ABSTRACT

HINES, DANIEL SCOTT. Veiling Glare and Its Influence on Measurements with Optical Instruments. (Under the direction of Dr. Renzo Shamey).

DSLR cameras have become attractive options in fields where light measurements of a scene are of interest. Whether for determining luminance (perceived light intensity) or color measurement, DSLR cameras provide a more affordable option over traditional instruments such as radiometers or spectrophotometers. However, DSLR cameras are designed to capture an attractive image, rather than generate scientific data. Veiling glare decreases the contrast in an image by introducing stray light onto the image sensor, which thus affects the accuracy of measurements. Glare is present in virtually all systems that employ a lens, including the human eye. The extent of glare, however, is different depending on the complexity of the lens fixture. This work investigates the impact of veiling glare on measurements using DSLR cameras compared to a radiometer. Multiple experimental setups were used to quantify the amount of glare present at a given position in the image. The first part of the study compared a DSLR camera with a series of lenses against a radiometer by using a mask around the target that would produce either high or low amounts of glare. The second half of the study examined how a gradual change in the surround reflectance would influence the response intensity from a target. Results confirm that both cameras and radiometers are influenced by veiling glare due to changes in the surround of the target. The second part of the study allowed us to define a functional relationship for the glare in each instrument. A target’s measured luminance was changed by as much as 20% due to veiling glare for a DSLR camera depending on the color of the surround. For a radiometer the change was less severe but still apparent.
Veiling Glare and Its Influence on Measurements with Optical Instruments

by
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TABLE OF CONTENTS

LIST OF TABLES .................................................................................................................. v
LIST OF FIGURES .............................................................................................................. vi
LIST OF EQUATIONS .......................................................................................................... ix

CHAPTER 1: LITERATURE REVIEW ...................................................................................... 1
  1.1 Lenses .......................................................................................................................... 1
    1.1.1 Ray Optics ............................................................................................................ 1
    1.1.2 Lens Construction ............................................................................................... 5
    1.1.3 Veiling Glare ....................................................................................................... 10
  1.2 Colorimetry .................................................................................................................. 14
    1.2.1 Human Color Vision ......................................................................................... 14
    1.2.2 Tristimulus Values ............................................................................................. 17
    1.2.3 Color Space ........................................................................................................ 20
      1.2.3.1 Chromaticity Diagram .................................................................................. 20
      1.2.3.2 CIELAB Space ............................................................................................. 21
      1.2.3.3 Color Difference Calculations ...................................................................... 23
      1.2.3.4 RGB Color Spaces and Conversions ............................................................ 24
  1.3 Veiling Glare Assessment Methodology ......................................................................... 26
    1.3.1 ISO ...................................................................................................................... 26
    1.3.2 Other Methods ................................................................................................... 29
  1.4 DigiEye Illumination Chamber .................................................................................... 30
  1.5 ColorChecker ............................................................................................................... 33
  1.6 Digital Camera Based Colorimetry .............................................................................. 34
    1.6.1 Digital Camera Sensor ....................................................................................... 34
    1.6.2 Image Processing Methods ................................................................................ 37
  1.7 Other Light Measurement Techniques ......................................................................... 39

CHAPTER 2: METHODOLOGY AND INSTRUMENTATION ..................................................... 41
  2.1 Experimental Setup .................................................................................................... 41
  2.2 Image Capture Configuration .................................................................................... 44

CHAPTER 3: THE EFFECT OF VEILING GLARE ON MEASUREMENTS ......................... 46
  3.1 Effect of Surround on Veiling Glare ........................................................................... 46
  3.2 Effect of Sensor Location on Veiling Glare ................................................................. 51

CHAPTER 4: VEILING GLARE VARIATION BASED ON LENS CONSTRUCTION .......... 54
  4.1 Lens Construction Methodology ................................................................................ 54
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2 Effect of Lens Construction on Veiling Glare</td>
<td>54</td>
</tr>
<tr>
<td><strong>4.3 Comparison of Lens Construction</strong></td>
<td>56</td>
</tr>
<tr>
<td>CHAPTER 5: CHARACTERIZING SURROUND EFFECTS ON VEILING GLARE</td>
<td>58</td>
</tr>
<tr>
<td>5.1 Gradual Change in Surround</td>
<td>58</td>
</tr>
<tr>
<td>5.2 Constant Image Scene with Change in Distance from White Area</td>
<td>62</td>
</tr>
<tr>
<td>CHAPTER 6: CONCLUSIONS</td>
<td>68</td>
</tr>
<tr>
<td>6.1 Conclusions</td>
<td>68</td>
</tr>
<tr>
<td>6.1.1 Effect of Veiling Glare on Measurements</td>
<td>69</td>
</tr>
<tr>
<td>6.1.2 Veiling Glare Variation Based on Lens Construction</td>
<td>69</td>
</tr>
<tr>
<td>6.1.3 Characterizing Surround Effects on Veiling Glare</td>
<td>70</td>
</tr>
<tr>
<td>6.2 Recommendations for Future Work</td>
<td>72</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>73</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 1.1: Characteristic components of Nikon Lenses [5]...................................................... 7
Table 1.2: Light measurement instruments.................................................................................. 39
Table 2.1: Settings Used for Spectrophotometer........................................................................ 42
Table 2.2: Settings used for Spectroradiometer.......................................................................... 42
Table 2.3: Nikkor Lenses Used for Experiments......................................................................... 45
Table 5.1: Edge and Center Green Channel Values. ................................................................. 65
LIST OF FIGURES

