be categorized as global, where global algorithms map the entire scene using the same function as in Ward's model from 1994 [3] and local where local adaptation is considered which may lead to the irregular mapping of neighboring pixels, as in Pattanaik's operator from 1998 [4]. Rahman's operator from 1996 [5] was based on Retinex Theory which tries to imitate visual sensitivity to lightness. Reinhard's model from 2002 was based on photography and his model from 2005 tried to simulate the photobiology of retinal sensors. Other operators include dynamic operators developed by Pattanaik et al. in 2000; Durand and Dorsey in 2000 and Irawan and Marschner in 2005 which model the temporal visual adaptation. Choudhary and Tumblin in 2003 [6] was an improvement of Durand's model from 2002 which used tri-lateral filters as compared in bi-lateral filters in the original model. This helped improve the quality of tone reproduction.

Some of the tone mapping operators were implemented and compared for HDR photographs of urban environments at night [7]. Rahman (1996), Irawan and Marschner (2005) and Choudhary and Tumblin (2003) were ranked the best operators, followed by Wards (1997) and Durand and Dorsey (2002); Reinhard's models and Wards (1994) were the last ones based on the similarity between the

physical scene and tone mapped images. A previous study involved testing the TMOs for HDR videos recorded from immersive experiences in a nighttime VR environment. The subjects were asked to rank the operators based on their experience in an urban environment at night. Irawan et al.'s model performed the best among other operators. Reinhard's 2005 gave reasonable results along with Ward et al. (1997), Rahman et al. (1996) and Durand and Dorsey (2002). Ward et al. model from 1997 performed better in tone mapping HDR videos as compared to still images which indicates that dynamic conditions may have different requirements for tone reproduction.

The study in this paper focusses on finding the effect of immersion in building a preference for a suitable tone reproduction model in a VR environment. The work involves comparing tone mapped results obtained for immersive and non-immersive conditions and learn about the consequences of different viewing conditions.

## 2.5 Tone Mapping Operators

A functional description of the three tone mapping operators implemented in this thesis is presented in the following subsections.

### 2.5.1 Ward et al. from Graphics Gems IV, 1994

This is a heuristic model based on perceptual tests which also includes some visual adaptation [3]. The first step is to calculate the absolute luminance value at each pixel, given its RGB illuminance values in HDR. This is done with the help of the formula {1}:

$$L(x, y) = 0.27R(x, y) + 0.67G(x, y) + 0.06B(x, y)$$

based on the CRT color space. Absolute luminance is a scalar value which represents the luminance (L) at each pixel and is helpful as tone reproduction models operate in luminances.

The compression model of this operator defines a scaling factor for each pixel's luminance value and scale it down to a range of zero to the maximum display luminance of the display device. The scaling factor (sf) is generated based on the values of the lighting range (Lmax) and adaptation luminance (Lwa) of the scene. It is calculated as {2}:

$$sf = \left( \frac{1.219 + (Lmax / 2)^{0.4}}{1.219 + Lwa^{0.4}} \right)^{2.5}$$



The log average luminance value is used as the adaptation luminance ( $L_{wa}$ ) used earlier to compute the scaling factor. The value of  $L_{wa}$  for a pixel is calculated with the help of luminance values of the four surrounding pixels; their coordinates are calculated by adding discrete 4D vertex coordinates to the input pixel coordinates. A small float value called delta, ( $\delta = 0.0001$ ) is added to the luminance values to avoid computing value of  $\log(0)$  which can be the case when a pixel's overall luminance value is zero. To compute the average luminance value, a log average is taken of the luminance values of the four pixels. The final log average luminance value is calculated by taking the exponent value of the average luminance. The formula looks like this {3}:

$$L_{wa} = \exp\left(\frac{1}{N} \sum \ln(\delta + L(x, y))\right)$$

where  $N$  is the total number of pixels considered while calculating the log average luminance value.

The target RGB color is obtained by multiplying the scaling factor of the pixel with its RGB irradiance values. The last step is to apply the device model, which is achieved by scaling the target image by the maximum display luminance of the device. Here, the display device is assumed to have a maximum output equal to the maximum display luminance with a gamma of 1 and standard sRGB color space. The result of this step is the display color of the pixel returned by the compute shader and later rendered on the main camera. The tone reproduction process can be summarized in Figure 2.3 summarizes the steps involved in the tone mapping process discussed above.

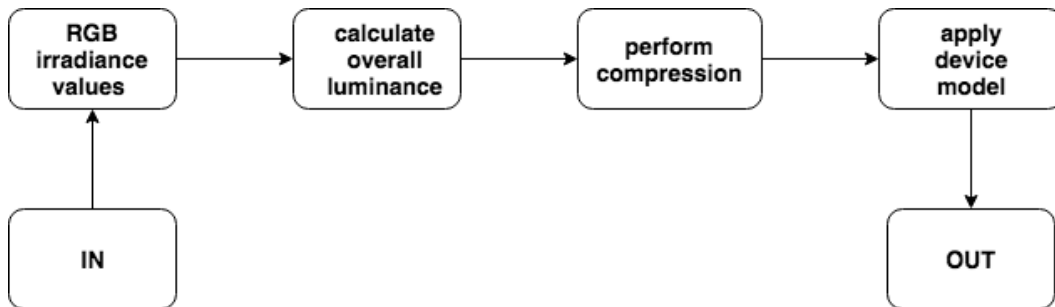


Figure 2.3 Flow diagram for Ward et al. 1994 model

### 2.5.2 Ward et al., 1997

This model is commonly referred as the Histogram Adjustment technique and it draws on the fact that luminance levels occur in clusters when projected as a

histogram [8]. Mapping a large range of sparsely populated luminance levels to a large range of display values would not be very helpful as the eye is only sensitive to the relative difference in luminance values of bright and dark areas. Therefore, this operator modifies the histogram based on cumulative distribution and fills the gaps between the display values of the high and low luminance regions. This allows us to work with a larger number of display luminance values to render a scene. The model tries to reproduce human visibility without any kind of feature loss and provides a model to incorporate human contrast sensitivity, space acuity, glare and color sensitivity.

