Bachelor Degree Project

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SIMULATING PERCEPTION

Perception based colours in virtual environments

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Rebecca Forsmark

Supervisor: Lissa Holloway-Attaway
Examiner: Stefan Ekman

Abstract

This research explores the differences between how game engine cameras and the human visual system (HVS) render colour. The study is motivated by a two part research question: will HVS colours or game camera colours be preferred when experiencing a virtual environment from a 1st-person perspective and how does light intensity relate to preference? While previous research defines perceptual processes which influence the interpretation of colour information this study advances the understanding of how these theories may be applied to 3D colour grading.

When evaluating the two colour modes with a combination of quantitative data and qualitative reflections it was possible to establish a correlation between preference and light intensity, in the sense that HVS colours were preferred in high illumination and camera colours in low. The findings implicate that in order to be well received the colours of a virtual environment need to be adjusted according to illumination.

Keywords: colour, colour grading, perception, human visual system, preference

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1 Introduction

Realism is dependent on perception. The degree of perceived realism depends on how a virtual environment replicates the sensory information received from experiencing a real environment. Thus the sense of a virtual reality is affected by how well the artificial world is able to simulate human visual perception. Digital environments differ from the real world in the sense that they are visualized through the use of a virtual camera and not through the use of the human visual system.

In order to simulate perception the virtual camera can be adjusted to interpret colour similarly to the way the human visual system does. The visual system capacity to see different shades of colour depends on the amount of light reaches the eye and therefore will the dark-adapted eye not see the same colours as the light-adapted. To be able to replicate perception one needs to have knowledge of how the visual system functions and how factors of human visual perception affect colour at different lighting conditions. This knowledge can then be used to create a global colour grade which alters the colour and contrast of the 3D-environment.

Even though colour adjustments can be made to replicate perception it doesn't mean that the modified colours will be preferred to the standard camera colours. To test this, the colour modes will be applied to two identical virtual 3d-evironments at four different levels of illumination in order to establish whether the adjusted colours have application value and if it is different depending on light intensity. A test group will then evaluate which colour mode is most preferred at each different level of illumination. To be able to separate aesthetical values from a sense of realism, the test group will also provide data on which colour mode is believed to correlate closest to a real experience. The test also distinguishes between people with different amount of experience playing digital games to explore whether game experience affects colour preference. These variables will contribute data to be used when analyzing the colour models and provide opportunity to approach the problem from several different perspectives.

2 Background

The background relates theories, concepts and reviews previous research in relation to four main subjects; virtual reality, aesthetics, colour vision and contrast vision. These subjects provide the foundation on which the rest of the research will be based.

The first part of the background defines virtual reality and its relation to naturalness and realism. Included are also the theories connecting human visual perception to the way an artificial environment is experienced and what affect this may have on the sense of reality.

The second part relates to aesthetic principles which influence the way colours are perceived and interpreted based on concepts such as genre, contrast and colourfulness.

The third part, colour vision, outlines the mechanisms involved in the human perception of colour. The many theories regarding the way colour is processed and interpreted are introduced and summarized, providing an overview of previous research relating to the field. Building on the theories of perception, colour is then described in relation to luminance and how the perceived colour of an object is affected by light intensity.

The last part of the background describes the physical and psychological mechanisms that relates to achromatic contrast vision. The human visual system reacts and adapts to light which affects the way dark and light values are perceived, as well as contrast. These qualities of visual perception also result in a non-linear correlation between stimuli and response. The theories regarding visual perception provides the framework on which the practical element of the research will be built.

2.1 Virtual Reality

Karen Carr, researcher at the British Aerospace Sowerby Research Centre and Director of the award winning VR-company Interface Technology Ltd discusses virtual reality at length in her book *Simulated and Virtual Realities* (1995). She reasons since the term *virtual reality* is used to describe several different ideas it needs to be defined and broken down into subcategories in order to be properly utilized.

On a fundamental level virtual reality may be divided into two categories, tool and concept. Virtual reality as a tool is a technological device which is used to allow for physical action to be integrated into a virtual setting. Virtual reality as a concept, however, is the notion of achieving a virtual experience that is a perfect representation of reality. The concept of virtual reality can be broken down into either *simulated reality*, which is the process of creating the virtual experience, or *virtual reality* which is the result of the process and the aim that the simulated reality is trying to achieve. (Carr, 1995)

2.1.1 Simulating Reality

According to Carr (1995) perceiving something as reality entails complete conviction of its existence. Realism does not have to mean reality, but rather a certain 'sense of reality'. One may experience realism, without having to believe that the situation is real if the perceptual input is able to impart a strong enough sense of reality. Carr differentiates between two types of realism. One is the simulation and replication of possible real worlds and real experiences, such as walking around in a forest or standing on the bridge of a futuristic spaceship. The other type of realism is providing an experience which is impossible in the real world, but is simulated by stimulating certain perceptual experiences. An example of this would be the ability to fly.

Chris Christou and A.J. Parker (1995), of the University Laboratory of Physiology at Oxford, states that the degree of perceived realism depends on how well the virtual environment replicates the sensory information received from experiencing a possible equivalent real environment. As of yet perfect realism cannot be achieved as current technology is unable to artificially reproduce all the aspects of the real world. Christou and Parker (1995) however declare that “the more information provided, the greater sense of reality.”

Visual realism may be accomplished by having the virtual world output the same visual stimuli as the real world, thus the sensory information would be identical and a sense of reality can be achieved. For the result to be as naturalistic as possible it is then not only required to provide the proper visual information, but it is vital that this information is true to life. Understanding how the properties of light affect the visual experience is therefore necessary to realize a credible representation of the real world. (Christou and Parker 1995)

2.1.2 Synthesizing Perception

To achieve virtual reality one must create a perceptual experience which will cause the perceiver to interpret something which it not there as something real. Since an experience is part external and part internal events the challenge is to convince the perceiver to accept a reality based on internal, perceptual, events only. (Carr, 1995)

Perception is key to achieving virtual reality. Carr even describes virtual reality as “making a synthetic perceptual experience match a real perceptual experience” (Carr, 1995 p.5) By identifying aspects which provides sensory input and how perceptual processes interpret the input this information can be applied when creating virtual worlds. Having an understanding of these elements of human nature will help control the perceiver experience and assist in the design of synthetic perceptual environments.

Stephen Ellis, Virtual Reality researcher at NASA Ames Research Center, argues for the importance of considering context in connection to perception. Previous knowledge and experiences offer the framework on which to base the interpretation of our experience. Accurate perceptual judgment is thus dependent upon each person’s contextual knowledge, making perception, and thus also virtual reality, subjective in nature. (Ellis 1995)

Both Carr (1995) and Ellis (1995) stress the effect of viewpoint on the perceptual interpretation. In an environment, real as well as artificial, the self provides a reference point to the relative position of the perceiver, which in turn affects the context. The experience and mental reconstruction of one’s surroundings originates from the perceiver’s place within the environment. The implications of applying different viewpoints as the perceiver's own is important to keep in mind, especially if the artificial environment lacks certain elements of the real world.

2.2 Aesthetics

2.2.1 Mood and Genre

The mood of colour or colour combination may be influenced by a great amount of different factors. Colour researcher Eric P. Danger describes mood in his *The Colour Handbook* (1987) where colour temperature was identified as one of the main factors of colour which influence mood. Colour temperature has been proven to affect biological responses, such as heart rate, and there are a lot of research done in regards to the psychological and emotional effects of different colours. Red, oranges and yellows are generally categorized as warm colours while blues and purples are perceived as cool colours.

Colourist Carla Lind-Valdan describes the relation between colour, mood and genre in her master *Genre Specific Color Grading and Ideals in Film* (2013). The frequent use of colour grading in film has caused certain colour schemes to become genre-specific. In this sense it has caused viewers to expert certain elements in relation to certain properties of colour and colour combinations. Due to exposure to genre-specific visual cues it is possible to gain some sense of the genre of a movie with only the use of colour information. Lind-Valdan outlines the main colour characteristics of five different common genres;

1. Horror movies tend to be dark and blue with white skin tones and dark red blood

2. Futuristic/sci-fi movies tend to be blue or green with most examples on green

3. Post-apocalyptic movies tend to be desaturated with washed out grey, yellow, and paste colours

4. Comedies have bright saturated colours

5. Action movies are desaturated with mostly red, yellow and paste colours and hard shadows

2.2.2 Image quality

Sergej Yendrikhovskij (1998) at the Center for Research on User-System Interaction, Eindhoven University of Technology, discusses they relation between aesthetics and colour fidelity. He defines an algorithm for the quality of an image;

Quality = Naturalness + Colourfulness + Discriminability

Naturalness combines aspects of physiological vision and psychological perception. Yendrikhovskij (1998) argues that both the colour and the naturalness of an object's colour are established in relation to the surrounding colours. Naturalness is not experienced, but rather perceived and thus affected by certain subjective mental notions of what is real. Naturalness is therefore closely related to the concepts of memory colours and expectation.

Memory colours are a form of colour constancy and derive from a psychological phenomenon causing a known object to maintain the same colour regardless of lighting conditions. Lind-Valdan (2013) states that memory colours differ from actual colours in the sense that they are affected by ideals and associations. For example, the memory colour of the sky is generally more cyan than purple and trees and grass are more blue-green than yellow-green in the minds of most humans. Memory Colours have the most impact on familiar objects and phenomena. A more unfamiliar object is bound to have less associated attributes as the mind has less experience with its properties. Prolonged experience of an object causes colour to be viewed not only as a colour, but as a quality of the object. This causes the colour to move from relative to constant as our mind auto-adjust the perceived, actual, colour towards the predetermined quality of the object.

Chroma or colour glow are two terms used to describe the purity or the physical colourfulness of a colour. Overheim (1982) defines purity of colour as the relative to "how far it is removed from white toward the full color of the spectrum locus". Davis (2000) however points out that a third dimension of chroma, included in the Munsell colour system, need also be considered. This theory of a three dimensional colour space is backed up by Valberg who describes that different colours appear to be most 'pure' with different levels of lightness.

The perception of hue and colourfulness is also influenced by psychological factors and optical illusions. Illustrator Richard Yot describes in his book *Light for Visual Artists* (2011) that "colors are not assessed in isolation but in relation to the colors around them." This is the reason why shadows appear to have a complementary hue to the colours of surrounding objects or lights. Images and objects with high colour contrast are perceived as more colourful than those with lesser colour contrast. Colour contrast does not directly affect hue, but the human mind interprets the enhanced colour. The same is true with objects in light and darkness. Lighter objects often appear to be more colourful than dark ones, but truth is that the midtone is the purest form of a colour. When a colour drifts toward white it means that it reflects a wider spectra of wavelength, i.e. a greater mix of different colours which in turn makes the colour less pure.

Discriminability is the ability to distinguish and perceive a difference. When applied to colour theory discriminability may be replaced by the term contrast. (Lind-Valdan 2013) A greater difference between colours will result in greater contrast. Contrast can be applied to the various properties of a colour; hue, value, chroma. Value or lightness contrast is the range between the lightest and the darkest point of any chosen area in an image. Hue contrast is based on relative wavelength, meaning the distance between two hues in the colour spectrum. Chroma affected by both hue and value and chrome contrast will therefore be based on the relative difference between the combined hue and value contrast. Contrast may also be influenced by physiological processes. Valberg (2005) discusses colour induction, a form of optical illusion that arises when different coloured areas are close to each other. Colour induction enhances the differences between coloured areas, thus creating a greater degree of visual contrast. This phenomenon is what causes neutral grey colour to adopt a complementary hue to the surrounding colour and shadows to appear to be tinted in a complementary hue to that of the light.