Figure 1.1: Reflection and Refraction of Light from an Air to Glass Surface.......................... 2
Figure 1.2: Schematic Representation of Snell’s Law................................................................. 2
Figure 1.3: Chromatic Dispersion of Light.................................................................................. 4
Figure 1.4: Thin Lens Ray Tracing and Focal Length of Lenses....................................................... 5
Figure 1.5: AF-S Nikkor 50mm f/1.8G [5].................................................................................. 7
Figure 1.6: AF-S DX Nikkor 35mm f/1.8G [5]............................................................................. 8
Figure 1.7: AF-S DX Zoom-Nikkor ED 18-55mm f/3.5-5.6G [5].................................................... 8
Figure 1.8: AF-S DX Nikkor 18-140mm f/3.5-5.6G ED VR [5]. ..................................................... 9
Figure 1.9: Circled areas show a decrease in contrast between the banner and the background due to veiling glare from excess sunlight (Left)......................................................... 11
Figure 1.10: Schematic Representation of Light Rays Reflecting in a Single Lens System......... 13
Figure 1.11: Schematic Representation of Observing an Object Color........................................ 14
Figure 1.12: Schematic diagram of the human eye with some key structures labeled [12]. ....... 15
Figure 1.13: Spectral Sensitivities of L,M, and S cones in the human eye [12]............................ 17
Figure 1.14: Spectral sensitivity of human eye to light represented as Luminosity function
(V) [15]. ....................................................................................................................................... 17
Figure 1.15: Spectral Power Distribution of Illuminant D75 [15]................................................... 18
Figure 1.16: Spectral tristimulus values of the CIE 1931 standard colorimetric observer
[15]................................................................................................................................................. 19
Figure 1.17: CIExy Artist’s Representation of Chromaticity Diagram (1931) [16]........................ 21
Figure 1.18: Cartesian and Polar Representation of LAB Color Space [12]................................. 23
Figure 1.19: Gamuts of sRGB (black line) and Adobe RGB (1998) (red line) [16].................... 25
Figure 1.20: Veiling glare measurement in the case of an unlimited object field [6]................................. 27
Figure 1.21: Arrangement of measuring equipment for reflection-type test chart [7]................................. 28
Figure 1.22: Window pattern charts for single spot measurement [7]......................................................... 29
Figure 1.23: A schematic representation of the DigiEye illumination chamber and the digital camera setup employed to assess veiling glare................................................................. 31
Figure 1.24: Illumination stability in the DigiEye Unit [19]................................................................. 32
Figure 1.25: GretagMacbeth ColorChecker DC .................................................................................... 34
Figure 1.26: Example of a color filter array called a “Bayer pattern”....................................................... 35
Figure 1.27: Spectral response of various digital cameras [24]................................................................. 36
Figure 1.28: ‘GBRG’ Bayer array repeat pattern [27].............................................................................. 38
Figure 2.1: Illuminance measurements (in lux) within a 7 × 7 grid inside the DigiEye illumination chamber using a surface graph to extrapolate and visualize data ......................... 44
Figure 3.1: Diagram of the veiling glare experiment within the DigiEye Unit ............................................ 46
Figure 3.2: Gray patch labels from the highest (J6) to the lowest (L8) L* value...................................... 47
Figure 3.3: Patch J6 centered in the DigiEye with white mask (top), without mask (middle), and with black mask (bottom).................................................................................... 48
Figure 3.4: White and Black Mask Surround Effect on Veiling Glare for DSLR........................................ 50
Figure 3.5: White and Black Mask Surround Effect on Veiling Glare for Radiometer................................. 50
Figure 3.6: Thin White Mask Effect on Veiling Glare for DSLR................................................................. 51
Figure 3.7: ColorChecker positioned in the DigiEye corners labelled 1, 2, 3, and 4....................................... 52
Figure 3.8: Corner and Center measurements of patch J6 within the DigiEye after Uniformity Corrections.............................................................................................................. 53
Figure 4.1: No Mask Lens Comparison.................................................................................................. 55
Figure 4.2: Black Mask Lens Comparison. .......................................................... 55
Figure 4.3: White Mask Lens Comparison. ........................................................ 56
Figure 4.4: Percentage Difference between No Mask and Black Mask. .................. 57
Figure 5.1: Diagram of Laser Cut White Mask. .................................................... 58
Figure 5.2: Images of the surround radius increasing. ........................................... 59
Figure 5.3: Black Cardboard Radiometer Uniformity. ........................................... 60
Figure 5.4: Painted White Cardboard Radiometer Uniformity .................................. 60
Figure 5.5: Gradual Surround Change with DSLR ................................................. 61
Figure 5.6: Gradual Change in Surround with Radiometer ....................................... 61
Figure 5.7: Diagram of pixel locations used for DSLR Images. ................................ 62
Figure 5.8: Uniformity of Black Cardboard Compared to Uniformity Board ............... 64
Figure 5.9: Relative Intensity of Half Black, Half White Image. ................................. 65
Figure 5.10: Edge experiment adjusted for vignetting ............................................ 66
Figure 5.11: Radiometer Edge Experiment ............................................................ 67
LIST OF EQUATIONS

Equation 1.1: Fresnel equations ........................................................................................................ 3
Equation 1.2: XYZ Tristimulus Equations ...................................................................................... 20
Equation 1.3 Transformation of Tristimulus Values to Chromaticity Coordinates ................... 20
Equation 1.4: XYZ to LAB conversion ............................................................................................ 22
Equation 1.5: L*a*b* transformation to Cab* and h_ab ................................................................ 23
Equation 1.6: CIEDE2000 Color Difference Equation ................................................................. 24
Equation 1.7: sRGB relationship to XYZ with XYZ scaled 0-1 [16] ........................................... 25
CHAPTER 1: LITERATURE REVIEW

1.1 Lenses

This work investigates the use of DSLR cameras as an instrument to measure light and color. To form an image, light must first pass through the camera lens and there are several basic interactions between light with the glass in the camera lens.

1.1.1 Ray Optics

Glass used for the construction of camera lenses is similar in its properties across lens manufacturers, but the construction of the lens can vary. This leaves the shape of the glass in a lens as the main factor in controlling where light travels. Light that encounters a surface between two materials such as air and glass behaves the same way each time it encounters that specific transition. When light hits a surface, it will either reflect from the surface, or refract into the new material as shown in Figure 1.1. For a surface such as glass, the reflection angle will be equal to the initial incidence angle, i.e. the angle at which the light encounters the surface. This is also known as the specular reflection due to surface acting like a mirror. Refraction of light occurs when light transitions between materials with different refractive indices, as illustrated in Figure 1.2 [1]. There are several equations that help describe refraction and reflection.

Refractive index, denoted by $n_i$ in Figure 1.2, can be used to indicate the change in speed of light when it travels through a material other than air. In a material with a higher refractive index, light travels slower than in air. Using the refractive index of a material, Snell’s law can be employed to predict refraction angle through that material [1]. Some lens parts will have higher refractive indices to bend (refract) light more, but these pieces are limited due to higher cost [2].
When light travels through a surface such as air to glass, a percentage of light will refract and a percentage will be reflected. The percentage of light that refracts or transmits can be calculated using Snell’s Law:

\[ n_1 \sin \theta_{\text{incident}} = n_2 \sin \theta_1 \]
\[ n_1 \sin \theta_{\text{incident}} = n_3 \sin \theta_2 \]

where \( \theta_1 < \theta_2 \) and \( n_1 > n_2 > n_3 \).
described by Fresnel model, which is given in Equation 1.1. This equation uses angles of refraction obtained from Snell’s Law. The values obtained are the percentage of light reflected \( (r) \) and transmitted \( (t) \). The \( x \) and \( y \) subscripts are the two types of polarized light. The \( x \)-polarized light is TE (transverse electric) or orthogonal while \( y \)-polarized light is TM (Transverse Magnetic) or parallel. This designation represents the direction the electric field of light is polarized to the plane of incidence (this plane is perpendicular to the surface that the light is transitioning through [1]).

\[
\begin{align*}
    r_x &= \frac{n_1 \cos \theta_1 - n_2 \cos \theta_2}{n_1 \cos \theta_1 + n_2 \cos \theta_2}, \quad t_x = 1 + r_x \\
    r_y &= \frac{n_1 \sec \theta_1 - n_2 \sec \theta_2}{n_1 \sec \theta_1 + n_2 \sec \theta_2}, \quad t_y = (1 + r_y) \frac{\cos \theta_1}{\cos \theta_2}
\end{align*}
\]

Equation 1.1: Fresnel equations

One final source of reflection is the total internal reflection of light that can occur when travelling from a medium of high refractive index to a medium of lower refractive index. Total internal reflection occurs at angles larger than the critical angle. The critical angle is that causes light to exit the higher index medium into the lower index medium at 90°, which would be parallel to the surface. The critical angle can be calculated using Snell’s law (Figure 1.2) and using 90° as the refracted angle. Any light coming to the glass-air surface at an angle greater than the critical angle will be completely reflected [1].

Different wavelengths of light do not travel at the same speed. Thus, shorter wavelengths (blue) experience a higher refractive index than longer wavelengths of light (red). This causes a dispersion effect when light passes into a material, as schematically shown in Figure 1.3. [1]
When a light ray encounters a spherical boundary such as those in camera lenses, it travels in a predictable path depending on the radius of that spherical surface [1]. When two surfaces are put together, a lens object is made. The thickness of the lens produces a negligible change in the vertical distance that a ray travels through the lens. Light rays can be traced depending on the curvature of the two lens surfaces as well as via calculation of the focal length \( f \) [1]. For a multicomponent camera lens, the focal length is considered the effective focal length of a single thin lens that would produce the same image, as illustrated in Figure 1.4.
1.1.2 Lens Construction

The goal of a digital camera lens is to accurately focus the light from a scene onto the camera’s sensor. Manufacturers consider a number of factors when designing a camera lens, but the goal of the manufacturer is to produce an appealing image rather than perfectly reproduce colors within the scene. Physically, all lenses reflect and refract light regardless of their shape. Optically, lens shape determines where light is guided because it determines the angle light reaches the surface. An antireflection coating can be used to improve lens performance. There are multiple glass elements in a lens and at each air-glass surface most of the light passes through but a small amount is reflected. A single coating can reduce reflection from 4% to 1%, and this reduction adds up because lenses contain multiple elements that each reflect small percentages of light [2]. Optical glass used in lens elements have a refractive index around 1.5 [3], which is greater than antireflection coatings like magnesium fluoride [2] that have a refractive index of about 1.37 [4]. An antireflection coating is thin enough that the final angle and location of light rays that pass into the glass lens are not impacted as reach material behaves under Snell’s law and refractive index changes. The number of elements in a lens can range widely. For instance, the AF-S DX Nikkor
35mm f/1.8G contains 8 elements while the AF-S DX Nikkor 18-140mm f/3.5-5.6G ED VR contains 17 elements [5]. The reason for the difference in the number of elements in these lenses is due to differences in complexity of the operation. The 35mm lens is considered a fixed lens that does not change its field of view. The 18-140mm lens is a zoom lens, which means its focal length and field of view can be adjusted [2]. Even with the addition of antireflection coatings these “partial mirrors” are impossible to eliminate completely and the reflections add up.