The first step includes building a histogram to represent the population of luminance levels in the scene and a cumulative distribution of these values. The logarithmic value of luminance is used to approximate the subjective response associated with the world luminance values and build the histogram. Since human eye adapts to a view of 1 degree in the fovea, the image is filtered into pixel blocks which correspond to 1-degree squares in the visual field. The width/height ( $S$ ) of the pixel is given by {4}:

$$S = \frac{2 \tan(\frac{\theta}{2})}{0.01745}$$

where  $\theta$  is the view angle and 0.01745 is the number of radians in 1 degree. The log luminance values are distributed in equal sized bins. The cumulative distribution provides a mapping that counts the cumulative number of observations in all the bins up to a specified bin  $b$ , it is calculated as {5}:

$$P(b) = \frac{\sum_{b_i < b} f(b_i)}{T}$$

here  $f(b_i)$  is the frequency count for histogram bin at  $b_i$  and  $T$  equals to  $\sum_{b_i} f(b_i)$  i.e. the total number of samples. The derivative of the cumulative distribution represents the histogram with an appropriate normalization factor. It is calculated as {6}:

$$\frac{dP(b)}{db} = \frac{f(b)}{T \Delta b}$$

where  $\Delta b = \frac{[\log(L_{wmax}) - \log(L_{wmin})]}{N}$  which is the size of the bin in the histogram. The first effort in performing histogram equalization was based on the formula {7}:

$$\log(L_d(x, y)) = \log(L_{dmin}) + [\log(L_{dmax}) - \log(L_{dmin})] \cdot P(\log(L_w(x, y)))$$

where  $L_d$  is the compressed luminance value of the pixel,  $L_{dmin}$  is the minimum display luminance value and  $\log(L_{dmax}) - \log(L_{dmin})$  represents the display range

of the device.  $L_w$  is the world luminance value in a high dynamic range. Unfortunately, this model ended up exaggerating contrast in the highly populated areas of the histogram. To overcome this, a ceiling was applied to the values in the histogram. At first, a linear ceiling was proposed which was written as {8}:

$$\frac{dL_d}{dL_w} \leq \frac{L_d}{L_w}$$

which implies that the derivative of the display luminance with respect to world luminance should not exceed the display luminance divided by the world luminance. The derivative of display luminance can be obtained by taking the differentiation of exponentiation of equation {7} using the chain rule and take the derivative of equation {6} which gives us a constant ceiling on  $f(b)$  represented as {9}:

$$f(b) \leq \frac{T \Delta b}{\log(L_{dmax}) - \log(L_{dmin})}$$

This step ensures that if no frequency count exceeds the ceiling value, the histogram adjustment process will not exaggerate contrasts in the populated regions.

This model incorporates human contrast sensitivity by using a detection threshold function to define the relationship between adaptation luminance and minimum detectable luminance. This function is used to control the maximum reproduced contrast and is defined as {10}:

$$\Delta L_t(L_a) = \text{just noticeable difference for adaptation level } L_a$$

To account for the fact that human contrast sensitivity is worse in low illumination than high illumination, the slope of the operator is constrained to the ratio of the adaptation thresholds of display and world luminance values respectively. This looks like {11}:

$$\frac{dL_d}{dL_w} \leq \frac{\Delta L_t(L_d)}{\Delta L_t(L_w)}$$

After computing the derivative of the histogram equalization function from equation {7} the new value of ceiling is calculated as {12}:

$$f(\log(L_w)) \leq \frac{\Delta L_t(L_d)}{\Delta L_t(L_w)} \cdot \frac{T \Delta b L_w}{[\log(L_{dmax}) - \log(L_{dmin})] L_d}$$

The above calculate ceiling is applied to the frequency of bins in the histogram by truncating the larger counts at the ceiling and redistributing them to other histogram bins. This is an iterative process and runs until a tolerance criterion is

met which states that fewer than 2.5% of original samples should exceed the ceiling. Figure 2.4 represents a block diagram listing the steps in this tone reproduction model.

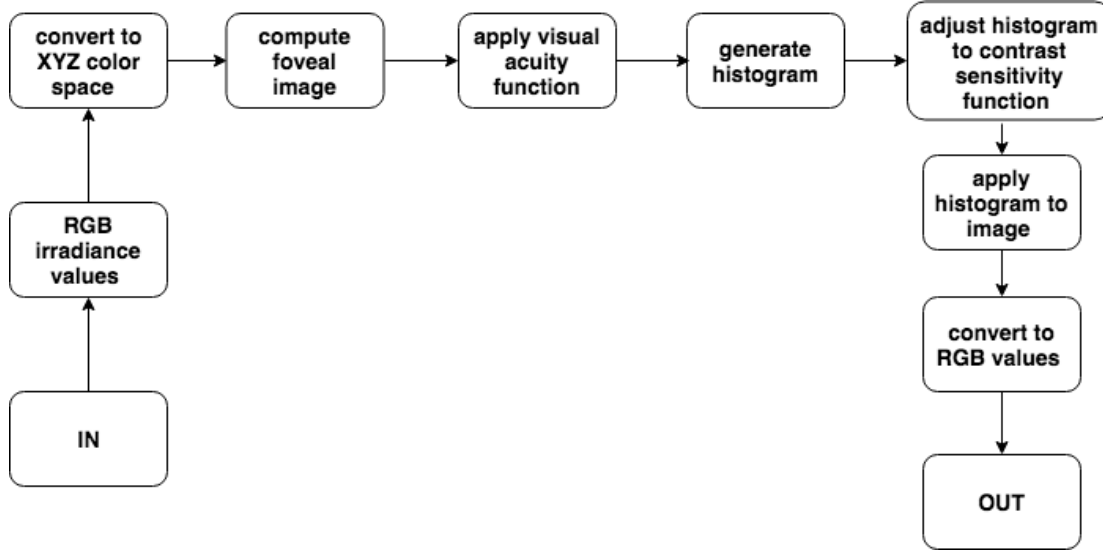


Figure 2.4 Flow diagram for Ward et al. 1997 model

### 2.5.3 Irawan, Ferwerda and Marschner, 2005

This is a perceptually based tone mapping operator which does some modifications to the Histogram Adjustment technique and proposes a new generalized threshold versus intensity (TVI) model responsible for providing thresholds for any combination of a luminance level and adaptation state [9]. Using equation {6} and {12}, the ceiling relation for Ward et al. 1997 model can be rephrased as {13}:

$$f(b_i) \leq \frac{T}{N} \cdot \frac{\log(L_{wmax}) - \log(L_{wmin})}{\log(L_{dmax}) - \log(L_{dmin})} \cdot \frac{\Delta L_t(L_{d_i})/L_{d_i}}{\Delta L_t(L_{w_i})/L_{w_i}}$$

Unlike Ward's iterative approach to applying this constraint and simply truncating the histogram, this operator redistributes the counts that exceed the ceiling by keeping track of all the truncated counts and reallocating the counts to the other bins, keeping the limit to the ceiling. For this to work, the sum of all the ceilings should be greater than or equal to the total number of samples, which gives rise to the following relation {14}:

$$\sum_{i=1}^N \frac{T}{N} \cdot \frac{\log(L_{wmax}) - \log(L_{wmin})}{\log(L_{dmax}) - \log(L_{dmin})} \cdot \frac{\Delta L_t(L_{d_i})/L_{d_i}}{\Delta L_t(L_{w_i})/L_{w_i}} \geq T$$

The TVI function used by Ward et al. in 1997 to define luminance threshold function is given by equation {10}. This operator expands the function by adding a new variable to model the adaptation state and denote it as  $\Delta L(L, \sigma(L_a))$ .  $\sigma(L_a)$  represents the adaptation state reached when the eye is fully adapted to  $L_a$ . This operator takes help of the visual response model to come up with a threshold. The following equation describes the response of retinal photoreceptors {15}:

$$R(L, \sigma(L_a)) = \frac{L^n}{L^n + \sigma(L_a)^n}$$

$\Delta R$  is defined as the criterion response required to produce a just noticeable difference (JND). Therefore, adding  $\Delta L(L, \sigma(L_a))$  to  $L$  will result in increasing the retinal response by  $\Delta R$ . This can be written as {16}:

$$R(L, \sigma(L_a)) + \Delta R = \frac{(L + \Delta L(L, \sigma(L_a)))^n}{(L + \Delta L(L, \sigma(L_a)))^n + \sigma(L_a)^n}$$