2.3 Colour Vision

Colour vision is part physics and biology, and part psychology. The field of study which relates to the colour vision and its different processes falls under the name psychophysics. The physical properties of vision are quite well defined, the psychological ones however we know less about. Therefore the way colour is actually seen and perceived has to still be regarded as part fact, part theory. When discussing colour, an important concept to keep in mind is that colour is not constant. (Choudhury, 2014, Overheim & Wagner, 1982, Valberg, 2005) Newton, as early as the 15th century, was able to conclude that light by itself doesn't have any colour, but is able to produce the sensation of colour.

Colour is a reaction to a certain stimuli and the sensation of colour is influenced by both physical and psychological factors. This puts colour sensation somewhere between the external world and the internal representation. (Mausfeld, 1998) An object cannot have colour as a property as colour is a subjective reaction and not constant attribute of the object itself. This is turn would profess that the colour of an object is dependent upon the media which interpret the physical stimuli. An environment would thus be perceived different depending on the medium.

The eye is often compared to a camera and the analogy has been used by well-known names in the fields of optics and visual perception. Among others these were astronomer Johannes Kepler (1571 -1630), a key figure in the scientific revolution and inventor of the Keplerian telescope, and René Descartes (1596 –1650), while most famous for his philosophical view also established the Law of Refraction. The eye versus camera analogy was also used by the German scientist and physician Hermann Helmholtz (1821 –1894) who made great contributions to psychophysics and is one of the biggest names in regards to early theories of colour vision. These early scientists tried to take properties of the camera and apply the concepts to that of human vision. However this simplification omits vital elements of visual perception and contemporary sources establish that the eye is not like a camera and cannot be described as such. (Valberg 2005)

2.3.1 Theories of Colour Vision

The Trichromatic Theory is most often contributed to Helmholtz; however he was not the first one to formalize such a theory. (Kliegl & Volbrecht, 1998). In fact Helmholtz built upon the previous work of both Thomas Young and James Maxwell. Young introduced the idea that coloured light was connected to different frequencies of wavelengths. Young lay the basis for the Trichromatic Theory by proposing that the eye had three different types of receptors which each reacted to frequencies relating to blue, green and red colour sensation. Maxwell was able to prove Young's theory of the three colour channels and also applied the theory to photography, thus creating a method of taking colour photographs. Hermann Helmholtz then refined the theory further into what is now more known as the Young-Helmholtz theory of colour vision. The theory states that the relative output of the three receptors determined the hue of the experienced colour and the sum of the output determined the colour's brightness. (Kliegl & Volbrecht, 1998. Overheim & Wagner, 1982)

The relationship between colour vision and the cone-photoreceptors in the eye was initiated by the German anatomist Max Schultze's studies in 1866. By studying animals he was able to conclude that animals which were active during the day had more cones than nocturnal animals. The German psychophysicist Johannes von Kries, who followed closely in the footsteps of Helmholtz, expanded on the relation between cones and colour vision and formulated the so called Duplicity Theory. The theory states that brightness and contrast vision is related to rods and work on a separate channel than that of colour. Colour instead relates to cones and colour vision would then be more active during high intensities of illumination. (Cahan 1993, Valberg 2005,)

Another theory which is regarded alongside the trichromatic theory is the Opponent Theory. This theory was formulated by Ewald Hering, professor of physiology at Charles University in Prague, based on Von Kries ideas. Hering proposed that there were two colours channels which each corresponded to two different colours, these being either red-green or yellow-blue. There was also one achromatic channel to constitute for black and white. Depending on the balance of stimulation a photoreceptor could either output an excitatory colour (red, yellow, white) or an inhibitory colour (green, blue, black). (Kliegl & Volbrecht, 1998. Overheim & Wagner, 1982)

The Zone theory (sometimes called the Hurvich and Jameson's opponent-theory) combines aspects of both the trichromatic and the opponent theory and introduces the concept of a multilevel processing system. The three cones are the first components to react to light and depending on the spectral quality of the light the cones will output different responses. In this sense it is like the trichromatic theory. The signals then passes to a secondary system of 'opponent-cells'. Each cone is connected to three opponent-cells, the red-green cell, the yellow-blue cell and the achromatic white-black cell. The responses of these cells are then combined in higher visual centers. (Kliegl & Volbrecht, 1998. Overheim & Wagner, 1982. Valberg 2005.)

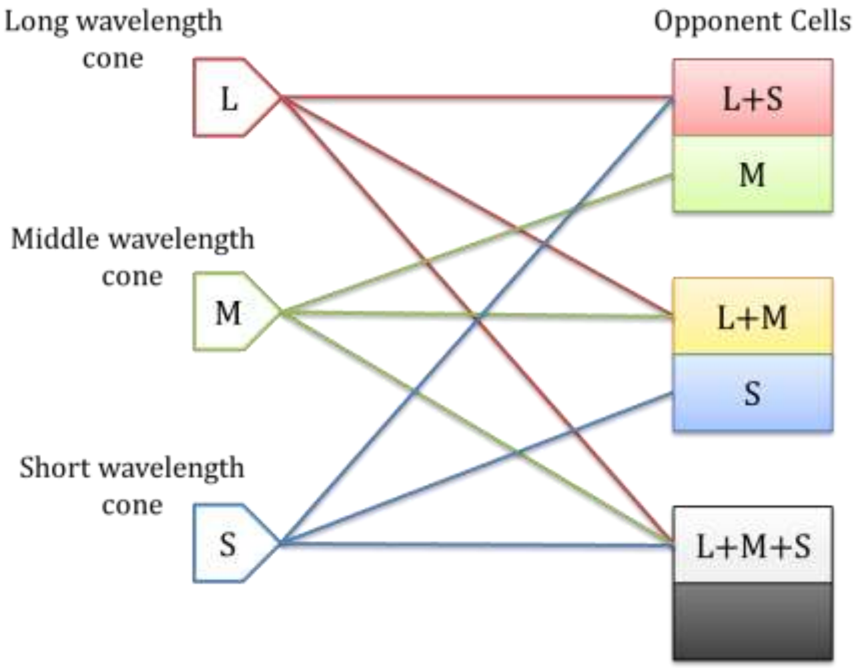

Figure 1 Schematic diagram of the Zone Theory of colour vision

Since each cone are related to the sensation of several colours they are no longer given a name relating to a specific colour, but rather relating to which wavelengths the receptors are most sensitive to, hence the terms, long, middle and short-range cones.

According to Overheim & Wagner (1982.) the zone theory allow for colour response to be calculated based on the responses of the three cones using a mathematical formula. If the sum of responses of the long and short cone is greater than that of the middle-cone the colour seen would be red and if it is the other way around green would be seen.

$$\frac{Red\ (+)}{Green\ (-)} = (L + S) - M$$

The same principle is true for the yellow-blue opponent-cell.

$$\frac{Yellow\ (+)}{Blue\ (-)} = (L + M) - S$$

Valberg (2005) however calls to attention that one should keep in mind that this is a representation of a system and therefore does not relate all the neurological functions and the complexity of the visual system.

2.3.2 Perception of Colour

The visual system is able to distinguish between 180 different so called pure colours, but has a tendency to group these together into a small number of colour bands. Colour researcher Eric P. Danger describes in his *The Colour Handbook* (Danger 1987) how the different bands produce different responses because of the way the sensitivity of the eye depends on wavelengths. The eye's sensitivity is highest in the middle of the spectrum, which is why it is possible to focus on yellow without any aberration as opposed to the colours blue and red. The ratio of different cones also affects the way colours are perceived. Contemporary colourist and film editor Steve Hullfish (2002) explains in his book on colour correction that the eye is unable to fully detect higher resolutions in the blue spectrum because the ratio of short to long cones is 1:14. This causes blue colours to come across as somewhat blurry and sometime even emit a halo-effect of bleeding blue colour.

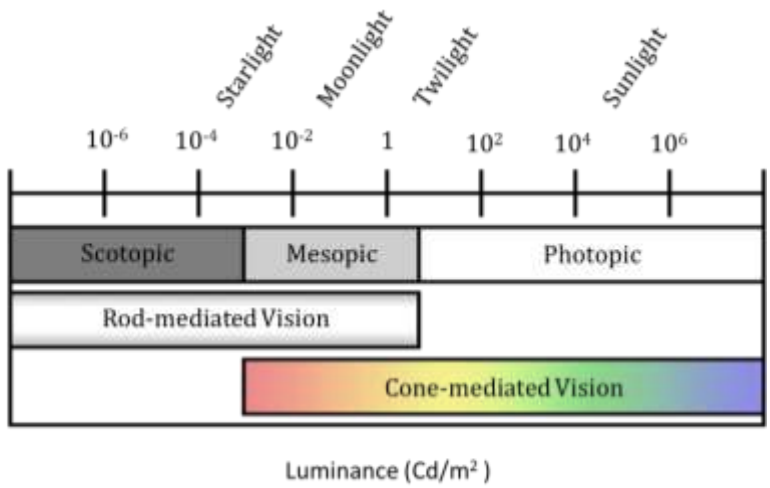

Figure 2 Types of vision in relation to luminance.

Cones need a luminance value around 0.01cd/m² to become active. This means that at lighting conditions of less than 0.01cd/m² (around the illumination of a starry night) our vision is provided exclusively by the more light sensitive rods and our vision during these conditions is completely achromatic. The range in which achromatic vision is active is called the scotopic levels. At luminance levels above 0.01cd/m² the cones will hence provide the sensation of colour. These levels are called the photopic levels. The rods contribute to vision up to a luminance of 10/m² where they become fully sensitized and thus cannot convey any more stimuli. This means that there is a range where both the chromatic and the achromatic system are active, this range is known as the mesopic range. Because of these qualities of the human visual system the sensation of colour is closely connected to lighting conditions. Consequently the perception of a colour will change depending on to the intensity of the illumination. (Devlin, 2004)

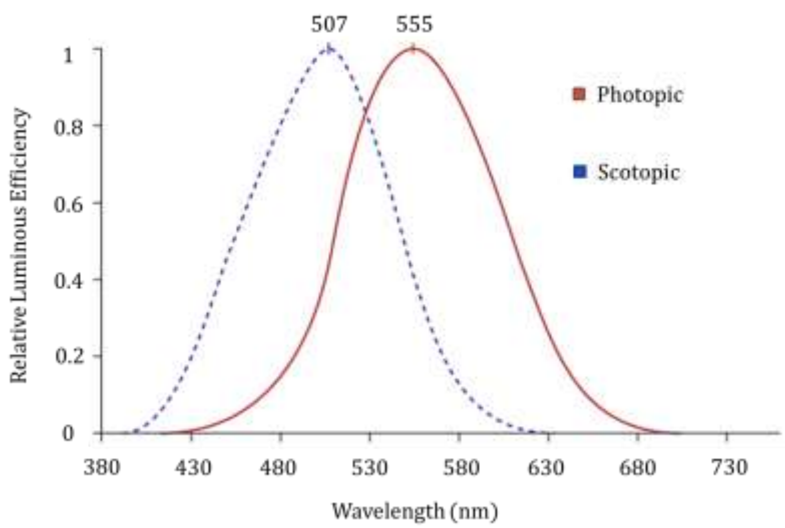

Figure 3 Photopic and Scotopic luminous efficiency curves for daylight and night vision.

Each type of cone has different sensitivity to spectral energy, which means that they become active at different levels of light. At very low level of illumination, 0.001cd/m^2 only the short range-cone output a response. At this luminance the s-cone respond to wavelengths of about 435nm to 500nm, but only to a fraction of the cones full capacity. The human visual system would experience the hue-ranges from purple to blue at a response rate of 40% to 10%, this means that while the colours can be seen they will still be experienced as having low saturation. As the luminance value is increased to 0.01cd/m^2 the M and the L-cones will also become active and it will be perceiving hues of all wavelengths. (Valberg, 2005) The relative sensitivity of the visual system, and with that our perception of colour, at low versus high values of illumination can be expressed by the Scotopic–Photopic Luminous efficiency curve (figure 3).