There are two types of elements, spherical and aspherical. Spherical elements are shaped in the curvature of a sphere either concave or convex and have the benefit of being less costly. Aspherical lenses are more expensive than spherical ones due to the techniques used for manufacturing. Due to high price aspherical lenses are limited in their use, but most lenses will contain at least one [2].

Lens types can vary in the number and types of elements depending on their end use. For use in this work, some lenses were considered to be impractical and therefore were not examined. Thus, very wide angle lenses and fish eye lenses that allow a large amount of stray light into the system were excluded. An example of a lens considered is the 35mm focal length lens, which was the lens being used in this project. The Nikon lenses, listed in Table 1.1: Characteristic components of Nikon Lenses. Table 1.1, were considered for this work and their specifications are provided by the manufacturer’s website in Figures 1.5-1.8. The information provided by the manufacturer are the number of elements and groupings of elements, the construction of the lens, and Modulation Transfer Function (MTF) charts, that help show the resolution properties of the lens as a form of determining lens quality.
Table 1.1: Characteristic components of Nikon Lenses [5].

<table>
<thead>
<tr>
<th>Nikon Lens Name</th>
<th>Type</th>
<th>Elements</th>
<th>Groups</th>
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<tbody>
<tr>
<td>AF-S Nikkor 50mm f/1.8G</td>
<td>Fixed</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>AF-S DX Nikkor 35mm f/1.8G</td>
<td>Fixed</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>AF-S DX Zoom-Nikkor ED 18-55mm f/3.5-5.6G</td>
<td>Zoom</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>AF-S DX Nikkor 18-140mm f/3.5-5.6G ED VR</td>
<td>Zoom</td>
<td>17</td>
<td>12</td>
</tr>
</tbody>
</table>

Figure 1.5: AF-S Nikkor 50mm f/1.8G [5].
Figure 1.6: AF-S DX Nikkor 35mm f/1.8G [5].

Figure 1.7: AF-S DX Zoom-Nikkor ED 18-55mm f/3.5-5.6G [5].
For the most part, majority of the elements in the Nikon lenses are spherical thin lenses, and one element is an aspherical lens. The additional labels in the construction are glass of different refraction indices, and other technology implemented for zoom lenses. Each element is a lens, and each grouping comprises two or more elements glued together.

Lens quality for commercial lenses is typically given to consumers in the form of Modulation Transfer Function (MTF) charts. This is the basic information for users to understand how a lens will image in certain settings and provides useful information on some lens factors, but is not useful in estimating other factors [2]. The main information provided by MTF charts is given as the resolution of closely placed black and white bars. The x axis on the chart is the distance from the center of the lens in millimeters and the y axis is the resolution, which ranges from 100% to 0%. When resolution is 1.0, there is clear definition between the lines. As the resolution between these lines decreases, the lines become less defined and appear grey or blurred [2]. For most lenses, the resolution decreases as the image moves away from the center of the lens.
MTF charts only describe lens quality in terms of resolution. This can give insight to image sharpness effects such as blurring and even distortion. This does not, however, give any direct insight to color reproduction qualities of the camera lens [2]. This information is useful however, as it indicates there will be blurring and decreased contrast at the edges of the image when selections are cropped out for analysis. It is important to be aware of this issue and provide an acceptable spacing from the edges of two colors to avoid reducing the contrast between them and altering color appearance in imaging.

1.1.3 Veiling Glare

Lenses require multiple elements to adjust for a number of effects that occur when light passes through glass. In ray optics, a combination of convex, flat, and concave surfaces can guide light to disperse or focus at a location and correct for some forms of error [2]. One type of error that these elements do not correct for is veiling glare.

Veiling glare is a source of error that occurs in any optical system that uses a lens. It is considered a source of unwanted radiation and is caused by reflection from surfaces, including elements within an optical system. The effect of veiling glare is a reduction in contrast due to parts of the image receiving excess amounts of light and this causes a brightening effect [6] [7]. This phenomenon occurs in every optical system including the human eye [8, 9, 10]. Images taken record the light of the scene plus veiling glare effects, which are dependent on the light from the scene [11]. A bright light source in a scene can reduce contrast in parts of an image so that the camera cannot distinguish the difference in color between the object and light source. This is due to the scattered light being a higher intensity at those pixels compared to the light intensity of the object (low signal-to-noise ratio). Taking an image with the light source outside of the scene or
even blocking the source will create an image with less noise from the scattered light as exemplified in Figure 1.9.

Figure 1.9: Circled areas show a decrease in contrast between the banner and the background due to veiling glare from excess sunlight (Left).

Veiling glare is caused primarily by reflection at lens surfaces. Each surface may be considered a (partial) mirror that can reflect light. With an antireflective coating layer, this reflection can be reduced to about 1% of light passing through the air-glass interface, which means 99% of the light passes through as normal. The ray can reflect multiple times within the lens system before it eventually reaches the sensor at a location, which may be different from where the incident ray would have originally reached. A lens with a single element would theoretically produce an image with the least veiling glare due to having minimal reflection surfaces; however, multiple elements are required to focus light onto a camera sensor and thus most lens systems contain more reflecting surfaces.

The following is a list of sources of stray light that cause veiling glare:
- Reflections at air-glass surfaces
- Excess light sources within an observed scene
- Glass imperfections
- Oils, dirt and scratches
- Reflections off the inside of the lens chamber and camera body

Of these effects that cause veiling glare, imperfections in the structure of a lens can be avoided with proper lens care and cleaning, and excess light can be avoided with diffuse lighting or observing scenes with the light source behind the observer. Reflections at the air-glass surface cannot be completely eliminated and veiling glare will still persist [6]. Within a camera, light can reflect or scatter off of a lens’ surfaces, the internal surface of a lens barrel, or even the camera parts such as the diaphragms and shutter blades of the aperture. Despite the dark color of these lens parts, not all of the light can be absorbed so some is reflected. In addition to veiling glare, another term ‘image flare’ has been used to describe the combined effect of the lens system with the camera and sensor [7]. Assessing veiling glare and image flare is based on the use of similar techniques.

When light enters a camera lens, it is generally refracted towards a focal point, which would be located on the camera sensor. Light passes through the boundary between two materials several times. This surface can be air-to-glass, glass-to-glass, and glass-to-air, which would cover refraction index changes of low-to-high, equal, and high-to-low magnitude. At each of the transparent surfaces, greater than 99% of the light passes through, but even as little as less than 1% of light may be reflected back. This occurs over each surface and thus light can repeatedly reflect infinite times and in nearly all directions. Eventually, this reflected light reaches the camera sensor from a location it was not incident from, as schematically represented in Figure 1.10. This
non-incident light is the veiling glare and results in decreased contrast in an image. This means that even for a scene with indirect lighting, there will still be light that is reflected and scattered to other parts of the scene, which will affect the contrast. Therefore, glare occurs in all images to some degree.