This model accounts for temporal adaptation over time by generating the adaptation state  $\sigma$  for each frame. Values for  $n$  between 0.7 and 1 have been reported in the literature. [13] It represents the response exponent value. A value of 0.9 has been used in this paper after some fine tuning to produce optimum results. The adaptation state is controlled by photoreceptor bleaching, slow neural adaptation and fast neural adaptation that is why the steady state function  $\sigma(L_a)$  is written as the product of three different terms representing adaptation due to each phenomenon as {17}:

$$\sigma(L_a) = \sigma_b(L_a) \cdot \sigma_c(L_a) \cdot \sigma_n(L_a)$$

where  $\sigma_b(L_a)$  is adaptation due to photopigment bleaching,  $\sigma_c(L_a)$  and  $\sigma_n(L_a)$  are due to slow and fast neural adaptation respectively.  $\sigma_b(L_a)$  can be measured as {18}:

$$\sigma_b(L_a) = \frac{1}{p(L_a)}$$

where  $p(L_a)$  denotes the fraction of unbleached pigment for a viewer that is fully adapted to  $L_a$ . The slow and fast neural adaptation states are computed separately for the rods and cones in the human visual system. The exponential decay function to model the time course of pigment depletion and regeneration is provided by equation {19}:

$$p = p(L_a) + (p_0 - p(L_a)) * e^{\frac{-t}{t_0 * p(L_a)}}$$

where  $t$  is the the time in seconds since the luminance changed from  $L_0$  to  $L_a$  and the portion of unbleached pigment was  $p_0$ . The function to simulate neural adaptation over time, Irawan et al. use the following {20}:

$$L = L_a + (L_0 - L_a) * e^{\frac{-t}{t_0}}$$

Figure 2.5 provides a flow diagram for this operator for better understanding.

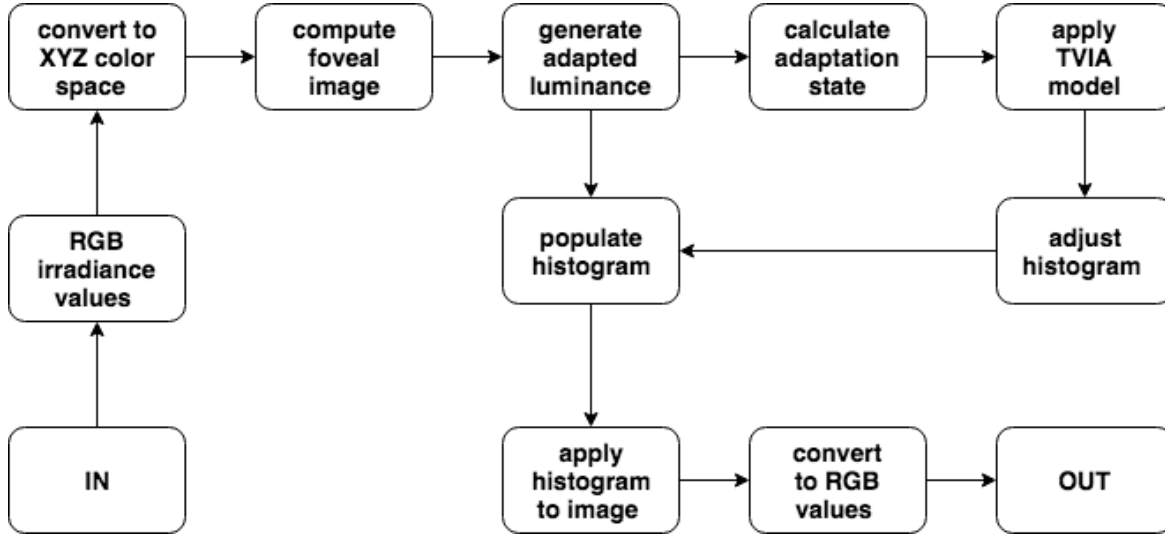


Figure 2.5 Flow diagram for Irawan et al. 2005 model

### 3 Hypothesis

The hypothesis of this thesis states that immersion plays a significant role in altering the preference for an appropriate tone reproduction model for scenes in virtual reality. In case of immersive viewing, the surround effect can change our perception of the scene. Tone reproduction models that are suitable for static HDR images may not be appropriate for immersive scenes in VR.

## **4 Design and Implementation**

### **4.1 Unity Game Engine**

The goal of this paper is to implement three tone mapping operators for static and virtual inputs and to be able to compare the results. A game engine provides the capability to produce high-quality renderings in real-time on a wide range of hardware. The UNITY game engine was chosen for this work as it can render HDR scenes rather seamlessly and has comprehensive documentation available on the internet. Moreover, UNITY comes with the feature to develop custom shader code in HLSL which brings us to our next discussion on the benefits of Compute Shaders.

### **4.2 GPU and Compute Shaders**

The tone mapping algorithms discussed in this paper involve calculations with a higher order of complexity and would require a parallel computing architecture to render the results in real time. The Graphics Processing Unit (GPU) provides the capability to perform parallel programming but to make the process even faster Compute shaders are used. These types of shaders can utilize the GPU for its calculations and are independent of the graphics rendering pipeline. A shader consists of one or more functions called kernels which are designed to carry out mathematical computations.

The GPU consists of processing units known as streaming multiprocessors (SM) which run in parallel. These multiprocessors can run multiple instances of a kernel; these instances are called threads, and they are processed in groups. The GPU hardware provides a limit to the number of threads in a group to accommodate the thread groups in the multiprocessors [11].

### **4.3 Setting up the scene**

Two HDR scenes were selected for this study with different lighting conditions. They depicted outdoor environments on a bright sunny day and during the night. Figure 4.1 and 4.2 show the HDR images used to build the virtual environments in this paper.



Figure 4.1 Daytime HDR scene



Figure 4.2 Nighttime HDR scene

The HDR scenes have the .hdr format and are imported as an asset in UNITY. They are converted to cube texture shape to create a skybox material. Figure 4.3 displays the details of this asset.