2.4 Contrast Vision

2.4.1 Light Adaptation

Light adaptation is the process of adjusting the input and output of visual data of the amount of illumination reaching the lens. A camera adapts to differences in light intensity by regulating the size of the entrance aperture. The human visual system applies the same principle by regulating the size of the pupil to affect the retinal intensity. The pupil is able to adjust from 1, 5 mm to 6mm. This process is vital for visual acuity in everyday life as it allows us to see and discern shapes in our surroundings in various lighting conditions. (Valberg, 2005, Overheim & Wagner, 1982)

It is not only the pupil which affect light adaptation, the photoreceptors in the eye also react and adapt to illumination. (Overheim & Wagner, 1982) It used to be believed that this adaptation was caused by the pigments in the photoreceptors being bleached by the light, but more recent research has proven that only 10% of the pigment is bleached. This has led to the conclusion that neural mechanisms and processes are the ones that influences light adaptation the most, 90% in fact. Even though there has been numerous psychophysical studies regarding light adaptation, the physiological mechanisms are still hard to completely identify (Valberg, 2005)

The human visual system can retain its functionality over a range of light intensity greater than 1x10^12 lux. Since light adaption enables the human visual system to maintain close to the same span of light and dark values, regardless of differences in luminance intensity, the image seen will not be overexposed nor underexposed. Light adaption also causes lightness constancy, which is that objects and surfaces are perceived to maintain the same lightness even though the illumination changes. Light adaption happen so quickly that the human visual system is able to see details of a dark area and a light area almost simultaneously, which affects the perceived contrast of an area. The effect of this is that the eye will perceive greater contrast than a camera. To push digital image contrast towards that of perceived object contrast post process and retouching is needed. (Danger, 1987, Overheim & Wagner, 1982. Valberg, 2005)

2.4.2 Luminance Contrast

There are several models to determine contrast. Many relate to local contrast, the discriminability of an object against a background with a constant luminance, and are based on the relationship between a luminance difference (ΔI) and the average luminance.

Below is shown the Michelson formula which can be used to determine the level of contrast of an object, with I_{max} and I_{min} representing the highest and lowest luminance levels. (Devlin 2004)

$$Contrast = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

However there is no simple way to determine the contrast of an entire image through the use of an algorithm. Doing so would involve establishing the ratio of darks and lights by making a comparison of each pixel to the average luminance of the image. Different types of tools for visualizing contrast ratios are available in many image-editing applications. However, using these tools, without knowing the exact mechanism behind the data presented, may not be a reliable method to determine the global contrast.

Experiments have been done in in order to determine the contrast sensitivity as a function of luminance. Physiologist E.H Weber was able to establish the increment threshold in relation to the background intensity as early as 1834. (Devlin 2004. Valberg, 2005)

Drago et. al (2003) describes the *Difference threshold* as the minimum amount the intensity of a stimuli can be changed (ΔI) before it is detectable.

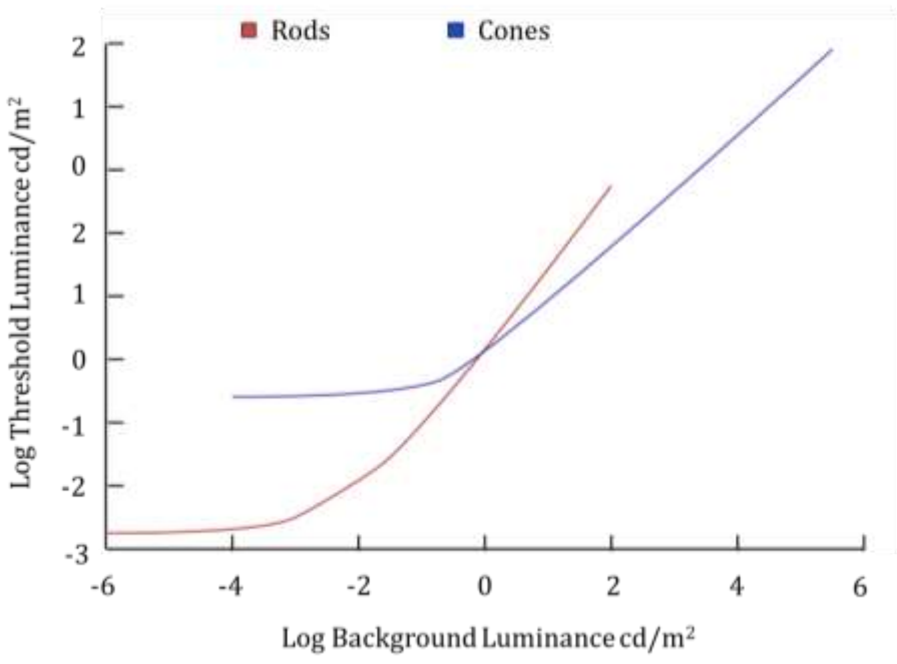

Figure 4 Threshold versus intensity function for the rod and cone systems. (Drago et al. 2003)

Experiments show the contrast sensitivity of rods and cones respectively. The threshold increases proportionally to the background luminance indicating a system of constant contrast sensitivity. The linear proportionality applies to log luminance values between -1 to 6, and is described by Weber's Law. (Devlin 2004. Valberg, 2005)

Weber's law can be expressed by the function:

$$\frac{\Delta I}{I} = k$$

The linearity would be true for a luminance range between 0.1 (a full moon lit night) to 1 000 000 cd/m² (noon sunlight) (Choudhury, 2014)

2.4.3 Luminance, Lightness and Brightness

Lightness is the response of the human visual system to a specific physical luminance. Luminance describes the amount of light hitting an area while brightness describes a perceptual response. In this sense luminance is in linear proportion to the amount of light, while lightness is not. Lightness' non-linear proportion to luminance is expressed by the Weber-Fechner law. (Drago et al. 2003. Valberg, 2005)

$$S = kI^a$$

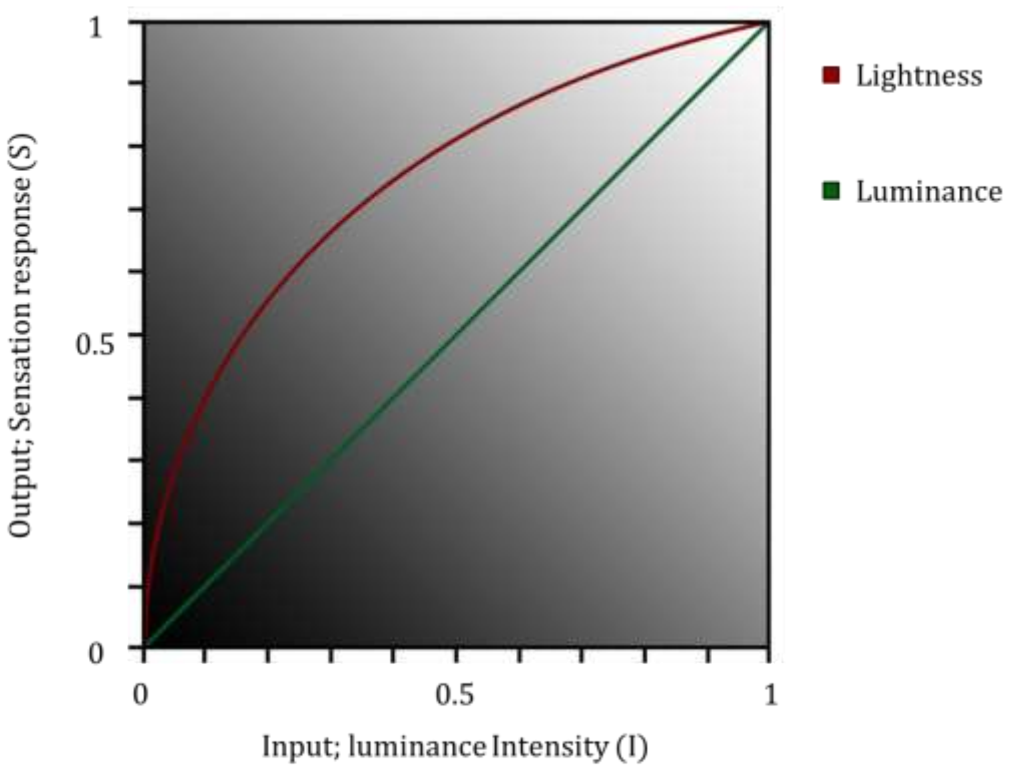

Figure 5 Weber-Fechner's law applied to the sensation of lightness as a function of luminance.

It is to be kept in mind that since the algorithm is dependent upon Weber's law, the proportionality is limited to the ranges of luminance where Weber's law is constant. Brightness is sometimes used intermittently with lightness, as it also can be described as a non-linear response to luminance. The term lightness only describes a colour’s achromatic value, while brightness relates to the lightness of a colour as well as the colour’s apparent chroma, or colour glow. Consequently two colours may output different levels of brightness even though their lightness is identical.

3 Problem

The way the light and colour behaves depends both on the quality of light and the medium through which the light is observed. Humans, most often, observe their surroundings through the medium of the eye and the human visual system (HVS). An attribute of the HVS is that the interpretation of colour information is affected by lighting conditions. The amount of light the eye perceives determines which colours can be seen and how well the HVS is able to interpret the colour information of the environment.

When working with virtual environments in digital games, the visual information of the environments is translated and mediated through the use of a virtual camera. As opposed to the human visual system, light intensity will not affect the way a game engine camera renders different shades in the colour spectrum. In 1st person games the player sees the environment through the eyes of the game character. Generally the character, if human, would interpret colours the way the HVS does and not like the standard game engine camera.

This thesis aims to answer the questions;

Will HVS colours or game camera colours be preferred when experiencing a virtual environment from a 1st person perspective?

How does light intensity relate to preference of HVS colours versus game camera colours?

In order to answer these two questions one first needs to establish how a game engine camera may be modified to simulate the way the human visual system experience colour in different intensity of light.

3.1 Method

The colours processed by game engine camera in Unreal Engine are adjusted through the use of manually made colour grades. The colour grades are created based on theories of visual perception and psychophysics. Four different colour grades are made to visualize how the intensity of light affect colour and illustrate how the human visual system process colour from light-adapted to dark-adapted vision.

The two colour modes (game camera colour mode and HVS colour mode) are applied to two separate, but identical rooms. The rooms are connected to each other by a short corridor, in which the two colour modes are blended equally. The preferred colour mode will be established qualitatively by having a test group walk around in the environment for a limited time and then state their colour preference. The test will be done in four different lighting conditions in order to explore whether luminance is an influencing factor and how it related to colour mode preference.

3.1.1 Artifact

A confined 3D environment was created in *Unreal Engine 4* using the starter content provided by *Epic Games* (20012) for. The environment was divided into four areas in order to create variation and include different types of materials. One white light source was placed in the middle of the room and was presumed to radiate the entire spectrum of wavelengths and thus all colours. One wall of the room was appointed a texture of colour swatches and spectra which were used in creating colour grades.

Screenshots of the room was taken at four different levels of luminance, a range representing the transition from light adapted vision (photopic) to dark adapted vision (scotopic). The screenshots were then used when creating the colour grade LUTs (look up tables) in the software *DaVinci Resolve* (Blackmagic Design, 2014). When implemented into the 3D environment, the LUTs become a three dimensional colour grade.

The final artifact is a simulation with four different levels, each with less light intensity than the previous. The environment consists of two rooms which are identical in every aspect except that one room is colour graded and one is not. The two rooms are connected through a corridor where the colours are blended. The neutral coloured corridor is also the place where the player spawns when a level is chosen.

3.1.2 Quantitative testing

The artifact will be used to quantitatively test colour mode preference. Four different levels will be tested by 5 respondents respectively, which brings the total amount of respondents to 20. It is important that the respondents have, to their knowledge, full colour vision and no known colour vision deficiency. The reason for this is that the colour grade is created based on perception of full colour vision and thus neither designed not adapted to be tested on respondents with colour vision deficiency.