Figure 1.10: Schematic Representation of Light Rays Reflecting in a Single Lens System.

An important consideration when investigating the effect of veiling glare on an image is understanding the effect of vignetting has on light intensity. Vignetting is a form of error that occurs when the light reaches the edge of the camera sensor at an angle [2]. The result is the edge of an image becomes darker than the center. Compared to light that is directed straight towards the center of the sensor, light rays that reach the sensor at an angle, travel further and a longer distance
to reach the edge of the sensor [2] and this decreases the light intensity of light towards the edges. Thus, vignetting does not brighten the center of an image.

1.2 Colorimetry

1.2.1 Human Color Vision

Color is a visual phenomenon perceived by observers. Individuals with abnormal color vision do not observe the colors in the same way as individuals with normal color vision [12]. To understand how color is characterized, it is important to understand how color is seen. Characterizing the color of an object begins with colorimetry, the measurement of color, which can be performed with a number of devices including a spectrophotometer. Three elements interact to result in observing an object color: a visible light source, an object, and an observer, as schematically shown in Figure 1.11 [12]. It should be noted, however, that to observe the color of a light source, an object is not necessary.

Figure 1.11: Schematic Representation of Observing an Object Color.
A schematic representation of the human eye is given in Figure 1.12. In comparison to a digital camera, humors and lens in the eye would act as the camera lens, the pupil would be the aperture, and the retina would be the camera sensor. This comparison indicates that the human eye is clearly an optical system, which means it can be subjected to the same optical effects as a camera system, including the veiling glare [6]. While the eye is susceptible to glare effects, the brain also has an effect on the perception of color and adjusts to surrounding effects [10].

![Figure 1.12: Schematic diagram of the human eye with some key structures labeled](image)

The lens of the eye has a refractive index ranging from 1.36 to 1.43 [13]. The cornea has a refractive index of about 1.34 [14]. The aqueous and vitreous humors are the liquid/gel that fill the eye and give it shape. Both humors have a refractive index similar to water (slightly less than the cornea and lens) [12]. For comparison, air has a refractive index of 1.0003 (effectively 1.00) and
optical glass has a refractive index around 1.5 [3]. Most of the ability for the eye to focus light comes from the air-cornea interface, but there are still refractive index changes within the eye for veiling glare reflection to occur.

The layer in the back of the eye is the retina. The retina absorbs light to send signals to the brain that are interpreted as color. There are two types of receptors called rods and cones located in this part of the eye. Rods are located in the most of retina and function at low light levels. Rods do not affect normal color vision [12]. Cones are the cells that provide color vision and are concentrated in the fovea. Most cones are located within 2° of the fovea. There are three types of cones known as L, M, and S, which represent long, medium, and short wavelengths of visible light. L, M, and S cones have different sensitivities and absorb light from different but overlapping portions of the visible spectrum. While strictly speaking this is not an accurate description, these cones have been referred to as the RGB (red, green, and blue lights) cones because of their approximate sensitivity in these regions of the electromagnetic spectrum. The combination of signals from all three cones give humans the ability to see and distinguish color [12].

In well-lit situations, rods are saturated and become inactive while cones provide vision and color perception. The relative spectral sensitivities of cones are plotted in Figure 1.13. Additionally, in Figure 1.14, the sensitivities are combined to produce the luminosity function (V). This function represents the eye’s spectral luminous sensitivity under photopic (well-lit) conditions. The M cones’ spectral sensitivity function is most similar to the luminosity function meaning humans are most sensitive to detecting luminous changes in green light [12].
Figure 1.13: Spectral Sensitivities of L,M, and S cones in the human eye [12]

Figure 1.14: Spectral sensitivity of human eye to light represented as Luminosity function (V) [15].

1.2.2 Tristimulus Values

Spectrophotometers use physical representations of the three elements of color vision (light source, object, and observer) to measure color. The light source in a spectrophotometer is a white
light that reflects or transmits from the targeted object. Part of the visible light is absorbed into the object and the remaining part reaches the sensor to produce a reflectance (or transmittance) curve to represent the percentage of initial light that remains in the visible light range. This is the first data set (S) that is used to determine color appearance. To represent the light source used to observer a color, a set of data known as a Standard Illuminant is used. Illuminants are described by their spectral power distribution (I), which represents the relative light intensity in the visible spectrum [12]. Examples of standard illuminants include D65, D75, and A which represent outdoor daylight and incandescent light respectively. The SPD of illuminant D75 is shown in Figure 1.15 as provided by the data in [15].

![Figure 1.15: Spectral Power Distribution of Illuminant D75 [15].](image)

The observer is also represented as a standard for spectrophotometric color measurements by three functions known as $\bar{x}, \bar{y}, \bar{z}$. These three functions are based on average color matching responses of observers ($\bar{r}, \bar{g}, \bar{b}$) who matched a series of colors with red, green, and blue lights in
a series of experiments in 1931 and 1964. The 1931 data set used a 2° field of view size, while the 1964 functions employed a 10° field of view size. These are known as 2° and 10° Standard Observer functions and represent the part of the retina that was used for the color matching. The CIE $\bar{x}, \bar{y}, \bar{z}$ functions, shown in Figure 1.16, are based on algebraic conversion of the original color matching functions and represent matches based on theoretical red, green and blue primaries that would not be possible to create for actual observers [12]. This is because the real observer functions $(\bar{r}, \bar{g}, \bar{b})$ have negative values due to limitations of the primary lights being used to color match and the extrapolation of those functions into $\bar{x}, \bar{y}, \bar{z}$ remove the negative values.

![CIE Colour-Matching Functions](image)

Figure 1.16: Spectral tristimulus values of the CIE 1931 standard colorimetric observer [15].

The final step in producing a numerical representation of color by a spectrophotometer is to combine the data from the observer, illuminant, and reflectance functions. The spectral products of these functions, integrated and suitably normalized, are XYZ, also known as the Tristimulus Values. X, Y and Z, defined in Equation 1.2, are the building blocks for calculations of color
spaces, color difference, and are one of the basic numerical descriptors of color [12]. In Equation 1.2, k is the normalization constant so that Y is equal to 100 for a perfect diffuse or reflector [12], R is the spectral reflectance of the object is obtained by the spectrophotometer, and I is the spectral power distribution of an illuminant.

\[
X = k \int \lambda I(\lambda) \bar{x}(\lambda) R(\lambda) d\lambda \\
Y = k \int \lambda I(\lambda) \bar{y}(\lambda) R(\lambda) d\lambda \\
Z = k \int \lambda I(\lambda) \bar{z}(\lambda) R(\lambda) d\lambda
\]

Equation 1.2: XYZ Tristimulus Equations

1.2.3 Color Space

1.2.3.1 Chromaticity Diagram

Color spaces are computational representations of color mapped onto a two or three dimensional space. The CIE1931 color space is also called the CIExyY. The CIExy chromaticity diagram in Figure 1.17, shows the chromatic representation of colors observable by humans on a two-dimensional plane and is obtained via normalization of the tristimulus values (X,Y,Z) to generate x, y, and z values, as shown in Equation 1.3 [16].

\[
x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}, \quad z = \frac{Z}{X+Y+Z}
\]

\[1.0 = x + y + z\]

Equation 1.3 Transformation of Tristimulus Values to Chromaticity Coordinates
The $x$ and $y$ coordinates are used to plot colors onto the chromaticity diagram in Figure 1.17. Because $x$ and $y$ have a direct relationship to $z$, as shown in Equation 1.3, plotting $z$ does not add any more information. Luminance information for a color is not provided in this diagram but can be obtained from $Y$, which is most closely related to the visual response to variations in luminance [12].

![Chromaticity Diagram](image)

Figure 1.17: CIE$\text{xy}$ Artist’s Representation of Chromaticity Diagram (1931) [16].