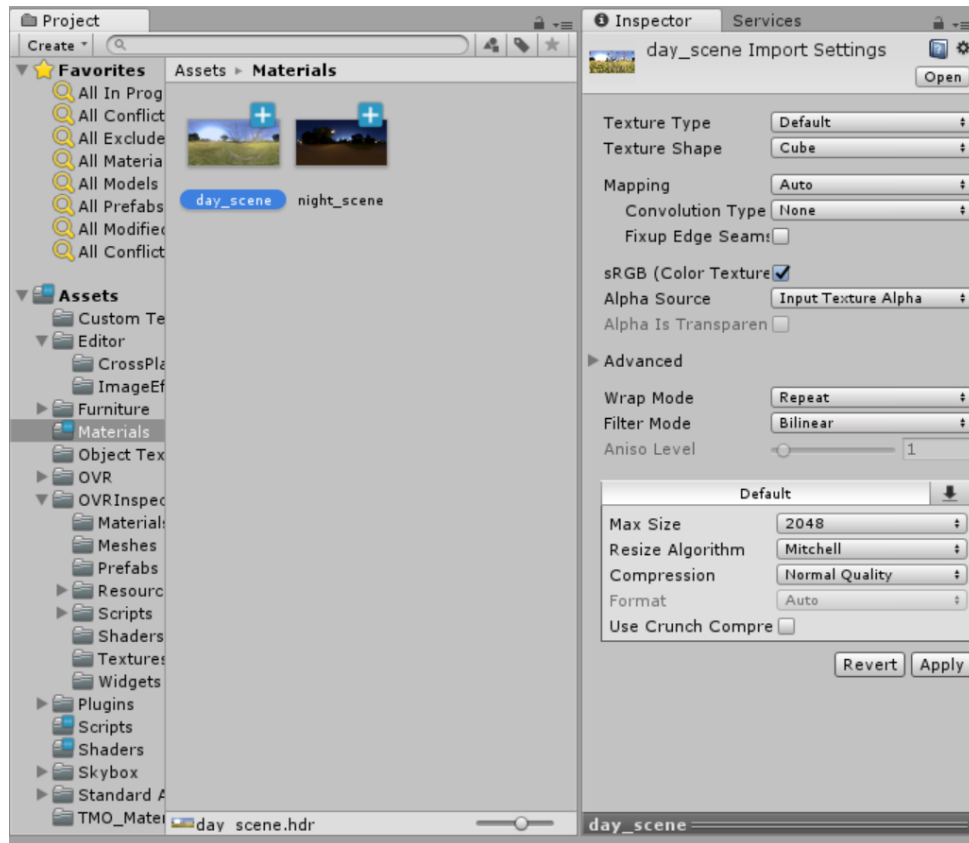


Figure 4.3 .hdr file imported as cubemap texture asset in Unity

Next step is to create a new Skybox material of type cubemap and use the cubemap asset created above to generate the material. Figure 4.4 shows the details of the skybox material.

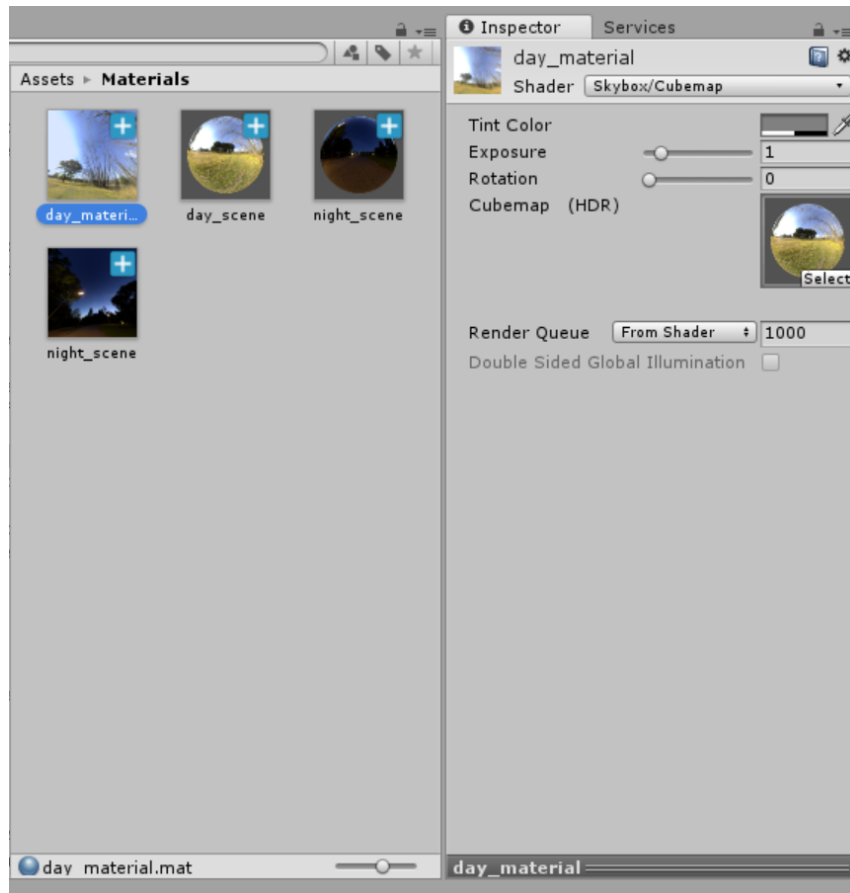


Figure 4.4 Skybox material built using the cubemap texture

As the last step the skybox material is applied to the lighting of the scene in UNITY. This option can be found under the Environment section. The skybox created in the previous step is used as the Skybox Material to create the virtual environment. Figure 4.5 provides the details of this step.

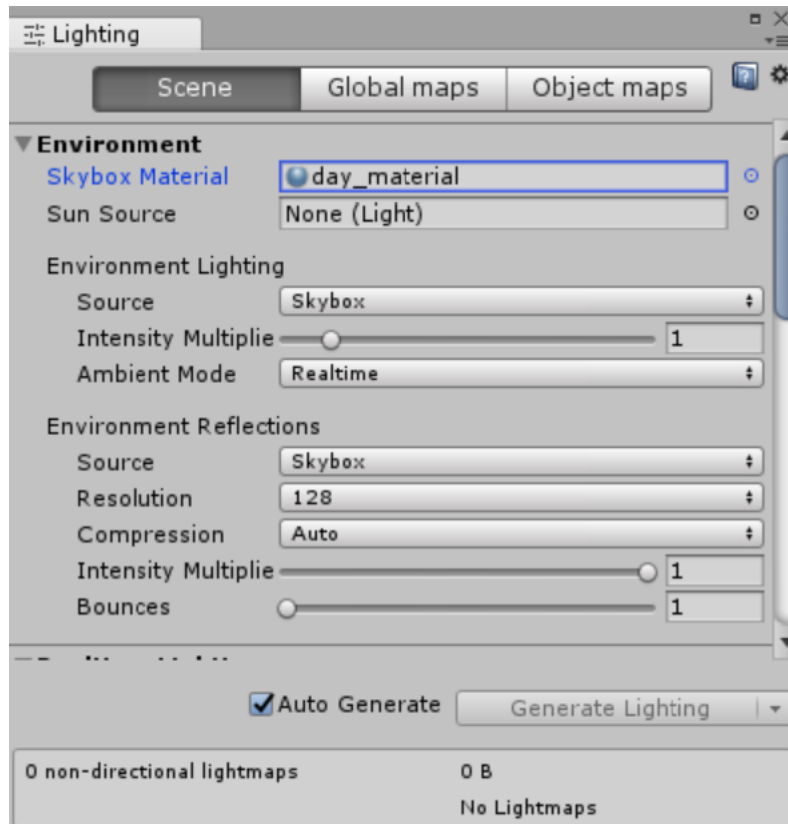


Figure 4.5 Daytime skybox used under the scene lighting

## 4.4 Implementation details

The tone mapping operators are applied to the HDR scene with the help of C# scripts in UNITY. There are three scripts in this project one for each operator. These scripts are attached to the main camera one at a time. The camera used in this study is the OVRCameraRig game object in UNITY and the scripts are attached to the center eye anchor of the camera's tracking space. They contain the logic portion of the operator and are executed on the CPU. For all the time-consuming mathematical calculations, the GPU is utilized with the help of Compute Shaders. They are written in the HLSL language and are of the format .compute. They are attached to the Tone Mapper script section in UNITY and are invoked from the C# script. This relationship between the script and shader can be visualized with the help of Figure 4.6.