The respondent’s experience of digital games will be noted in relation to each responder. People with a lot of experience of digital games are more familiar with the colours rendered by a game engine camera which may influence the colour preference. By noting game experience it may be possible to establish a possible correlation between game experience and colour preference. The question relating to game experience is phrased accordingly:

During the last 12 month, what is your estimate of average time playing digital games during a week?

12 month was chosen as an appropriate time span to measure an average of time spent playing digital games. It would be more accurate to have a greater time span, but also more difficult for the respondents to answer. The time span was included as a shorter time may not accurately represent the respondent’s general habits in regards to gaming and the previous experience of digital games. There are numerous factors which may temporarily influence a person’s habits. The answers which can be chosen are given in ranges of 10 hours with one null option of 0 hours.

a) 0 hours
b) 1-10 hours
c) 11-20
d) 20+

These questions will be asked prior to the testing of the artefact in the form of a printed anonymous survey. On the printed survey are also written instructions for the test (see Appendix A - Survey).

After testing the artefact the respondents will express which colour version or room they prefer. There will also be a null option to express the opinion of “I don’t know” and/or “I saw no difference between the two”. The respondents will also answer which room they thought is most similar to the colours they would have seen if they had been present in the environment. The preferred colour model will answer the general inclination towards the two colour models. This data is vital when trying to establish the potential uses of camera and HVS colours. When designing a virtual environment or creating graphical assets for a large target group it is important to know how the asset is received. As the asset is created to for a clientele the preference may be more important than the reasons behind that preference. The reason may differ among the individuals in the target group while the preference remains the same. In either way the graphic designer need to take the preference of the target group into consideration.

The question second question communicates how the respondent relate the two different colour models to his or hers experience of the real world. The data may be used to establish whether neurological aspects may have an effect on how the colour modes are perceived. According to research the HVS colour mode ought to correlate closer to what colour information the human eye is physically able to process. However there are a lot of other neurological processes that influence and regulates the way colour is perceived.

By combining these two questions it is possible to triangulate the data received to establish how the colour models are perceived by the respondents and how they relate to real life experience.

3.1.3 Rework and Edit of the Method

To establish the viability of the colour grading a quantitative survey was going to be used. It was believed that the theories regarding correct colour and value alteration were not going to contribute enough information to singularly determine the visuals of the colour grading. The idea was to create several versions of the colour grades and receive feedback through an online survey. However, as the work progressed and the theories were applied to the reference texture there were not a lot of room for variation and the quantitative survey would not have contributed viable data. Some changes could be made without creating banding effects and loss of detail, but even though these changes could be seen in the reference texture they were indistinguishable when applied to the actual environment. The reason why the colour reference texture should not be used to evaluate a correct colour grade is that, according to the colourist Lind-Valdan (2013) colours cannot be deemed as true to life or realistic if the viewer does not have any experience with the environment/object seen. An incorrectly coloured object will not come across as unnatural if the object is unfamiliar.

In addition to game experience, experience of graphical work was going to be included as a variable in the study. This was based on the hypothesis that people who have an understanding of light and colour may come to see and analyse the two colour modes in a way that differs from those people that don’t. This variable was later omitted doe to several factors. Firstly that graphical experience or artistic knowledge is difficult to quantify. How does a degree in graphics of art compare to work experience? An amateur photographer may have more knowledge of colour and light than a post-graduate graphical artist who specializes in logotypes and web design. The second factor is the consequence this variable would have on the test group. To be able to achieve a viable comparison between colour preference of those with graphical experience to those without the two groups would have had to be approximately the same size. This condition in turn would put a limitation on who would be fit to be included in the test group. The final reason why this variable was excluded was based on the results of the pilot study. Even though two of the testers had graphical experience none of the comments made during the pilot test were related to artistic principles, but rather the psychological effects of the two colour modes. In this sense they showed no distinction from the two other testers who also commented on the mood and feelings they associated to the two colour modes.

3.1.4 Limitations

To limit the scope only a few aspects of visual perception were be applied. Theories regarding focal length, depth perception and acuity were not applied, neither was how colour and contrast vision are connected to central and peripheral vision. According to Carr (1995) “vision should not be considered in isolation from the other senses” which is something to be kept in mind. Ideally, when synthesizing perception, one should apply concepts relating to as many of the perceptual mechanisms as possible. The research can therefore not be used as representative of the concept *visual perception*, but only of the perceptual relation between light and colour. (England 1995)

The prototype includes one white light source only. Light sources which emit a limited spectrum of colours as well as tinted light sources have been omitted in the artifact. Since the theory relates to the correlation between luminance and perceived colour it is vital that the lighting is easily quantifiable. Lighting conditions with several influencing factors may result in a loss of accuracy. The research question and the data collected will therefore only be viable when applied to areas which are uniformly lit.

4 Implementation

4.1 Progression

4.1.1 3D Environment

Initially the colour grading was going to be applied to an outdoor 3D environment with a day and night cycle. The grade was going to be animated in a way which would allow the colours to change over time. This would visualize how the colours the human visual system can process are affected and allow for testers to experience the transition from photopic to scotopic vision. However this initial implementation was discarded due to the amount of factors which would affect the visual appearance and colours of the scene. Even though the sun is regarded as a white light source its appearance and properties change over time as a result of atmospheric factors. Certain wavelengths are more affected by atmospheric scattering effects than others and as the angle of the sun changes these effects also increase. This is the reason why the colours during sunrise and sunset differ greatly from the colours during midday.

In order to provide viable, conclusive results it was decided that the artefact be reworked to include less influencing factors. The reworked environment has an indoor, closed, setting which excludes atmospheric effects from the sky. In a virtual environment created in Unreal Engine certain atmospheric effects has to be included in order for light to be rendered correctly, correctly meaning the way the light is optimally supposed to be rendered in the specific game engine (Epic Games 2015). One of effect is an element which enables the rendering of ambient light. Ambient light exists in some form as soon as there is a light source. It is the effect of light bouncing off numerous surfaces, creating a general light that reaches areas not touched by direct light. Without a manually added ambient light the cast shadows in the 3D environment will be pitch black.

The standard element for ambient light in Unreal Engine is a *skylight*. Because this light is developed to mimic the atmospheric qualities of the sky, this light would reintroduce some of the aspects the reworked environment tries to avoid. To bypass the complications of a *skylight* would bring, ambient light is instead provided by an *ambient cube map*. A cube map allows for manual control over the intensity of the ambient light, but also means that the intensity is not affected or regulated by the direct light sources in the vicinity. The intensity of the ambient light was given an approximate value in relation to the intensity of the single white point light that was placed in the middle of the room.

The materials and props used to furnish the environment are assets which are created by Epic Games and included in the starter content of the game engine and thus designed to be used and implemented in Unreal Engine. The props were placed to create varied amount of shadows in the different areas and the room divided into four sections in order to test the colour grading in various different settings. The sections allow for different types of materials and props to be used while maintaining a system in the way the environment is laid out.

Figure 6 The finished 3D environment

On one of the walls a custom texture was applied (See Appendix B – Colour Reference Texture). This texture is later used as a point of reference when creating the individual colour grades. There are many different ways to systemize colour, two of these were included in the texture. The first one is a classic spectrum of fully saturated colours in a range from minimum to maximum brightness. The seamless nature of the spectrum is a good tool as it clearly shows if the adjustments will lead to unwanted banding, that is when the colours appears as separate bands of colour instead of a seamless gradient. In colour grading the effect of this is a loss of colour range.

As the spectrum only shows colours of full saturation an IT8 chart, a collection of colour swatches picked for calibrating screens, was also included in the colour reference texture. The IT8 charts include three different colour modes which are common ways of representing digital colour. The colour modes are:

HCL colour, which differ in Hue, Chroma, and Lightness

CMYK-Colours; Cyan, Magenta, Yellow, and Key (black) in different steps of brightness

RGB-Colours; Red, Green, and Blue in different steps of brightness

When combined the colour swatches cover a wide range of colours which is useful in colour grading. The swatches make it easy to see which colours are affected by which adjustments and whether there is a loss of colour information as a result of the colour grading.

The third aspect of the colour reference texture is based on an experiment on mesopic colour made by on MacEvoy (2005). MacEvoy is a professional painter and has created a great amount of material in regards to how visual perception affect colour. MacEvoy's work combines theory with experimental methods to show how the theory applies to real life situations. The subjective appearance of colour was established by MacEvoy by observing 24 different swatches of colours through the mesopic light range of 200 to 0.02 lux. The result of the experiment is used as a reference for illumination as it shows the appearance of the colour white during different illuminations. The other colours are used as guidelines, but will not be used as a basis for the colour adjustments as more theoretical sources already provide methods that will be used.

4.1.2 Settings, Lighting and Screenshots

Post processing effects are certain attributes that affects the way the game engine camera interprets the visual information of the scene. Unreal Engine has some post processing effects enabled as standard, however these were turned off to allow for more manual control of the visual appearance of the environment. Anti-aliasing was enabled as it lessens the amount of artefacts visible on edges of geometry and texture seams. A property of light is that, because of the way the photons bounces, the light will not reach corners and spaces where objects are situated close to each other. Since this effect does not occur as a consequence of the lighting in Unreal Engine, it was added manually to the environment by enabling the *screen space ambient occlusion* option.

Auto exposure is a feature that is available in Unreal Engine. It is developed to mimic the way the human eyes uses light adaption. However it behaves very similar to exposure settings in a camera. Even at maximum speed the light adaptions happen slower than they should. Auto exposure interferes with the appearance of every aspect of the lighting in the environment, causing the lighting to become imprecise. Consequently the colours and contrasts in the scene would not be constant, but be affected and influenced by the auto exposure. Because of these complications it was decided that auto exposure should not be used to create the effect of light adaption. Colour grading tools will instead be used to mimic the phenomena in this prototype. Auto exposure may be used well in a game or a similar final product, but not when testing a theory in a controlled environment.

MacEvoy (2005) identified four major stages of mesopic vision where certain colours start to blend together. These four stages were chosen as a basis for intensity of illumination in the 3D environment. It is important to remember that the transition from photopic to scotopic vision is nonlinear. This will result in a non-linear relation between the intensity of the four light stages chosen. As the point light intensity in Unreal Engine has no real correlation to real life luminance the intensity of the lighting therefore had to be established through comparison. This was done by adjusting light until the white point of the wall showed approximately the same level of lightness as the white point of MacEvoy's colour swatches. For example the brightest light setting (setting A) was made by comparing the wall to the swatches observed in 200 lux.

	Point Light Intensity	Luminance
Setting A	100	~200 lux
Setting B	20	~20 lux
Setting C	5	~2 lux
Setting D	1	~0.02 lux

Table 1 Established values for Unreal Engine point light intensity and the relating luminance (cd/m^2 or lux)

As the intensity of the *ambient cube map* remain constant regardless of the intensity of other lights this value had to be adjusted manually to each of the four light intensities. The intensity of the ambient light becomes weaker as the intensity of the point light decreases. An important factor to keep in mind is that the ambient light needs to be weak enough that it primarily affects the cast shadows and not the overall luminance of the environment.

Screenshots of the reference texture were taken in the four different light intensities as well as screenshots of the nature area of the environment. As the nature area has variation in light, depth and texture it can be used to test the colour grading while it is being made. Some adjustments (such as value balance) may be seen more clearly in those images as compared to the flat image of the reference texture.

4.1.3 Colour Grading

The colour grading was done using *DaVinci Resolve* by Blackmagic Design (2014). DaVinci Resolve is the leading software used when colour grading linear media, such as movies, and provides sophisticated tools and features to apply colour grading and analyse the visual properties of an image. The final colour grading textures used in visualizing the HVS based colours in the game engine can be seen in Appendix C – Look Up Textures.