1.2.3.2 CIELAB Space

CIELAB is a three dimensional space composed of an achromatic lightness ($L^*$) scale, and two opponent red-green ($a^*$) and yellow-blue ($b^*$) chromatic scales. CIELAB is the most common color space used for quantifying colors and color differences in many industries, including textiles. A major reason for the preferred use of the CIELAB space is due to the improved perceptual uniformity of this space when compared to CIE$\text{xy}Y$. Perceptual uniformity aids in determining
comparable color differences between batch and standard samples throughout the space and improving the accuracy and consistency (repeatability and reproducibility) of pass/fail assessments. The perceptual uniformity enhances the agreement between perceived and calculated color difference magnitudes for a pair of samples represented by two points in the color space regardless of their location on the space; although the performance of the system in some sections of the space can be further improved [12]. A nonlinear transformation of XYZ values was employed to improve the perceptual uniformity of the space. For the calculation of $L^*$, $a^*$, and $b^*$, XYZ tristimulus values are required for the measured color and the reference white, which are often represented by $X_nY_nZ_n$ as shown in Equation 1.4 [12].

$$L^* = 116 \left( \frac{Y}{Y_n} \right)^{1/3} - 16$$

$$a^* = 500 \left[ \left( \frac{X}{X_n} \right)^{1/3} - \left( \frac{Y}{Y_n} \right)^{1/3} \right]$$

$$b^* = 200 \left[ \left( \frac{Y}{Y_n} \right)^{1/3} - \left( \frac{Z}{Z_n} \right)^{1/3} \right]$$

Equation 1.4: XYZ to LAB conversion

One simple transformation of CIELAB is to CIELCH where $C^*$ (chroma) and $h_{ab}$ (hue) represent polar coordinates of the color. This transformation is given in Equation 1.5 and uses the same space, but different descriptors for color coordinates. Compared to the basic CIELAB and CIELCH model, more advanced transformations have been developed with the goal of improving the perceptual uniformity of the space to get it closer to human color vision. For many industries, CIELAB space, shown in Figure 1.18, is still the main model used [12].
\[ C_{ab}^* = \sqrt{a'^2 + b'^2} \]
\[ h_{ab} = \tan^{-1} \left( \frac{b^*}{a^*} \right) \]

Equation 1.5: \( L^* a^* b^* \) transformation to \( C_{ab}^* \) and \( h_{ab} \).

Figure 1.18: Cartesian and Polar Representation of LAB Color Space [12].

### 1.2.3.3 Color Difference Calculations

CIELAB is the color space used in most color difference calculations due to its perceptual uniformity. Each point in the 3D color space represents a color and the Euclidean distance between two points may be used to represent the most basic form of the color difference between them. The basic formula implies that a difference of 1.0 unit will generate the same perceptual experience in all directions, which is mathematically represented with a tolerance sphere with a radius of one. However, unfortunately, the assumption that color differences are equal in all three dimensions give color differences that would be inconsistent with the color difference seen by human observers. To improve the accuracy of color difference estimations, the basic equation has been modified over the years in numerous iterations. These changes include adjustments to differences...
in chroma ($\Delta C^*$) and hue ($\Delta H^*$) components to better fit experimental data. In addition, hue
dependent tolerance adjustments for each axis in the color difference space are incorporated. The
most recent CIE approved model is known as the CIEDE2000, shown in Equation 1.6, which has
been shown to perform better at producing pass/fail results when compared against classic visual
datasets [12]. The additions incorporated in the CIEDE2000 model over the Euclidean distance
include the parametric factors $k_L, k_C, k_H$ and $S$ adjustment functions for the material being measured
that change the tolerance shape from a circle to an oval. This is because perceptual uniformity is
not the same in all color directions [12]. Newer color difference equations are continually
introduced to further tune the performance of the model and enhance its accuracy or incorporate
color appearance and relevant vision phenomena.

$$\Delta E_{00}^* = \sqrt{\left( \frac{\Delta L'}{k_L S_L} \right)^2 + \left( \frac{\Delta C'}{k_C S_C} \right)^2 + \left( \frac{\Delta H'}{k_H S_H} \right)^2 + \frac{R_T}{k_C S_C} \frac{\Delta C'}{k_C S_C} \frac{\Delta H'}{k_H S_H}}$$

Equation 1.6: CIEDE2000 Color Difference Equation.

1.2.3.4 RGB Color Spaces and Conversions

The RGB (Red, Green, Blue) color space is used for digital imaging devices. To simplify
communications a standard (sRGB) space was developed so that images could be displayed by
monitors [16]. Other RGB color spaces such as Adobe’s provide a larger color gamut at the cost
of not being properly displayed on all devices. RGB spaces can vary based on the device display
capabilities, and the shape of those spaces is based on a transformation of the CIE XYZ to RGB
values based on the primaries of that space. For the sRGB space, the conversion is given in
Equation 1.7.
\[
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix} = 
\begin{bmatrix}
3.2406 & -1.5372 & -0.4986 \\
-0.9689 & 1.8758 & 0.0415 \\
0.0557 & -0.2040 & 1.0570
\end{bmatrix}
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
\]

Equation 1.7: sRGB relationship to XYZ with XYZ scaled 0-1 [16].

For an eight-bit system RGB values range from 0 to 255 in digital displays [16]. Red, green, and blue light signals are combined to create color through additive color mixing. The color gamut for RGB color spaces is dependent on the primaries of the device displaying the color. This means that the spaces are dependent on real physical colors and the space will be contained within the CIExyY (1931) color space that uses theoretical primaries. The result is a triangle shaped gamut as shown in Figure 1.19.

Figure 1.19: Gamuts of sRGB (black line) and Adobe RGB (1998) (red line) [16].
Conversions between LAB and RGB color spaces are less direct than from XYZ to either of these systems. The sRGB to LAB conversion can be performed in Matlab with code such as that provided in the text [16]. Nonetheless, a knowledge of the specific RGB system being used is needed to properly convert the values because each RGB system can have different primaries. This would also be the same case for conversion of RGB to XYZ since the RGB primaries can change depending on the system being used [16].

1.3 Veiling Glare Assessment Methodology

Several methodology techniques have been considered for the evaluation of veiling glare.

- ISO 9358 – Veiling Glare [6];
- ISO 18844 Image Flare [7];
- Commercial image processing software [17];
- Research on veiling glare in HDR images [8, 9].

Aspects of these methods were used in the final experimentation, however ISO 18844 for Image Flare analysis was the most similar to equipment used in this study. The commercial image processing software and research on veiling glare in HDR images provided examples for effective veiling glare evaluation without using the exact ISO methods.

1.3.1 ISO

Characterizing veiling glare can be a challenging task because there are other phenomena that can occur to affect light before it reaches the camera sensor. ISO 9358 describes a method (and associated variations) to determine veiling glare using an index denoted Veiling Glare Index (VGI) and a function known as the Glare Spread Function (GSF) [6]. This method does not test
the entire camera as a system, but rather tests the lens system as a source of veiling glare. This method uses a setup where light is evenly distributed on a white surface. In the center of the surface is an absorbing cavity to create a black center. This black center is then removed and the difference between the black and white areas is used to determine the VGI. The setup is shown in Figure 1.20. Glare spread function is measured with a large dark area with an aperture for a light source. The lens is then used to measure the dark area from the aperture to the edge and create a plot of how glare causes a spread of the light. The most relevant part of this ISO method is clear definitions of veiling glare and its effects.

![Figure 1.20: Veiling glare measurement in the case of an unlimited object field [6].](image)

Since the previous ISO method focused on the lens only, an updated method for determination of image flare (ISO 18844) was developed which incorporates the entire digital camera system that generates RGB images [7]. Image processing is required after collecting the
images to calculate the flare in the system. The main equipment difference between this approach and the veiling glare method is that the new method uses charts to reflect light for the assessment of flare, rather than using a light source directly in the image of an integrating sphere. The setup for this system is shown in Figure 1.21 [7].