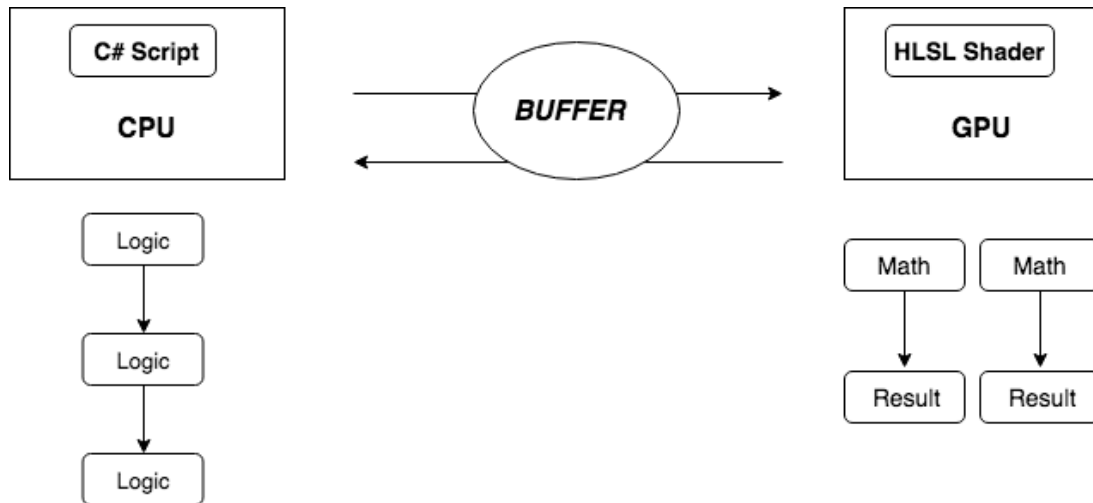


Figure 4.6 Data flow and execution architecture

The tone mapping script begins with defining the parameters with pre-defined values. These parameters include constants and minimum and maximum display luminance value to name a few. They are editable in the UNITY Editor GUI to test various effects. The scripts use the PostEffectBase utility class from the standard assets to build image post-processing effects. The OnRenderImage function is called with two texture parameters, one for the source image and one for the tone reproduced image. As these scripts are attached to the main camera in the scene, the resultant tone reproduced image is rendered on the display device.

The C# script executes a compute shader by creating an object of the ComputeShader class made available by UNITY. The luminance and chrominance values of each pixel in the source image is set as a texture in the computer shader object along with other parameters like the width and height of the source image. The buffer used to transfer data from the CPU to the GPU and vice versa is the ComputeBuffer. A ComputeBuffer is initialized by providing the number of elements in the buffer and size of each element in the buffer.

A compute shader consists of functions that carry out mathematical calculations. They are called kernels. Compute shaders are executed by calling the Dispatch method in the ComputeShader class. The first argument of this method is the kernel index of the function to be executed in the shader file. The functions defined in the shader are listed at the start of the file using the #pragma section. The kernel index directly correlates with the order in which the functions are defined under in this section. The next three arguments are the number of threads to be initiated in the x, y and z dimension which were chosen as 32, 32 and 1 respectively for this experiment [10].

The compute shaders used in this thesis used multiple kernels to perform complex computations. The first kernel performs color space conversion for RGB to XYZ color space. This step involves matrix multiplications and calculations for every pixel in the source image. The second kernel reduces the input image to a foveal image using a parallel add-reduce algorithm. The third kernel is responsible for creating the histogram based on the minimum and maximum luminance values. The values in the histogram bins are interpolated linearly to a range of [0,1]. This kernel also converts the tone mapped luminance values to RGB color space using the standard conversion matrix.

The computer shaders use the `RWStructuredBuffer` to store the data received from the CPU. As multiple threads try to read and modify the data in the texture and buffer objects at a time, memory synchronization becomes very critical. This is achieved using the `GroupMemoryBarrierWithGroupSync` method.

After the shader code is executed, data is read from the buffer using the `GetData` method into arrays in the C# script. The destination texture returned by the last kernel executed is passed to the `Graphics.Blit` method and is rendered on the main camera.

## 5 Experiments

### 5.1 User experiment

An IRB approved in-person survey was conducted to showcase the results of this thesis and gather data to conclude. The first step was to perform an Ishihara color blindness test. The Ishihara's Tests for Color Blindness book [12] was used for this purpose. This book contains colorful circular images with a number at the center. Subjects were asked to identify the hidden number within 5 seconds for each image. Figure 5.1 shows one the images used for the color blindness test. Failure to recognize the number in the image would imply color blindness in the participant. None of the subjects were tested color blind during this study.

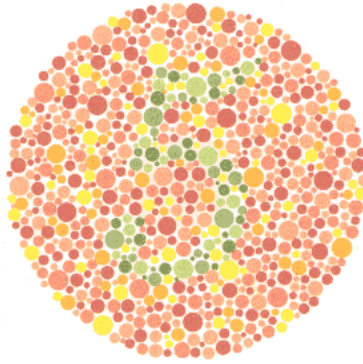


Figure 5.1 Plate 10 from Ishihara color blindness test

The study required subjects to enter their responses on a tablet device. The first section contained questions about the subject's age group, their level of understanding of the tone reproduction process, and their years of experience building virtual reality applications. These questions were presented in the form of multiple-choice questions with predefined answer options to avoid any confusion. The second section of the survey required the subjects to rate the tone mapped results in static and immersive viewing conditions. Participants were provided with clear instructions at each step to prevent unwanted bias and ambiguity. They were informed about the nature of the scenes beforehand and were asked to enter their responses accordingly.

The static tone mapped results were displayed on a Dell E2417H monitor covering the entire screen region. Subjects wore the Oculus Rift DK2 VR headset in experiencing the immersive scenes. They were given a few minutes to adapt the immersive environment and to orient themselves based on a few landmarks in the scene. The participants were encouraged to rotate freely in the immersive space and locate the bright and dark regions in the environment. I entered the scores for the results in the immersive viewing condition for the subjects' comfort and to keep them adapted to the virtual space. The tone reproduced results were rated against three parameters, their overall resemblance to an outdoor day or night scene and the level of visibility in the lighter and darker regions. A scale of 1-5 was used to collect the scores. Figure 5.2 to 5.7 show the tone reproduced results used in the survey.