Usually, when colour grading, one wants to begin by adjusting those features that are affected by the least amount of factors. The colours of an image are affected by the values (the lightness) and it is often difficult to adjust colours separately from the values. The value of a hue may for example affect whether we perceive the colour yellow or the colour brown. It is, however, easy to adjust only the values of an image which is done by rendering the image completely into grey scale and then adjusting the values. Images B to D only needed minor value adjustments while A needed to be heavily retouched as it looked overexposed even in rather dim illumination. This is most probably due to the adding effect of the point light, in which the white colour of the light is added on top of the colours instead of illuminating the colours themselves. By adjusting the values of the image it was possible to reintroduce the image's original colours which had been lost when the light was added.

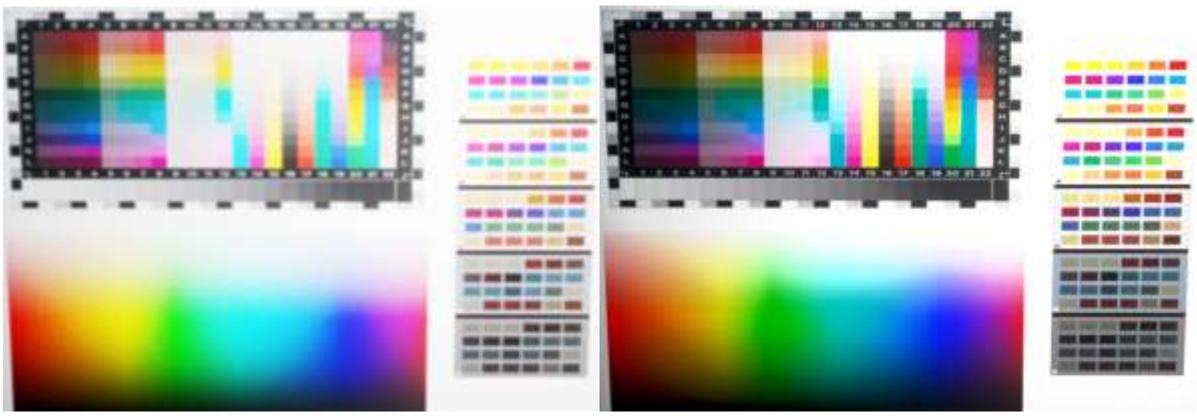

Figure 7 Colour reference texture at ~200 lux before and after value adjustment.

As luminance decrease, the human visual system's ability to efficiently process certain wavelengths of light is affected. The result of this is that some hues will start to shift into others. This colour shift can be calculated through the use of the zone-theory formula described by Overheim & Wagner (1982.). (See section 2.2.1)

What follows is an example of the application of Overheim & Wagner's formula on the hue yellow. Pure yellow, with a wavelength around 570nm, is a result of a positive response of the yellow-blue opponent-cell and a neutral response of the red-green opponent-cell.

$$\frac{Red\ (+)}{Green\ (-)} = (L + S) - M = 0$$

$$\frac{Yellow\ (+)}{Blue\ (-)} = (L + M) - S\ > 0$$

The formula leads to the following relation between Long, Medium and Shot range cones:

$$M > S$$

$$L > 0$$

Example values can be used to illustrate what happens to the responses as we go towards scotopic vision. The yellow wavelengths are halfway between the red and green. It can therefore be presumed that the responses of the long-range (red) cone and the medium-range (green) cone are equal. The short-range blue cone in this case would not give any response. Example values which take both this and the relation between the responses into consideration can be following.

$$L = 10 \qquad M = 10 \qquad S = 0$$

Formula for yellow when the values are applied:

$$\frac{Red\ (+)}{Green\ (-)} = (L + S) - M = (10 + 0) - 10 = 0$$

$$\frac{Yellow\ (+)}{Blue\ (-)} = (L + M) - S = (10 + 10) - 0 = 20\ > 0$$

As illumination decreases the response of the cones is affected. In a simplified manner one can say that the efficiency of the s-cone is increased while that of the L and M-cones are decreased, L more so than M. The new values could now be represented as;

$$L = 2 \qquad M = 5 \qquad S = 10$$

The new, dark adapted, formula would then look like this:

$$\frac{Red\ (+)}{Green\ (-)} = (L + S) - M = (2 + 10) - 5 = 7$$

$$\frac{Yellow\ (+)}{Blue\ (-)} = (L + M) - S = (2 + 10) - 5 = 7\ > 0$$

The yellow-blue opponent cell still has a positive response and will communicate the sensation of yellow, though its response is slightly lessened. The red-green opponent cell however is no longer giving of a neutral response as it did before. It now communicates the sensation of red. The conclusion of this example is that the colour yellow will hue shift towards the sensation of orange as the illumination decreases. Similar calculations can be used determine the hue shift of red, green and blue.

Figure 8 Colour reference texture at ~0.02 lux before and after hue adjustment.

The sensation of the colour white is created by the combined responses of the three cones, short, medium and long-ranged. As the response change depending on illumination the hue of the white areas will be affected. At low mesopic vision the red and yellow colours that contribute to the impression of white are seen less efficiently by the eye and as a result the white point will start to shift towards blue. White surfaces will therefore change appearance from an almost luminous to a dull blue grey colour. (MacEvoy)

Figure 9 Screenshot of 3D environment in luminance of ~2 lux before and after hue-offset adjustment.

As vision moves from photopic to scotopic vision the saturation of individual hues will change accordingly. The efficiency of which the human eye is able to process certain wavelength is illustrated by the luminous efficiency curves (figure 3). The scotopic curve determines the hue versus saturation in the case of grade D as the luminance of 0.02 is very close to scotopic vision. B and C were given estimated values between the photopic and the scotopic curve as well as being compared to the swatches created in MacEvoy's (2005) experiment. The adjustment is made through the use of the hue versus saturation tool in DaVinci Resolve. At low illumination the ability to see yellow and green decreases while the ability to see wavelengths around the colour sensations blue and purple increases.

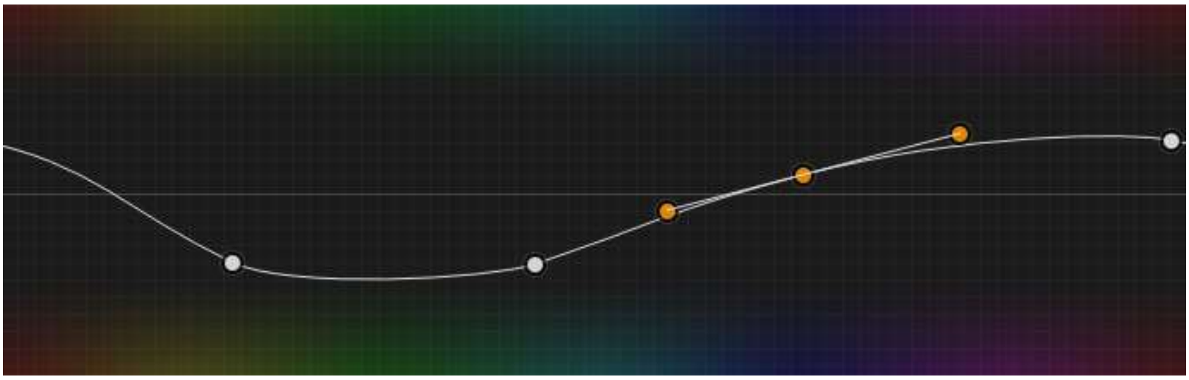

Figure 10 Hue vs. Saturation adjustment based on HVS luminance efficiency at illumination of ~0.02 lux.

4.2 Pilot Study

The pilot study was done with the purpose of confirming whether the established methodology was going to be sufficient to collect the data needed. It was also used as a way to identify potential flaws or points which could be improved. To evaluate the entire test the pilot test should provide the same type of date as the real test, but on a smaller scale. The respondents need therefore be fairly few since the number of testers in the pilot test may hamper the process of finding testers for the real test. Since the pilot test would only include a small number of testers it was decided that it would be more beneficial to only evaluate one of the levels not all four. As the level chosen would be a representation of the artefact the maximum and minimum luminance levels (A and D) should be avoided. Level C was picked over level B on the basis that differences between the two colour modes are greater at lower luminance.

Four respondents were involved in pilot testing level C. The respondents answered the first part of the survey and were then given verbal instructions for the test. They were also told which questions they would be answering after testing the level in order to give the respondents a focus during the test. As the test is assessing attitudes the instructions will give the respondents time to assimilate their thoughts and consider their point of view. The type of question might be the reason for why all four respondents talked out loud while testing. One of the respondents expressed being influenced by the opinion of the preceding tester which is something which should be avoided in the real test. Since thinking out loud is a common way to gather ones thoughts it the real test will be taken one person at a time instead of trying to restrict this type of behaviour.

Giving the instruction verbally may come to be a problem in bigger test. Verbal instructions give greater room for questions which may result in the respondents receiving different amount of information in regards to the test or the artefact. To improve accuracy and fairness the instructions will instead be communicated to the tested through writing and be included as a part of the questionnaire. This will make sure that all testers receive the same amount of information.

It became apparent that the artefact is affected by the lighting in room. Since ambient lighting affect the way colours and contrast are seen on the screen it is important that the real life lighting conditions are the same throughout the test. The test should therefore not be done in different locations and the light in the room should not be influenced by sunlight. To keep the conditions as consistent as possible it would be most reliable to use a single screen throughout the entire test. This because the colours rendered are dependent on the monitor used and an image may look dramatically different when viewed on different monitors.

5 Evaluation

5.1 The Study

The test was done during two consecutive days in a controlled setting. The testing was done in an isolated room with constant lighting. The windows were covered and the three lights in the room were positioned in a way which eliminated direct light onto the screen. This was done to create a lighting condition which behaved more like ambient light than direct light. Direct light usually result in clear reflections in the monitors and the colour and temperature of the light sources will affect the colours on the screen.

The test was run on dual screens, with the survey on one screen and the artefact on the other. The screens' brightness was adjusted so that the survey showed approximately the same brightness as that of the 3D environment. Contrasting brightness would result in lightness adaption by the eye which would affect the way the 3D-environment is perceived. To make sure that the previous adaption of the eye was neutralized the respondents were to be present in the test room for at least a minute to allow for the eyes to adapt to the light in the room. According to Valberg (2005) it takes approximately 9-10 min for the eye to adapt from sunlight to complete darkness (from 100 000 to 0,001 lux). As the respondents waited in a lit corridor without outdoor light before entering the test room the estimated adaption would be somewhere from 500 lux to 10 lux and therefore the full ten minutes would not be needed.

The respondents were reached through social media and personal contact. The information given prior to the test was estimate of the test time and that the data would be used anonymous in a thesis. The rest of the information was communicated through written instructions in the survey in order to control the information given. The respondents began by with answering the questions regarding colour vision and game experience and on the next page of the survey read though the instructions. The testers were then given two minutes to walk around, but were given the option to quit earlier if they felt ready to answer the two questions. Most needed around a minute to reach a decision. Afterward the test the testers answered the two evaluation questions.

The evaluation questions which were to be answered after the test were shown prior and during the testing in order to help the respondents and direct their focus to the colour of the environment rather than the environment itself. As the environment is interactive in the sense that the tester is able to walk around and look around there a many different factors which may draw the attention of the tester.

5.2 Result

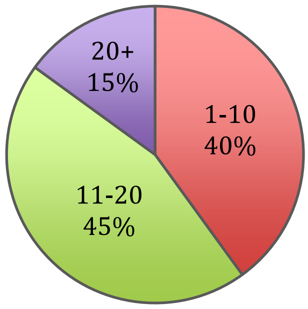

Figure 11 Average hours of play time a week during the last 12 months

The average play time per week were divided quite evenly between 1-10 hours, 40%, and 11-20 hours, 45%. 15% of the responders estimated their play time to be more than 20 hours per week during the year. None of the responders played 0 hours of digital games.