![Diagram of measuring equipment](image)

**Figure 1.21:** Arrangement of measuring equipment for reflection-type test chart [7].

Two charts are used in this method. One chart is dark with some light areas (chart 1), and the other is light with some dark areas (chart 2). A representation of the charts is given in Figure 1.22. Each chart is photographed under separate camera conditions, and finally chart 2 is photographed a second time under a mixture of the previous two camera conditions. Luma values are the units used for this method to describe light intensity. Luma values are calculated from the
RGB pixels of the images, which are then used to calculate image flare (F). Additionally there are three types of measurements recommended depending on the capabilities of the camera and the contrast ratio between chart 1 and 2 [7].

![Figure 1.22: Window pattern charts for single spot measurement [7].](image)

### 1.3.2 Other Methods

Similar methods in other studies, using the camera and lens as a whole system, have also been used to determine veiling glare [17, 8, 9], however, the basic elements of the approach, such as reducing external light and observing black and white images, remain the same.

A commercial image processing program [17] based their calculations and method on ISO 9358 [6]. This program was developed by an American company, Imatest LLC, (CO) to characterize veiling glare. Values used to calculate veiling glare comprise the pixel values in the light and dark regions of the image. The drawback in the case of this study was the need to purchase the software for these calculations, so other methods were used.

Other work has involved the use of a light source behind a black mask. The light source is exposed through openings in the black mask similar [6]. The purpose of this setup was to observe
veiling glare in High Dynamic Range (HDR) images. By combining the setup with filters to gradually reduce light, the researchers were able to create a gradient of observable veiling glare in their images [8, 9].

Both the ISO methods and the techniques used by other studies and companies were considered in the methodology for this study. The key similarities between all the methods are isolating the system from outside light flare, uniform lighting on the target, and a high contrast between light and dark areas in an image.

1.4 DigiEye Illumination Chamber

The setup for measuring veiling glare in [7] is similar to the DigiEye Illumination Cube used in this work. Verivide (UK) constructed a controlled illumination chamber, marketed as DigiEye Illumination Cube, which can be used for the color assessment of various objects using a digital camera [18]. In this study, DigiEye illumination chambers were used to assess color, analyze the extent of veiling glare, and the effect of veiling glare on digital imaging. In the unit used for this study, schematically shown in Figure 1.23, the chamber is illuminated with light sources that simulate illuminant D75.
Figure 1.23: A schematic representation of the DigiEye illumination chamber and the digital camera setup employed to assess veiling glare.

The unit requires a recommended 15 minute warm-up period prior to any measurements. However, when repeated measurements were taken, it was found that it is preferable to wait 30 minutes for the light source to reach a very stable state with a luminance of approximately 198 cd/m² as shown in Figure 1.24 [19]. After the warm-up is completed the stability of the unit is rated to have a change in illumination of <1.0% over eight hrs [18]. The stability and uniformity of the light source is important when accounting for changes in luminance since only changes due to glare are of interest in this study rather than those associated with illumination non-uniformity.
Spatial non-uniformity details for the illumination within the chamber are not provided by Verivide for the DigiEye product. However, digital camera based analysis of uniformity has been performed by previous researchers [19] [20]. Attempts to examine the spatial non-uniformity of the DigiEye illumination chamber have involved the use of a uniform board for imaging. In the first test, the non-uniformity of an image taken outside the chamber under diffuse daylight (outdoors) was used to calibrate images taken within the DigiEye chamber [20]. The second non-uniformity comparison compared the spatial non-uniformity of a set of digital cameras separately housed on top of the DigiEye chamber.

To create an idea of the uniformity of the camera, a uniformity board was placed outside under daylight so that lighting was uniform. This image showed darkening around the edges [20]. That image was used to correct for non-uniformity for images taken within the DigiEye chamber. For images taken within the chamber a small target was moved within the scene. Non-uniformity correction for the camera reduced the standard deviation of the measurements of that target, but the variance for half of the measurements was still greater than 1, with a maximum variance of 3.4
in units of R, G, or B [20]. The other spatial non-uniformity test [19] showed that depending on the camera used, the difference in illumination intensity at the center and over the edges of the chamber can vary by 10-18% without any spatial non-uniformity corrections [19]. The difference in illumination between the center and edges of the image without any corrections are due to vignetting [2].

1.5 ColorChecker

The colorchecker chart used in this project was the GretagMacbeth ColorChecker DC. The chart was originally designed for characterizing digital cameras, which is why it was given the DC designation [21]. There are 237 color patches on the chart and they include achromatic (grey scale) colors, matte, and glossy patches, as shown in Figure 1.25. The area of interest for this project was the center gray scale that included a central white patch surrounded by twelve achromatic patches. These gray scale patches represent a change in lightness values, which are useful for veiling glare comparisons and characterizing the ability of a digital camera and lens to detect light at various reflected lightness values. Labelling of these patches is done using the column and row labels located on the border of the chart. The rows are labeled 1 to 12 starting from the top row and the 20 columns are labeled A to T starting from the leftmost side. The grey scale patches used in this system are located within the corner boundaries of I5, L5, I8, and L8.
1.6 Digital Camera Based Colorimetry

Colorimetry using DSLR cameras is an attractive option for both research and industry. The cost of a DSLR camera is significantly less than that of a radiometer or spectrophotometer. Even other types of cameras such as multispectral or luminance cameras are much more costly than DSLRs. Being able to take measurements with a camera at the same accuracy would be useful to anyone. For this reason, DSLR cameras are being investigated for their use as colorimetry devices [20].

1.6.1 Digital Camera Sensor

Digital cameras tend to contain either a CCD or CMOS sensor array, which is a chip containing a series of photodiodes arranged into an $M \times N$ pixel sized matrix [22]. The photodiodes are the part of the sensor that detect light intensity. What makes the DSLR camera sensor useful to colorimetry is the separation of red, green, and blue colored light in the sensor. This is done
with filters that are overlaid on the sensor pixels. Each pixel filter transmits either red, green, or blue light. Since each pixel detects only a single group of colors similar to the human eye, the response must later be processed to obtain R, G, B values at each pixel position [22]. To optimize the use of pixels, the red, green, and blue pixels are arranged into patterns called color filter arrays. One such array, called a Bayer pattern, is shown in Figure 1.26. For the color filter array shown in Figure 1.26, there are twice as many green pixels compared to the red or blue. The reason is due to the fact that the human eye is most sensitive to green light, where M (or green) cone’s spectral sensitivity is closest to the human photopic sensitivity to luminance.

Figure 1.26: Example of a color filter array called a “Bayer pattern”.
Camera sensor filters predominantly respond to red, green, or blue lights although their spectral sensitivity functions contain a degree of overlap, which is similar to the functions in the human visual system, as shown in Figure 1.27. The spectral sensitivities of filters in a camera can be characterized using a monochromator and a spectrophotometer to isolate wavelengths exposed to the camera [23].

![Figure 1.27: Spectral response of various digital cameras [24].](image)

Due to differences between among devices, as demonstrated in Figure 1.27, the color data from cameras is device dependent and additional steps should be taken to create device independent data [24] [25]. The green sensor channel of the camera covers the broadest range of wavelengths and contains significant overlap with the red and blue channels. For this reason and its’ similarity to M cone spectral sensitivity as well as the visual luminous sensitivity function under photopic conditions (V_\lambda function), the green channel is used as an estimate of the luminance function [22]. G channel responses were also used in this study for assessing luminance variations.
1.6.2 Image Processing Methods

DSLR cameras can save images as RAW files. RAW files are the unprocessed information that preserve sensor information. This is ideal because processes such as compression can cause a loss of information about the values measured from sensor pixels. In addition to the sensor array information, RAW data can provide information pertaining to the linearization of the image such as the black and white levels. For some users, the camera will automatically handle the white balancing, demosaicking, and compression [26]. The end results of those steps is an RGB image.