Figure 5.2 Daytime tone mapped result using Ward et al. 1994



Figure 5.3 Daytime tone mapped result using Ward et al. 1997



Figure 5.4 Daytime tone mapped result using Irawan et al. 2005





Figure 5.5 Nighttime tone mapped result using Ward et al. 1994



Figure 5.6 Nighttime tone mapped result using Ward et al. 1997



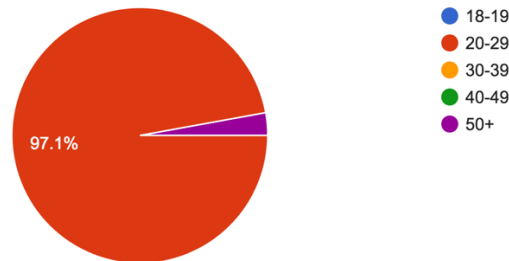
Figure 5.7 Nighttime tone mapped result using Irawan et al. 2005



A total of 35 participants took part in the survey. This survey was conducted in one of the labs in the Computer Science department. Based on the data obtained from the demographic section of the study, around 95 percent of the subjects had limited or no knowledge in the fields of tone reproduction and virtual reality development. When asked about how often they engage with VR applications, around 22 percent responded with more than once a month whereas 35 percent answered they had never experienced a virtual environment before this experiment. Figure 5.8 provides a detailed breakdown of the response gathered from the survey. A copy of the Tone Reproduction survey is provided in Appendix section C.

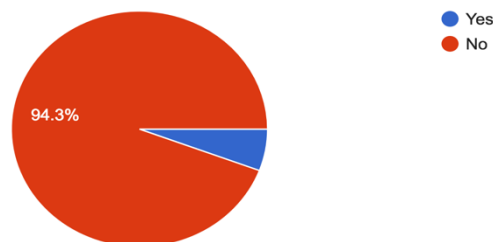
1. What is your age group?

35 responses



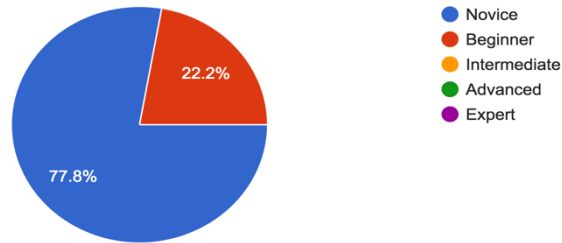
2. Do you have any expertise in the field of Tone Reproduction for High Dynamic Range Imaging?

35 responses



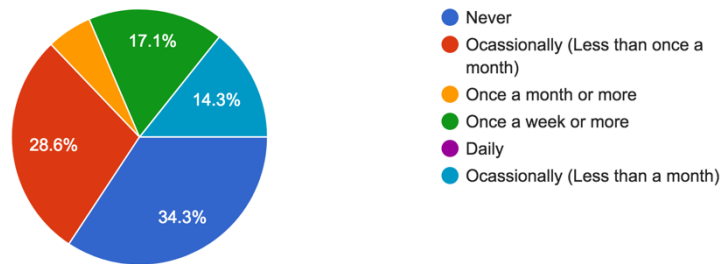
3. If yes to the previous question, please state your level of expertise in the field.

9 responses



4. How often do you engage with Virtual Reality applications?

35 responses



5. Do you have any experience in building Virtual Reality applications?

35 responses

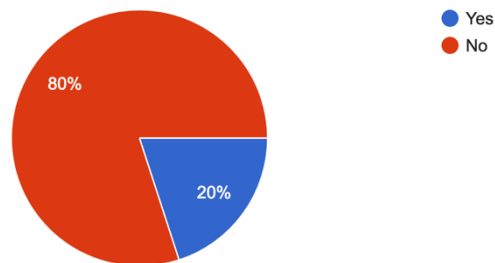


Figure 5.8 Breakdown of survey response from the demographic section

## 5.2 Statistical hypothesis testing

The approach used to test the hypothesis started by dividing the results for the day and nighttime scenes. The effect of varying lighting conditions in both environments can create a different impact on the preference for a particular tone reproduction operator. The results for the two environments were further divided based on the type of input or viewing condition, static and VR to perform null hypothesis testing. For our study, the null hypothesis states that immersion does not affect our choice for tone reproduction. Conversely, the alternative hypothesis implies that there is a measurable effect of immersion on our preference.

The scores obtained from the survey were normalized to perform regression analysis. A correlation factor was calculated between the scores for the overall resemblance, visibility in bright and dark regions. The correlation factor was positive for both the scenes and viewing conditions. Therefore, a combined weighted score was calculated from the three individual scores with a weight of 1 assigned to the resemblance score and 0.5 each attached to the visibility score. We had data from 12 different scenarios originating from three operators, two scenes and two types of viewing conditions. The VR and static scores of each TMO were compared against one another to test the hypothesis.

Initial statistical analysis provided us with measures like the mean, standard deviation, median, and mode. A significance criterion (or probability value,  $p$ ) of 0.05 was accepted for all the experiments in this study. The static and VR mean scores were used to perform t-test and z-test. These tests were used to determine if the mean scores for static inputs differed significantly from the mean scores received for VR inputs. They were two-sample tests representing the two populations (static and VR viewing condition). A two-tail analysis was performed to analyze the correlation in both directions which helped us examine the null and alternative hypotheses. Furthermore, a regression analysis was conducted to find out the correlation factor and plot the regression line using the static and VR mean scores.

## 6 Results

For analysis purpose, Ward et al. 1994 would be referred to as TMO1, Ward et al. 1997 as TMO 2 and Irawan et al. 2005 as TMO 3 in the statistical results and later discussions. Figure 6.1 summarizes the statistical values obtained after performing hypothesis testing and regression analysis. The  $p$ -value is the probability that the results from the data occurred by chance. In the case of the t-test and z-test, a rejection range is defined based on  $\pm$  critical value, and if the absolute t-stat or z-

stat falls in this range, the null hypothesis is rejected. The multiple R and R squared values signify how close the data points are to the fitted regression line. A larger R squared value would mean the static and VR scores have a higher correlation.