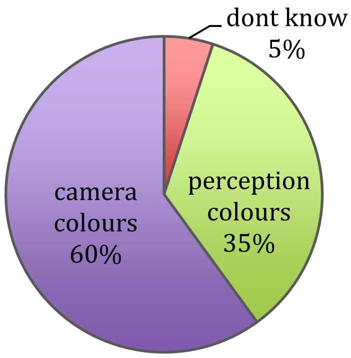

Figure 12 Preferred colour mode

When viewing the responses of the preferred colour mode at all four different light intensities the camera colours were most preferred at 60%. Perception colours were preferred by 35% of the responders while 5% did not know which colour mode they preferred.

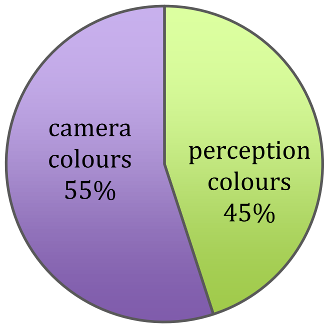

Figure 13 Colour mode believed to me most similar to what would be seen if present in the environment

The ratio between preferred colour mode the colour mode which was believed to be most similar to what the respondent would have seen if present in the environment is very similar. 55% of the respondents believed that camera colours are most similar to what they would have seen, while 45% believed perception colours to be more similar.

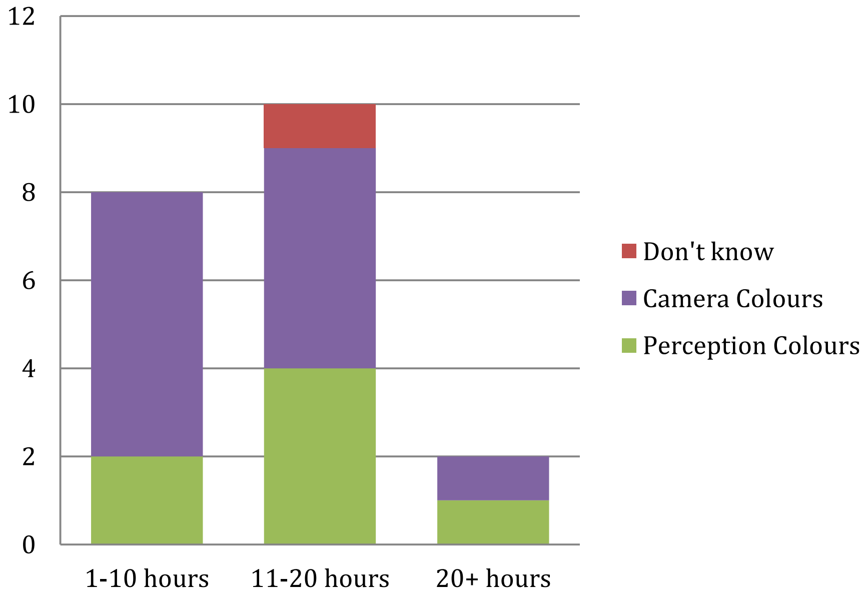

Figure 14 Relation between average game time a week and preferred colour mode

Figure 14 shows the relation between game time and preferred colour based on the answers regarding all four lighting conditions. Out of the 8 respondents who played 1-10 hours of digital games per week two of them preferred the perception based colours while the other 6 preferred the original camera colours. In the 11-20 hours span the ratio between the two colour modes evens out a bit with 4 out of 10 people prefer perception colours while 5 respondents prefer camera colours. In the 11-20 hours play time one person also expressed that they did not know which of the colour modes they preferred. The responses of the responders who played more than 20 hours a week were evenly distributed with one person preferring camera colours while the other preferred the perception based colours.

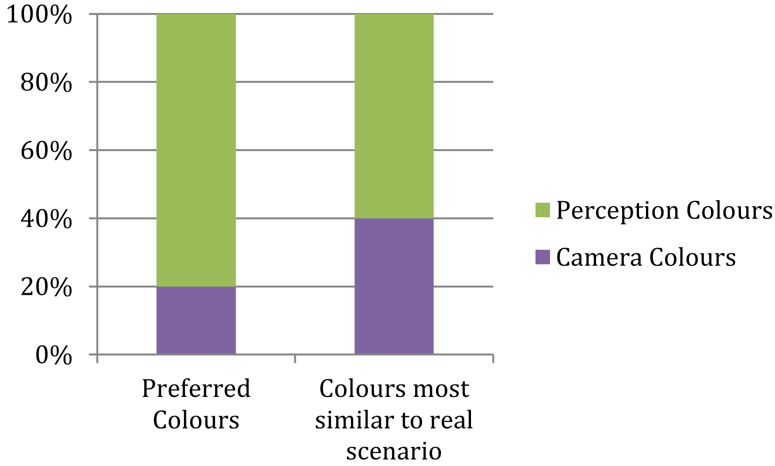

Figure 15 Light setting A

At the brightest light level, A, perception colours were preferred to 80% and were also believed to be most similar to a real scenario with 60% of the respondents choosing perception colours over that of camera colours.

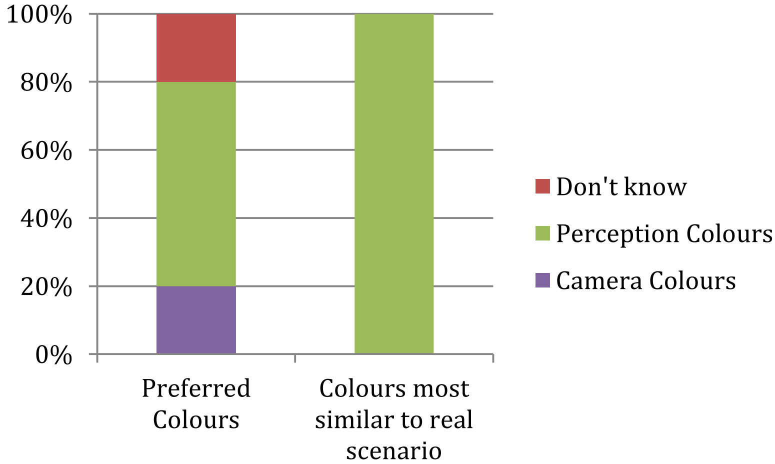

Figure 16 Light setting B

The results regarding Light level B was also predominately favourable to perception colours. 60% preferred perception colours while 20% preferred the original camera colours. The null option of "I don't know" is also represented by a percentage of 20. The results of the question regarding which colours were most similar to what would have been seen if the respondent present in the environment was exclusively perception colours. 100% of the respondents choose perception colours over that of camera colours.

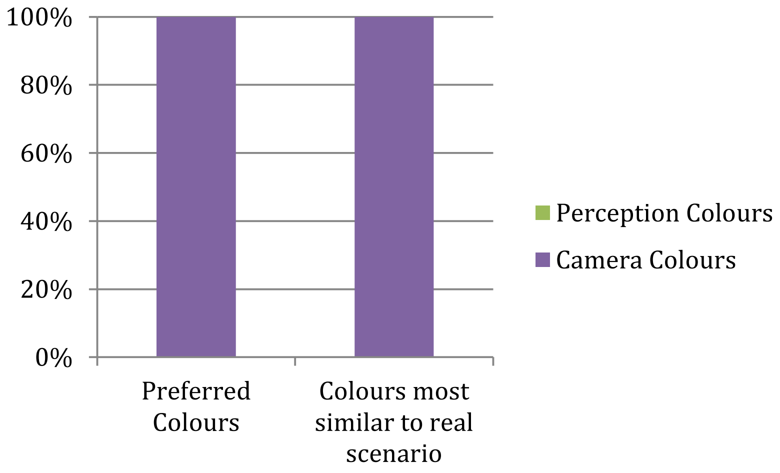

Figure 17 Light setting C

The next to darkest level, light setting C, has the most uniform answers. The respondents all preferred the camera colours and all 100% agreed that the camera colours were most similar to a corresponding real scenario.

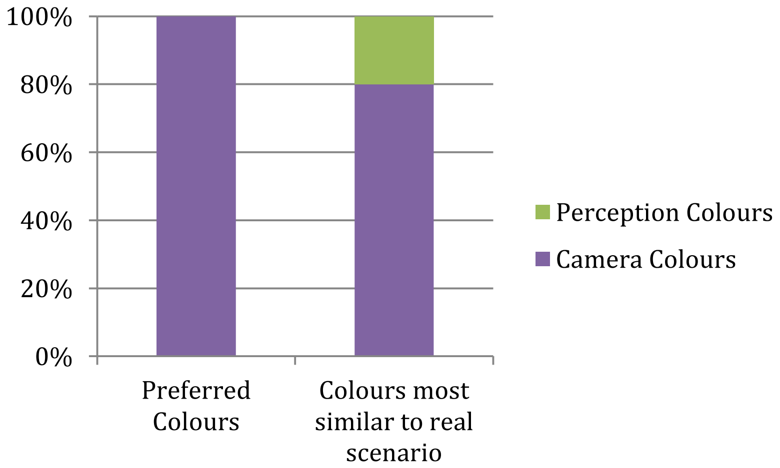

Figure 18 Light setting D

The results regarding the darkest level are very similar to that of setting C. Camera colours were preferred be 100% of the respondents, but in this case only 80% believed that the camera colours were closest to what they would have seen. 20% instead believed that the perception colours were most similar to the real scenario.

85% of the respondents answered the optional qualitative questions regarding the reason why the choose version A or B. These answers as well as the rest of the collected data can be viewed in Appendix D – Survey Results.

5.3 Analysis

The main reason why people preferred the camera colours was based on the principle of mood. As the camera colours are not limited by perception it is possible to see hues or wavelengths that are considered to be warm even though the illumination is low. These colours are often related to light and warmth since strong illumination enables the human eye perceives colours of these wavelengths. Red, orange and yellow are also known to physically increase body temperature which may also be a reason why these colours are attributed to sunlight and warmth (Danger 1987). Warm colours also tend to be perceived as more inviting since the human eye is able to focus on warm colours easier than cool colours. The responders described the camera colours using adjectives like “cosy”, “comfortable”, “happy” and “warm”.

In contrast to camera colours the perception colours were described using word like “uncomfortable”, “unsettling” and “sad”. These words are all related to the mood of the colours and the overall feel of the environment. The perception colours lack some of the warmer colours and the low saturation makes the overall appearance less colourful. As opposed to warm colours, cool colours tend to make objects recede and appear farther away as well as being less visible to the eye and more subdued than warm colours. (Danger 1987). An environment consisting of primarily cool colours will therefore appear to blend together, the blurring and bleeding of colour information causing difficulties when trying to define and distinguish between different shapes. The lack of visual information may be inherently stressful to humans as visual information is vital in detecting and identifying eventual hazards and threats. This may be one of the reasons why cool colours are quite often used in relation to horror themes. Lind-Valdan (2013) outlines horror movies to have “hard, cold blue borderline purple colors” as well as having high contrast.

Perception colours were only preferred in the two brightest levels. In these levels the camera colours were deemed to be too bright by several of the respondents. The reason for this may be that the value contrast of the perception colours was greater than that of the camera colours in the two levels. The perception based colours had more balance in the middle range of values, which may give the appearance of greater contrast. However there was no difference between the brightest parts of the two different coloured areas. Yendrikhovskij (1998) argues that contrast is a vital component when creating well perceived aesthetics. Contrast allow for greater variety of colours and therefore greater sense of depth and more subtle nuances in texture. The greater the value contrast the more information the image will be able to contain and mediate to a viewer. The same is true for colour contrast. A wide colour spectrum in an image will allow for the eye to easier differentiate between different objects and planes. In this sense the information in the image is better communicated and interpreted by the human visual system.