Many of these steps can be performed by software such as Matlab [16]. However, RAW images taken from a digital camera cannot be directly processed in Matlab. The first step to prepare the image for Matlab is to transform the RAW image into a usable format. One method is to covert the image to a .DNG file using Adobe DNG (Digital Negative) converter. This converter takes the RAW file, which is camera specific, and converts it to a file that is more compatible and universal with other programs. The resulting file contains all of the same information that a RAW file would and the information is not lost or changed. While most of the tests in this work used the green sensor array, some of the images required extra processing steps to use as an RGB image.

After reading the .DNG file, demosaicking as described below, is the next major step in processing the image when using RAW data. The color filter array must be known. This $2 \times 2$ array pattern is ‘gbrg’ for the Nikon D90 camera as shown in Figure 1.28.
The demosaicking step can vary, but the general idea is to interpolate the red, green, and blue values at each pixel. The end result is those pixels change from having either a red, green, and blue sensor reading to having a red, green, and blue (RGB) value that have been interpolated from the surrounding pixels. Methods can vary but interpolation is used in several of the strategies [26]. The only complication with demosaicking algorithms is that they are dependent on the surrounding pixel values. This means that the edges of an image are not as accurate as the remainder of the image. To avoid error in color reproduction the edge of a digital image would be removed before calculations are made for color measurement. Additionally, this interpolation takes into account the surrounding pixels so as to reduce the influence of interpolation. The green channel response was used as a luminance response estimate.

After the demosaicking step, the image would be white balanced. Since different light sources have different spectral power distributions, the image needs to be adjusted to the proper lighting. Using the incorrect white balance alters the appearance of the color in the final image. White is the easiest to spot as a known white object could appear reddish or bluish under the incorrect white balance [22]. The DigiEye used in this study employed a D75 type light source, which means using D65 white balance would not create the same color.
A method to provide spatial non-uniformity corrections for an image is provided elsewhere [16]. The tools required are a black image, and an image of a white uniformity board, as briefly described in Section 1.3. The information from the white uniformity board and the black image provide a ratio of a minimum light response and a maximum light response to the sensor. Non-uniformity will change depending on the camera being used [19], as well as the aperture and exposure settings [20]. This was shown to reduce the non-uniformity in the DigiEye chamber but did not completely eliminate it as there is still variation in RGB values ranging from 1-3 [20].

1.7 Other Light Measurement Techniques

The colorimetric techniques previously discussed included spectrophotometers or digital cameras. Both of these instruments can provide color data, specifically the Lightness (L), Brightness (Y), or a Luminance estimate (Green Channel in Digital Camera) to use as indicators of change in light intensity due to veiling glare. Other techniques and instruments may also be used or considered to evaluate luminance or light intensity as listed in Table 1.2.

Table 1.2: Light measurement instruments

<table>
<thead>
<tr>
<th>Light Measurement Instrument</th>
<th>Information Obtained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrophotometer</td>
<td>Object reflectance, XYZ, Lab</td>
</tr>
<tr>
<td>DSLR Camera</td>
<td>Sensor values, RGB</td>
</tr>
<tr>
<td>Spectroradiometer</td>
<td>Reflected spectra, light source spectra,</td>
</tr>
<tr>
<td></td>
<td>Luminance (cd/m²)</td>
</tr>
<tr>
<td>Luminance Camera</td>
<td>Sensor values, Luminance (cd/m²)</td>
</tr>
<tr>
<td>Multispectral Camera</td>
<td>Sensor values, more ranges than RGB</td>
</tr>
</tbody>
</table>
The spectroradiometer is an instrument that measures the light intensity within a spectrum [22]. This is different from the spectrophotometer that measures the percentage of reflected light (0-100%) of an object within a spectrum. A spectroradiometer can also be used to measure the spectrum emitted from light sources. The radiometer used in this study was a SpectraScan PR670 (Photo Research Labs, JADAK), which uses an MS-75 - MacroSpectar® Lens that zooms and has several aperture options [28]. Because the radiometer is an optical device, its lens is susceptible to veiling glare effects. However, Photo Research does not provide detailed information on the construction of their lenses. There is also the option of a light meter attachment that allows the spectroradiometer to be placed within a DigiEye illumination chamber to measure light as lux, rather than using the lens to measure light reflected from a target.

Luminance may also be measured with other devices such as a luminance camera or a DSLR camera [29]. A Luminance camera does not have color filters like a DSLR camera, but both cameras may be used to measure the luminance in parts of a scene with some image processing programs [29, 30]. Other strategies have also been developed to create meaningful luminance measurements from DSLR cameras. The same types of errors associated with the lens also occur in this setup. Using the green sensor channel response as an approximation of luminance intensity in these cameras was found to provide a similar result to values obtained from other techniques.
CHAPTER 2: METHODOLOGY AND INSTRUMENTATION

2.1 Experimental Setup

The methodology used in this work was designed and chosen to observe and define the effects glare would have on color measurements in a controlled setting. The DigiEye unit acts as the controlled setting where all experiments use the same lighting, and outside conditions. The only changing conditions would be the measurement device itself, and glare effects being manipulated. The first part of this work aims to observe whether or not the effect of glare is significant. The second part of the work compares lenses to determine the ideal conditions for color measurement using a digital camera when attempting to reduce glare effects. The final part of this work describes glare spread in more detail by observing the effect surround has on glare by gradually changing the surround and by keeping a constant surround to observe glare spread.

The majority of experimentation for this work used the DigiEye unit, shown in Figure 1.23. For all images taken, the D75 light sources was used, and a warm-up time of at least 30 minutes was provided. A lens hood was fixed to the camera lens to block stray light for the Nikon D90. When the SpectraScan PR670 was in use, the ambient lights were turned off to eliminate the effect of extraneous lights on measurements.

A DataColor SF600 spectrophotometer was used to measure the reflectance of the color patches on the Gretag Macbeth ColorChecker DC as well the boards that were used in this work. The reflectance data was used to calculate the XYZ and Lab values for each of the achromatic patches on the color checker, and the boards. The conditions used for the DataColor SF600 are given in Table 2.1.
Table 2.1: Settings Used for Spectrophotometer.

<table>
<thead>
<tr>
<th>DataColor SF600</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>SAV (9mm) – Small Aperture View</td>
</tr>
<tr>
<td>UV</td>
<td>UV Excluded</td>
</tr>
<tr>
<td>Mode</td>
<td>Reflectance</td>
</tr>
<tr>
<td>Specular Condition</td>
<td>Specular Included</td>
</tr>
<tr>
<td>Average</td>
<td>3 Measurements</td>
</tr>
<tr>
<td>Observer</td>
<td>2 degree</td>
</tr>
<tr>
<td>Illuminant</td>
<td>D65</td>
</tr>
</tbody>
</table>

Spectroradiometric measurements were made with a Spectrascan PR670 using a MacroSpectar 75mm lens. The difference in the setup between the radiometer and camera is that a lens hood was not fixed to the radiometer. To reduce external light from reaching the radiometer the lab lights were turned off and the lab door remained shut during measurements. Achromatic patches in the ColorChecker DC were measured at zero degrees by moving the ColorChecker DC inside the DigiEye chamber while leaving the radiometer in a fixed position. For calibration purposes, a standard white reflectance target was used to normalize the radiometer values with the target being 100% reflectance for calculations of lightness. The settings are described in Table 2.2.

Table 2.2: Settings used for Spectroradiometer.