MEASURES		DAY			NIGHT		
		TMO1	TMO2	TMO3	TMO1	TMO2	TMO3
Mean	Static Mean Score	0.716	0.376	0.818	0.853	0.361	0.724
	VR Mean Score	0.803	0.52	0.814	0.818	0.604	0.706
t-test	p-value	0.0007	0.0003	0.814	0.111	9.4578E-09	0.514
	t-stat	-3.709	-4.072	0.238	1.634	-7.536	0.659
	t-critical value	2.032	2.032	0.813	2.032	2.032	2.032
z-test	p-value	0.003	0.0001	0.877	0.208	1.0509E-07	0.612
	z-stat	-2.976	-3.884	0.154	1.258	-5.318	0.507
	z-critical value	1.96	1.96	1.96	1.96	1.96	1.96
Regression	p-value	2.863E-06	8.9986E-08	0.55	0.0001	1.0154E-07	0.0004
	Multiple R	0.45	0.102	0.684	0.439	0.504	0.422
	R Squared	0.202	0.0103	0.468	0.193	0.254	0.178

Figure 6.1 Results from hypothesis testing and regression analysis

Figure 6.2 and 6.3 plot the regression trendlines for the three operators with static mean scores on the x-axis, and VR mean scores on the y-axis.

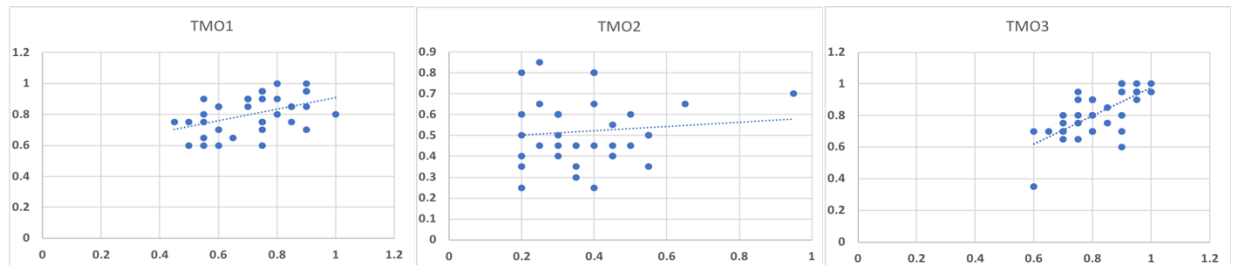


Figure 6.2 Regression plots for daytime scene

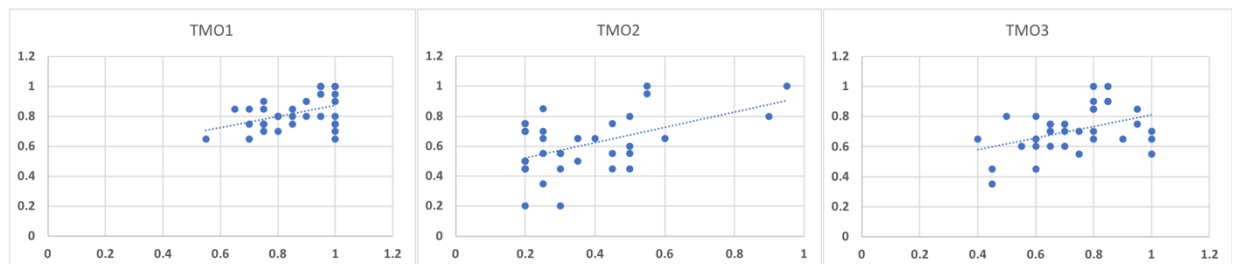


Figure 6.3 Regression plots for nighttime scene

## 7 Discussion

The statistical conclusions for daytime and nighttime environments were found to be moderately inconsistent. This might indicate that our preference in tone reproduction varies for different kind of scenes and lighting conditions. Therefore, the day and nighttime results are discussed separately for each tone mapping operator.

For the daytime scene, the null hypothesis was rejected for TMO1 and TMO2 after analyzing the scores from t-test and z-test and the alternate hypothesis that there is a measurable difference is assumed to be true. The p-values for the operator was less than 0.05 for both tone mapping operators. However, in the case of TMO3, the p-values obtained from t-test and z-test were higher than the accepted value of 0.05; hence the null hypothesis that there is no difference in preference could not be rejected.

The R squared values used to plot the regression line were less than 0.21 for TMO1 and TMO2 which implies that there was a weak correlation between the static and VR mean scores. This could indicate that there was a significant difference in preference with variation in the viewing conditions. In the case of TMO3, the correlation was stronger between the mean scores with the R squared value equal to 0.46.

In the case of the nighttime scene, the t-stat and z-stat for TMO2 the p-value were 0.0003 and 0.001 respectively. Hence, the null hypothesis was rejected for TMO2. For TMO1 and TMO3, the p-values were higher than 0.005; therefore, the null hypothesis could not be rejected.

The regression results obtained for nighttime scene varied significantly from the daytime scene. We saw a higher correlation in the mean scores for TMO3 for the daytime environment, whereas the correlation factor dropped as we went from TMO1 to TMO3 for the nighttime setting. The relatively lower R-squared values can be interpreted being in favor of the null hypothesis. The variation in the conclusion is an interesting find keeping in mind that earlier hypothesis testing results indicated that there is not a significant difference in preference with changing viewing conditions.

TMO2 showed the largest difference in preference between static and immersive viewing conditions. We expect the modern tone mapping operators to perform comparably when used for static and immersive inputs. With the advancements in the field of virtual reality, it would be considered a great asset if tone mapping operators could produce seamless results in the VR world.

## 8 Conclusions and Future Work

We were not able to confirm the alternate hypothesis for TMO3, i.e., Irawan et al. 2005 for both the scenes. Based on the results, the null hypothesis that there is no difference in perception could not be rejected in this case. This can be explained as this model executes an additional step in the human visual adaptation process as compared to the other models. This step calculates a temporal adaptation state over time accounting the photoreceptor bleaching, slow neural adaptation, and fast neural adaptation. This extra measure along with numerous trim and redistribute histogram operations per frame led to a significant increase in computation time for this model. The virtual environments experienced a delay in rendering each frame. Despite this, participants related most to the daytime TMO3 result. Conversely, the nighttime result was rated far less in resemblance. The tone mapped pixels appeared brighter, with exposure around bright light sources in the scene.

In the case of TMO1, the null hypothesis was rejected for the day scene, and the alternate hypothesis that there is a difference in perception was accepted. The alternate hypothesis could not be confirmed for TMO1 in case of the night scene. TMO2 showed results in favor of the null hypothesis for both the scenes. These models account for moderate adaptation of the human visual system which might result in a variation in the appearance of the scene for different viewing conditions. They were faster to compute and had a smoother transition between frames in VR.

One of the most prominent outcomes from this study is the requirement for faster tone reproduction models, with low computational time as a result of maximum parallelization. The compute shaders helped parallelize most of the mathematical calculations however the logic to adjust the histogram based on the adaptation state had a high order of complexity. Since the tone mapping results are rendered in real time, it would make sense to use some memoization to avoid recalculations. This would help in decreasing the complexity order and hence the computational time.

The regression trendline between the static and VR mean scores varied with the scenes. This implies that the lighting conditions are critical and not all tone mapping models might be preferred for nighttime scenes even though they produced satisfactory results for a daytime scene. The change in preference indicates that a tone reproduction model needs to be customized for virtual scenes with different lighting conditions.