Contrast may also be influenced by the human visual system as it automatically adapts to different amount of illumination. Given an adequate amount of time the eyes will adjust until maximum contrast has been established. In this sense an environment which lacks a certain amount of value contrast will appear artificial while a high contrast environment will appear more true to life. As a high contrast environment will contain more visual information the effect is that the scene will be perceived as sharper, clearer and more detailed. This may be the reason why the perception colours were deemed to be more true to life in the two brighter levels.

Yendrikhovskij (1998) also mentions naturalness as a factor which influences the quality of an image. Naturalness is related to experience and perceived notions of what should be seen. Exposure to camera colours through photographs, television and other type of media may affect which type of colours are perceived to be most true to life. As there were respondents who compared the colours to that of photographs it is not unlikely that camera colours are believed to be most true to life since photos are simple to observe. An environment interpreted by the visual system is hard to properly define as the eyes are always adjusting and adapting according to various internal and external processes. A photo, however, is stable which makes it easy to establish, observe and analyse the image. As most phones have an inbuilt camera of some sort photographs are easily taken anywhere. Apps and social media based on image communications encourage the use of a camera to capture moments in real life. Extended use of photography may result in a normalization of camera colours in the sense that these become more closely connected to the mental view of what the world looks like.

Colour constancy may also be one of the reasons why responders perceived camera colours to be most similar to the colours they would have seen had they been present in the 3D-environment. If the visual system is allowed to process the colours of an environment during the day, when the broadest spectrum of colour may be seen, this will affect the way the environment is perceived during other light conditions. Clarity of vision is an advantage and the mind will therefore try to create as much contrast, both in hue and in value, as possible. If the daytime colours of an environment are known the mind may enhance contrast by overlaying the night time environment with this type of memory colours. This creates a constancy of colour, where colours are exempted from being influenced and changed by various lighting conditions. In this sense the camera colours may be closest to what the mind sees even though, purely biologically, the eyes only perceive a limited spectrum of colours. This would then lead to the question whether the biological part of perception or the psychological factors are most true. As colours are reaction cannot be completely quantified and the consequence of the subjective nature of perceived colour information may be that both the camera colours and the perception colours are “true to life” depending on what aspect is considered.

30% of the respondents expressed that the camera colours appeared to be brighter than the perception colours. The only level which had any major value difference was the brightest level where the exposure has been adjusted to take lightness adaption into consideration, thus receiving more balanced contrast. The three darker levels had the same values and lights regardless of colour mode. The comments therefore suggest that even though the two rooms had similar values the perception colours were perceived as darker than the camera colours. The reason for this observation may be that the perceived lightness is affected by subconscious assumptions based on perception attributes. If the human visual system is able to view the entire spectrum of colours the area has to be exposed by a certain amount of light. In reality the visible colour spectrum is determined by the amount of light, or luminance, of the room. In the case of the test environment the visible colour spectrum is conflicting with the luminance. In this sense it seems like the perceived brightness of the room is dependent upon the colours seen rather than the other way around. The apparent brightness of the camera coloured room would therefore be an illusion caused by subconsciously applying principles of perception to the digital environment.

There are no apparent clear relation between colour preference and game experience and a lack of comprehensive data prevents the drawing of strong conclusions. The population showed a lack of diversity in regards to game experience as only 10% of the respondents played 20+ hours and 0 hours game time was not represented at all. 90% of the responders thus fell into the 1-20 hours of play time per week. The responses are also linked to the four different levels which will influence the data received and thus render the responses unfit to be compared to each other. The relation between game experience and preference may have been made if the responses had been more evenly distributed in the four different levels. In this case the polarization of the data would have made any conclusion too unreliable to be of any use in further research.

5.4 Conclusions

According to the research conducted game engine colours are preferred when experiencing a virtual environment from a 1st person perspective. Colour preference relates to and is affected by light intensity. At high light intensity, from around 200 to 20 lux, HVS perception based colours are preferred and at low light intensity, 2 to 0.02 lux the original game camera colours are preferred.

Colour mode preference seems to be influenced by aesthetics principles, mainly that of mood and contrast. Preferred colour mode often coincided with what the respondents believed would be most similar to what they would have seen if they had been physically present in the virtual environment. There is no proven direct relation between the two variables in this study, however according to Christou and Parkers (1995) there is a correlation between contrast and naturalness. Perceived realism is dependent upon the amount of visual information received and greater spectrums of hue and value will allow for more details to be made visible. Both contrast and naturalness are also factors which contribute to image quality according to Yendrikhovskij (1998).

In a virtual environment experienced from a first person perspective the original game engine camera colour are not unanimously preferred. There are conditions where adjusted, perception based colours are better received. Thus to receive a more universally positive reaction to the colours of a digital environment the colours need to be adjusted and modified according to light intensity.

6 Concluding Remarks

6.1 Summary

Game engine render 3D environments through the use of a game engine camera. Depending on the medium colour information is processed and communicated differently. Digital environments which are experienced from a first person perspective simulate that the environment is viewed with the use of the human visual system. In these situations colour processing based on visual perception may be applied as an alternative to the camera based colour processing. This thesis provides data in regards to which colour mode is most preferred and how the preference is affected by level of illumination.

The human visual system (HVS) ability to interpret colour information is affected by light intensity and the differences between the two colour modes therefore become more visible as the illumination decreases. As opposed to a camera, visual perception processes colours in a non-linear fashion. The HVS perceive colour information though three different channels, which results in colours being interpreted with various efficiency depending on illumination. The adaptive properties of the visual system also create a non-linear correlation between illumination and contrast.

By creating a 3D-environment consisting of two identical rooms and then applying one of the colour modes to each room direct interaction with the two modes was made possible. Four different versions of the environment were created, each with a different level of illumination, covering a luminance range from light adapted to dark adapted vision. A test group was then asked to evaluate the environment in terms of colour preference and similarity to real life. 60% of the respondents preferred the original camera colours, while 35% preferred the perception colours and 5% did not know which mode they preferred. 55% considered the camera colours to most similar to what they would have seen if they had been present in the environment, 45% choose perception based colours. In the two brightest versions of the test environment perception colours were most preferred as well as being deemed most true to life while the opposite was true for the two darker versions.

At high light intensity, from around 200 to 20 lux, colours based on the human visual system is preferred and at low light intensity, 2 to 0.02 lux the game engine camera colours are preferred. For the colours of a digital environment to be well received and perceived as true to life the colours thus need to be modified and adjusted according the illumination of different areas.

6.2 Discussion

The results may be used as a resource by game designers and game artists when discussing and applying colour grading in digital games. The research will hopefully contribute to the field of digital game graphics by providing a scientific approach to 3D colour grading. Having knowledge of the general reception of a 3d-environment with different colour modes will help when deciding in which mode to use depending on situations and even when to merge the two modes together. Scientific research which is based on a foundation of perception may be a good complement to resources regarding artistic principles and theories when designing a colour grade. The standard camera colours were not universally preferred which means that some kind of adjustment may be necessary to receive a more positive response to the colours of a 3D-environment.

Digital games and computer graphics are relatively new field which offer a lot of opportunity for progress. This study will contribute with the application and incorporation of different fields of study to that of digital games. By applying theories from different scientific subjects it is possible to find and synthesize new principles which may help to advance digital games. This study does not argue for or against any previous research, but instead tries to build upon and expand upon already established research as well as finding new ways that this research can be used. Instead of adding to previous research this study will provide further opportunity for innovative research in the field.

It is problematic to compare the study to previous studies as none of the studies test their theories in an interactive environment. There has been quite a lot of research in regards to the aesthetics of colour grading in 2D-media such as photographs and film. However these types of media differ greatly from interactive 3D-media, such as 3D-games and virtual reality games in which the player/viewer directly influences the experience. In this sense any comparison and parallels drawn between the subjects will be unreliable.

6.2.1 Validity

In order to for the data to be conclusive the artefact has to be tested on a more extensive group of testers, both in quantity and selection. To conclusively prove any type of correlation between several different factors professional statistical tools and software, such as *SPSS Statistics* (IBM Corporation 2016), need to be used. Since the quantitative data is compiled and analysed manually the data itself should not be used as any type of evidence or proof, but rather as a hint to the chosen population’s general inclination. The research conducted is better suited to be used as a starting point for further research in the subject of 3D colour grading.

The lighting created in the game engine is somewhat imprecise and illumination value was established through the use of visual comparison only. The light intensity in lux is therefore an estimate of the illumination of the environment rather than a precise established value. The perceived brightness of the digital environment is also affected by the eyes light adaption and may therefore be influenced by the respondents previously situation before entering the test room. A respondent who has just recently spend some time outdoors in direct sunlight will have a different light adaption than a respondent who has spent time in an indoor setting.

The result may have been affected by the uniform nature of the test group. The group lacks diversity in age and background as all of the testers were college students who had been reached through either social media or through association with other testers. A more diverse test group would have given more varied results and thus allowed for a more nuanced analysis of the collected data. Had the test group been more accurately defined, with statistics regarding age, gender, background etc. any type of analysis regarding the results would have been more representative of a specific group of people. Inference regarding eventual uses and applications of the results would have been easier to make and also more viable.

All of the respondents played digital games regularly, which will affect the data collected. The data may have been different had the test group consisted of people who does not have a lot of experience in playing digital games. In this sense the result and subsequent analysis may be more applicable to an entertainment setting rather than a simulation or game intentionally designed to be experienced by a group which has little experience of playing digital games.

6.2.2 Ethics

Those who participated in the study received information as to the purpose of the test as well as their right to anonymity. The participation was voluntary and could be called off at any point. No names or other points of identification was collected and questions regarding reasons for certain answers were optional question and not mandatory to complete the test. As the focus of the thesis is placed on biological principles and physical properties of light there are few aspects of the artefact which tie into ethics. Humanistic standpoints are minimal and there are no representations in the form of characters and avatars which may cause concern. The use of a first person perspective and basic environmental design was decided upon to eliminate gender and cultural issues.

When conduction the initial research into the field of colour grading there was no information found which relates to colour grading in 3d space. Research in regards to real time colour grading in 3D may be sparse as it is dependent upon recent technological progress. The research made contributes with knowledge of how colour theory and 2D colour grading techniques may be used in an interactive 3D environment. Theoretical progress will contribute with new aspects and knowledge which is imperative when considering the game industry's rapid expansion and increasing revenue.

6.3 Future Work

Given more time additional respondents could be asked to participate in the test in order to improve reliability of the result and thus also the viability of the study. Other variables such as gender could also be included to give the study a greater scope and refine the population. A more extensive test group would also have enabled a discussion regarding the relation between correlation between colour mode preference and experience of playing digital game.

In the artefact the colour grade has been applied manually to a restricted area. When creating larger and more extensive environment the illumination level may differ greatly between different areas. Instead of having a few specific colour grades it would then be beneficial to have a seamless blend of colour grades which corresponds to a spam from high to low luminance levels. There may be a way to then apply the correct grade automatically to its corresponding luminance level. The effect of this would be a dynamic colour grade which is constantly altering and adapting to the player's immediate surroundings. This would be more true to life than using colour grades globally over an entire area of the game as lighting conditions are very complex and may be affected by a great number of factors. Dynamic colour grading which take this into consideration may be a great asset to games with focus on atmosphere and lighting.

When using the theories discussed in this thesis in a game for entertainment it would be beneficial to take aesthetics and psychological principles into consideration. This thesis only incorporates one of Yendrikhovskij (1998) three factors; naturalness. To create image quality the colour grading would need to be adjusted to enhance colourfulness (variety of hue and saturation) and discriminability (colour and lightness contrast) as well. Ideals also affect the way an environment is perceived by the human mind. Even though the eyes might see one thing the mind will automatically correct and adjust this image based on ideals and previous experience. Research in regards to these factors may be added to this research to achieve a more substantial ground for creating and adjusting colours in games and 3D-environments.