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# Appendix A

## User Manual

1. Download UNITY 5.6 to open and run the UNITY project.
2. An Oculus Rift DK2 is required to experience the tone mapped results in virtual reality.
3. To run the scene in UNITY, click the play button and put on the VR headset.
4. By default, the daytime skybox material is applied to the scene, to use the nighttime skybox go to Window > Lighting > Settings. Select the nighttime skybox from the available materials and apply it as the Skybox Material under the Environment section.
5. To create a new Skybox Material from a .hdr file, import the .hdr file as a new asset and change its texture to cube. Create a new skybox material of type cubemap and apply the cube texture created above. This material is ready to use now.
6. To attach a tone mapping model to the camera, go to the inspector of the centerEyeAnchor of the OVRCameraRig's tracking space and attach the script there.
7. To choose from existing scripts, select the script to be executed. At a time, you can run only one tone reproduction model.
8. To add a new tone reproduction model, create a new C# script and the corresponding shader under the Scripts/Shader folder. Attach this new script to the main camera and select it to run the new model.
9. The values of the input parameters used in the model can be modified and monitored using the UNITY GUI.
10. The main scene in UNITY can be modified by changing the position of the main camera, introducing new game objects or adding extra light sources to the scene.

## **Appendix B**

### **Unity assets and Code listings**

All the code and data from the survey can be found on the provided disk submitted with this thesis report. The folder “Mishra\_TRInVRThesis” contains the UNITY project needed to experience the tone mapped results in VR. The day and night skybox materials can be found in the “Assets” folder. The C# scripts and shaders can be found in the “Scripts” and “Shaders” folders.

The parent folder also consists of two spreadsheets representing the day and night time data. This spreadsheet contains the statistical analysis results as well as the regression plots for the three operators. A “Readme.txt” is provided for step by step instructions to modify and/or play the scene in UNITY.

# Appendix C

## Survey Form

### Tone Reproduction Survey

The purpose of this research is to find if immersion alters our preference for an appropriate tone reproduction model in virtual reality. The first part of the survey consists of a few demographics questions followed by questions asking you to rate images and VR scenes based on your perception of them. There is no right or wrong answer to this kind of questions you are encouraged to provide your honest opinion.

Your participation is completely voluntary. You may choose not to participate and you may withdraw at any time. If you choose not to participate or withdraw from the survey, you will not be penalized. There are no known risks or discomforts associated with this survey. Your responses will be kept strictly confidential, and the digital data will be stored in secure computer files after submission. To help protect your confidentiality, the survey will not contain information that will personally identify you. Your name and contact information will not be stored. Your responses will be used to help study tone reproduction operators for scenes in virtual reality.

If you have any questions at any time please feel free to ask them.

\* Required

### Electronic Consent

---

Clicking the "agree" button below indicates that:  
-you agree to the information above.  
-you voluntarily agree to participate in the study.  
-you are ~~at least~~ 18 years old.

#### 1. I agree to participate in the study \*

*Check all that apply.*

- ☐ agree  
☐ disagree

### PART A

Demographic questions.

#### 2. 1. What is your age group? \*

*Mark only one oval.*

- ☐ 18-19  
☐ 20-29  
☐ 30-39  
☐ 40-49  
☐ 50+ |

**3. 2. Do you have any expertise in the field of Tone Reproduction for High Dynamic Range Imaging? \***

*Mark only one oval.*

- ☐ Yes  
☐ No

**4. 3. If yes to the previous question, please state your level of expertise in the field.**

*Mark only one oval.*

- ☐ Novice  
☐ Beginner  
☐ Intermediate  
☐ Advanced  
☐ Expert

**5. 4. How often do you engage with Virtual Reality applications? \***

*Mark only one oval.*

- ☐ Never  
☐ Ocassionally (Less than once a month)  
☐ Once a month or more  
☐ Once a week or more  
☐ Daily

**6. 5. Do you have any experience in building Virtual Reality applications? \***

*Mark only one oval.*

- ☐ Yes  
☐ No

## **PART B**

Please turn towards the monitor and rate the day-time images.

**7. 1. Please rate on a scale of 1-5 (1 being the lowest), based on the amount of resemblance of this image to an outdoor environment on a bright sunny day: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**8. 2. Please rate the visibility in the brighter regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**9. 3. Please rate the visibility in the darker regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**10. 4. Please rate on a scale of 1-5 based on the amount of resemblance of this image to an outdoor environment on a bright sunny day: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**11. 5. Please rate the visibility in the brighter regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**12. 6. Please rate the visibility in the darker regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**13. 7. Please rate on a scale of 1-5 based on the amount of resemblance of this image to an outdoor environment on a bright sunny day: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**14. 8. Please rate the visibility in the brighter regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**15. 9. Please rate the visibility in the darker regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High



## PART C

Please turn towards the monitor and rate the night-time images.

- 16. 1. Please rate on a scale of 1-5 based on the amount of resemblance of this image to an outdoor environment at night: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

- 17. 2. Please rate the visibility in the brighter regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

- 18. 3. Please rate the visibility in the darker regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

- 19. 4. Please rate on a scale of 1-5 based on the amount of resemblance of this image to an outdoor environment at night: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

- 20. 5. Please rate the visibility in the brighter regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

- 21. 6. Please rate the visibility in the darker regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**22. 7. Please rate on a scale of 1-5 based on the amount of resemblance of this image to an outdoor environment at night: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**23. 8. Please rate the visibility in the brighter regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**24. 9. Please rate the visibility in the darker regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

## PART D

Please wear the VR device and rate the day-time environments.

**25. 1. Please rate on a scale of 1-5 based on the amount of resemblance of this virtual environment to an outdoor environment on a bright sunny day: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**26. 2. Please rate the visibility in the brighter regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**27. 3. Please rate the visibility in the darker regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**28. 4. Please rate on a scale of 1-5 based on the amount of resemblance of this virtual environment to an outdoor environment on a bright sunny day: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**29. 5. Please rate the visibility in the brighter regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**30. 6. Please rate the visibility in the darker regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**31. 7. Please rate on a scale of 1-5 based on the amount of resemblance of this virtual environment to an outdoor environment on a bright sunny day: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**32. 8. Please rate the visibility in the brighter regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**33. 9. Please rate the visibility in the darker regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

## **PART E**

Please wear the VR device and rate the night-time environments.



**34. 1. Please rate on a scale of 1-5 based on the amount of resemblance of this virtual environment to an outdoor environment at night: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**35. 2. Please rate the visibility in the brighter regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**36. 3. Please rate the visibility in the darker regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**37. 4. Please rate on a scale of 1-5 based on the amount of resemblance of this virtual environment to an outdoor environment at night: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**38. 5. Please rate the visibility in the brighter regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**39. 6. Please rate the visibility in the darker regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**40. 7. Please rate on a scale of 1-5 based on the amount of resemblance of this virtual environment to an outdoor environment at night: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**41. 8. Please rate the visibility in the brighter regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High

**42. 9. Please rate the visibility in the darker regions in the scene on a scale of 1-5: \***

*Mark only one oval.*

	1	2	3	4	5	
Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High