The theories discussed in the thesis can contribute in developing a more complete synthesis of human vision. This task would require collaboration between graphical artist and students of biology or neuroscience as a more extensive project would quickly become more technical. Psychophysical processes and other aspects of human visual perceptions may be studied to find practical behaviours which may be applied towards digital visualisation and digital games. Examples of these are depth perception, focus, and discriminability as well as how these features are affected by central and peripheral vision. A science based model of human perception may be utilized in various simulation and scenarios in which perception are vital to the experience. These may be simulated training for various professional training for positions such as, fire fighting, police and military personnel.

In regards to entertainment games the research can be used when simulating real life scenarios, such as survival games, where human visual perception may be used as a mechanic or obstacle which the player has to work with or against. The almost monochrome night time vision may for example hinder the player from finding certain plants which may be a lot more visible during day light. This mechanic can thus be used to affect the dynamics of a game. For example the FPS game *Arma 3* (Bohemia Interactive 2013) utilizes complete darkness to allow for night vision goggles and light flares to become important tools in the game.

The colour grading theory can also be used to enhance effects in games with horror themes. As the ability to discern between colours become less effective as the light level decreases the lack of colour contrast will make it more difficult to discern between different shapes and objects. The effect may be used to create a greater sense of trepidation and suspense. The lack or reduction of visual input is closely related to the human fundamental fear of the dark. The supernatural horror game *SCP – Containment Breach* (Rikkonen 2012) uses a similar concept by using the act of blinking as one of the game's main mechanics.

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Appendix A - Survey

Questions to answer before the test

Do you have, to the best of your knowledge, full colour vision?

- ☐ Yes
- ☐ No

During the last 12 month, what is your estimate of average time playing digital games during a week?

- ☐ 0 hours
- ☐ 1-10 hours
- ☐ 11-20 hours
- ☐ 20+ hours

Instructions

For two minutes you are going to be able to walk around in a 3D environment consisting of two rooms (A and B). The two rooms are identical in every way except for the overall colours.

Move with WASD, jump with SPACE and change direction of camera with the mouse.

After the two minutes are over you will be asked to answer the two questions below;

Questions to answer after the test

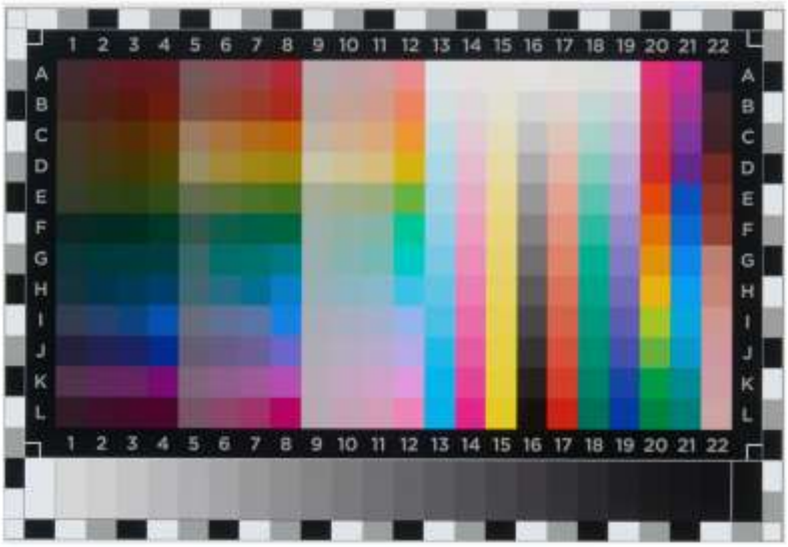
Which colours do you prefer?

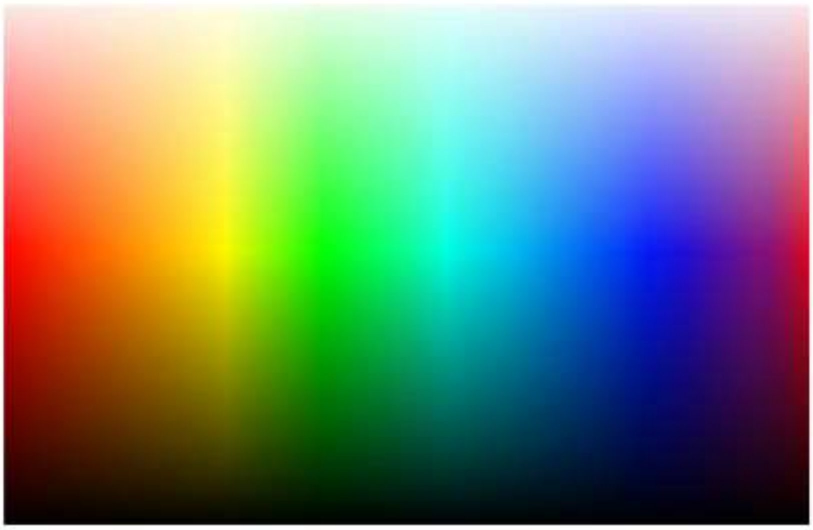
- ☐ A
- ☐ B

Which colours do you think is most similar to the colours you would have seen if you yourself had been present in the environment?

- ☐ A
- ☐ B

Appendix B - Colour Reference Texture





Appendix C - Look Up Textures

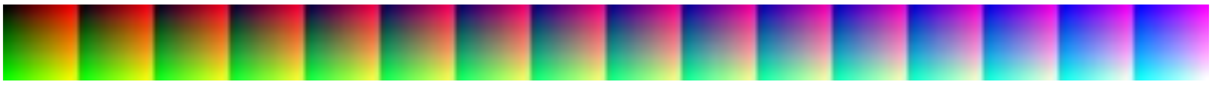


Figure 19 Original LUT

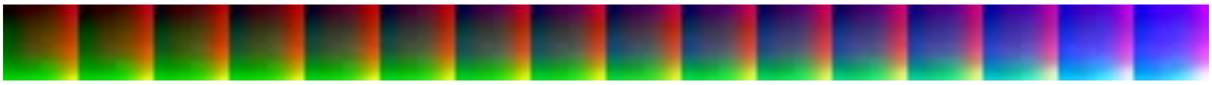


Figure 20 HVS perception based LUT created for light settings of ~200 lux

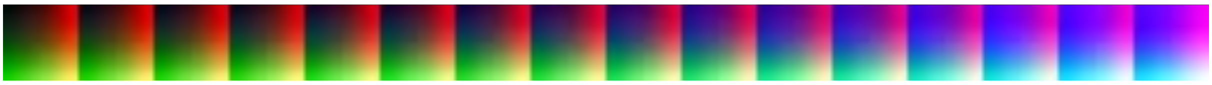


Figure 21 HVS perception based LUT created for light settings of ~20 lux

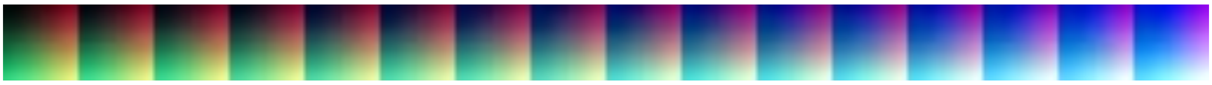


Figure 22 HVS perception based LUT created for light settings of ~2 lux

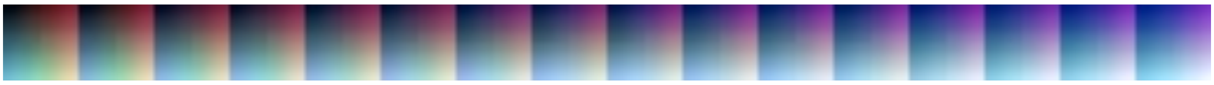


Figure 23 HVS perception based LUT created for light settings of ~0.02 lux

Appendix D - Survey Results

Do you have, to the best of your knowledge, full colour vision?	During the last 12 month, what is your estimate of average time playing digital games during a week?	Which colours do you prefer?	Why? (optional)	Which colours do you think is most similar to the colours you would have seen if you yourself had been present in the environment?	Why? (optional)
Light Setting A					
Yes	11-20 hours	B	Färgerna var starkare (eller hade mer mättnad - vet inte vad som är korrekt term) och därför upplevde jag miljö B som roligare och mer färgrann. Det var ett trevligt rum. Det enda jag egentligen inte gillade med B var att vissa ytor såg väldigt glansiga ut, nästan som att de var lite "sticky", eller som att de var nytvättade/polerade. Men overall blev jag gladare och mer taggad över färgerna i rum B än rum A.	A	Färgerna kändes nertonade på ett sätt, vilket känns mer likt verkligheten. Som van instagrammare brukar jag alltid höja mättnad i mina bilder och ibland även lägga ett tonat färgfilter över för att jag tycker att verklighetens färger "inte räcker till" (men ibland är det nog för att kameran tar upp färg på ett annat sätt än vad mitt öga gör...). Jag såg texturer, detaljer och mönster snabbare i rum A än i rum B. Ytorna var inte lika glansiga som i rum B, och det gav en ytterligare känsla av realism. Rum A kändes väldigt upplyst, som att en stark lampa lyste på. Färgerna såg "vitare" ut.
Yes	1-10 hours	A	Det kändes mycket mer ljusare och det påminde om solljus	B	Färgerna på sakerna kändes mer skarpare och klarare vilket jag tror att jag skulle sett eftersom att det inte hade någon ljuskälla och skulle inte då ha uppfattats som lika ljust som möblerna i rum A.
Yes	11-20 hours	B	Smoother light, easier for the eye.	A	I think it depends on how much time the eye has to adjust t the brightness, but A is what i think is the most common way you would experience a sunny day env.
Yes	20+ hours	B	it feel more the the games i usually plays	B	
Yes	1-10 hours	B		B	
Light Setting B					
Yes	11-20 hours	B	Greater contrast; less disturbing level of brightness	B	
Yes	20+ hours	A	För att miljön fick ett bättre djup. Miljö A kändes alldeles för ljus	B	Kändes mer naturligt
Yes	1-10 hours	B	It felt nicer to look at.	B	
Yes	11-20 hours	B	I liked it a bit darker. Or at least it felt darker.	B	
Yes	11-20 hours	I don't know	Depends on the context	B	They felt more realistic and softer than Room A

Do you have, to the best of your knowledge, full colour vision?	During the last 12 month, what is your estimate of average time playing digital games during a week?	Which colours do you prefer?	Why? (optional)	Which colours do you think is most similar to the colours you would have seen if you yourself had been present in the environment?	Why? (optional)
Light Setting C					
Yes	1-10 hours	A	Because the colors in Room A look more "real". Room B looks more washed out and "warped".	A	See above.
Yes	1-10 hours	A	Kändes mer som utomhus mitt på dagen, därför kändes det mer naturligt och bekvämt	A	Jag tror att det kändes så för att ljuset kändes mer som solljus vilket är mer naturligt och det kommer in i alla utrymmen om det inte är helt mörklagt.
Yes	1-10 hours	A	Ljusare och upplevs trevligare. Alternativ B känns mer obehagligt och mörk vilket ger ett obekväm och små läskig upplevelse. A känns allmänt mysig och glad, i jämförelse med på som tidigare nämnt känns obehaglig och sorglig.	A	Kändes mer verklighetstroget och är den typ av ljus jag strävar efter att ha runt mig. Det mörka blir för mörkt och ansträgande för ögonen.
Yes	11-20 hours	A	It feels warmer and more natural in a sense. At the same time it depends on context of the game. Id prefer B for a horror.	A	
Yes	1-10 hours	A	The tint in B feelt unnatural	A	The blue tint did not fit the lighting.
Light Setting D					
Yes	1-10 hours	A		A	
Yes	11-20 hours	A	the environment seemd more cozy	A	seemd to be in an arificial environment, so, the lamps and such would light the room up
No	11-20 hours	A	Det var ett mer 'naturligt' ljus och inte en blå 'natt-himma' som låg för linsen.	A	
Yes	1-10 hours	A	Mycket varmare och trevligare miljö	B	
Yes	11-20 hours	A		A	