<table>
<thead>
<tr>
<th>SpectraScan PR670</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>1 deg</td>
</tr>
<tr>
<td>Primary Accessory</td>
<td>MS-75</td>
</tr>
<tr>
<td>Exposure</td>
<td>Adaptive</td>
</tr>
<tr>
<td>Measurement Mode</td>
<td>Average of 3 Measurements</td>
</tr>
</tbody>
</table>
Before performing the experiments in the DigiEye unit the spatial uniformity of the chamber was investigated using a spectroradiometer. Previous work [19, 20] had investigated the DigiEye unit’s uniformity by using digital camera images, but not radiometric measurements of the platform area. Two strategies were used to give an idea of the illumination uniformity of the DigiEye unit.

- Angle the radiometer above the unit to measure specific locations.
- Use a light meter attachment to allow the radiometer to be placed within the unit.

When angling the radiometer above the DigiEye unit, a reflectance target was positioned towards the limits of where the radiometer could aim its lens. The drawback of this approach is that the reflectance off the target is no longer at 0 degrees which can affect luminance measurements. There was also a physical limit of where the radiometer could be positioned. In the end using the radiometer lens attachment was not practical to give an effective idea of lighting uniformity.

The light meter attachment allows light to be measured in a 180 degree field of view. This would not gather spot measurements of the DigiEye unit, but would allow the radiometer to be moved about inside the chamber and measure the light intensity in multiple locations within the unit. A grid was placed on the platform inside the DigiEye unit to mark where to place the light meter. The grid marked out a 7 × 7 rectangle shape to guide the light meter placement. This light meter measures illuminance in lux (lx) instead of luminance (cd/m²). Both units are used to describe light. Illuminance is the measure of light hitting the surface of the light meter, luminance is the measure of light reflected off a particular area. Figure 2.1 shows the distribution of lux measured by the light meter. A source of error in this method could have come from the light meter needing to be placed several inches above the platform surface rather than flat to the platform.
Despite that potential for error, measurements indicate less than 5% difference between the lowest and highest lux values.

![Lux measurements within the DigiEye Unit](image)

**Figure 2.1:** Illuminance measurements (in lux) within a $7 \times 7$ grid inside the DigiEye illumination chamber using a surface graph to extrapolate and visualize data.

### 2.2 Image Capture Configuration

A Nikon D90 camera was used for experimentation. Two fixed lenses and three zoom lenses were compared for veiling glare effects as specified in Table 2.2.
The general camera settings used were f/7.1, 100 ISO, and exposure times of $\frac{1}{4}$, $\frac{1}{5}$ and $\frac{1}{6}$ seconds were used to ensure proper exposure depending on the lens being used. Aperture remained the same for all images to control the amount of stray light entering the camera. Changing apertures would change the angles from which the stray light could enter the camera.

RAW images were used for processing in Matlab. After using a DNG converter on the RAW files, the key steps taken to create useful data were separating the red, green, and blue channels. In addition, demosaicking, white balance, and a spatial non-uniformity correction were used for images that required RGB information, rather than just RAW data. Of the experiments, only one (3.2 Effect of Sensor Location on Veiling Glare) used RGB information. The remaining experiments used RAW image data. The images for spatial non-uniformity calculations were a black image with the lens cap on the camera blocking all light and an image of a white uniformity board that covers the entirety of the image inside the DigiEye unit. The results were based on Red, Green, and Blue channel responses at each pixel which were used to calculate lightness, $L^*$, and luminance factor, $Y$, values.
3.1 Effect of Surround on Veiling Glare

The first experiment’s intention was to see how veiling glare affects the light intensity reaching a camera sensor. By changing the surround, the amount of light reflected towards the camera can be controlled. The setup to measure a target with a changing surround is shown in Figure 3.1.

Figure 3.1: Diagram of the veiling glare experiment within the DigiEye Unit.

The achromatic scale in the ColorChecker DC was the target of the images. The reflected light from the object was limited to three settings using different types of surfaces. Maximum reflectance and therefore lightness was obtained using a white mask that covered all but the center of the object being captured. The white board had a high reflectance value and was used to provide
the maximum opportunity for light to reach the lens and cause veiling glare effects. The second mask was a black cardboard which was used to minimize the amount of reflected light from the surrounding region of the object being captured. While the reflected light from the black mask was not eliminated, the difference between the reflectance of the white and black masks was significant. The final capture included reflectance from the object including its surround without any mask. This represented a full colored image, which included light and dark areas.

The achromatic scale located in the center of the ColorChecker, depicted and labelled in Figure 3.2, was photographed under all three conditions as well as measured using a spectroradiometer under the same conditions. The radiometer was used for comparison since it also employs a lens system that can be affected by the veiling glare. Images of the ColorChecker under all three conditions are shown in Figure 3.3. The raw green channel sensor values were used for comparison of different conditions to determine the amount of light passing through the lens. The values were not demosaicked or altered in any way.

Figure 3.2: Gray patch labels from the highest (J6) to the lowest (L8) L* value.
Figure 3.3: Patch J6 centered in the DigiEye with white mask (top), without mask (middle), and with black mask (bottom).

The results of measurements using the masks in Figure 3.4 showed that the sensor response decreased with a black mask, as expected, but it did not increase with the white mask for any of the target grey patches. This pattern was also repeated in the following experiments. Additionally, patches with low brightness experienced a higher green channel response under the white mask and high brightness patches had a lower response with the white mask when compared to results without a mask.
The thickness of the boards used to mask the image was between 1-2 mm, thus a slight shadow was thought to be cast from the mask onto the target patch, which were $1.5 \times 1.5$ cm squares. This would decrease the light reflected from the patches, but for low brightness patches, veiling glare would have an effect and still increase green channel response despite the shadow. A repeat of these measurements was done with a new white mask with a paper thickness in an attempt to eliminate the shadow and determine whether the white mask would increase the response of the camera and radiometer. Only measurements with the 35mm lens were repeated with the thin mask. This was in part because the radiometer is able to use a small enough aperture where the shadow would not have as large of an effect on measurements. In Figure 3.5, it is clear that the white mask did cause veiling glare and increased the luminance of measurements using the radiometer. Eliminating the thickness of the mask also revealed that the white surround does indeed increase the light recorded by the green channel for a targeted patch as shown in Figure 3.6. In the following figures, all values were normalized to the highest value. For Figure 3.4, this was the brightest patch with no mask. For Figure 3.5 and Figure 3.6, values were normalized to the brightest patch under the white mask. Some differences may have occurred in Figure 3.6 due to being measured on a later date than the other measurements. Some variation occurred when using the DigiEye unit for repeat camera measurements on different days.
Figure 3.4: White and Black Mask Surround Effect on Veiling Glare for DSLR.

Figure 3.5: White and Black Mask Surround Effect on Veiling Glare for Radiometer.
Figure 3.6: Thin White Mask Effect on Veiling Glare for DSLR.

3.2 Effect of Sensor Location on Veiling Glare

The second set of observations included a change of the location of patch J6, as shown in Figure 3.7. For this set of images, patch J6 was moved to the four corners of the image and all images underwent white balance, demosaicking, and corrections for spatial non-uniformity. To label these corners, corners 1 and 2 represented the back side of the DigiEye unit and corners two represented the front side of the DigiEye unit. The measurements were taken from right to left.
Figure 3.7: ColorChecker positioned in the DigiEye corners labelled 1, 2, 3, and 4.

The results in Figure 3.8 show that uniformity corrections do not completely correct for all non-uniformity within the DigiEye chamber similar to the experiments described in section 1.4 DigiEye Illumination Chamber. Additionally the use of a white mask provided similar RGB values for all corners of the DigiEye unit.
Figure 3.8: Corner and Center measurements of patch J6 within the DigiEye after Uniformity Corrections.
CHAPTER 4: VEILING GLARE VARIATION BASED ON LENS CONSTRUCTION

4.1 Lens Construction Methodology

The first two experiments generated data for the comparison of lenses. By using the same setup with a white and black mask, image sets were taken with camera lenses as described in Table 1.1. Additionally the radiometer was used for the comparison as a fifth lens system.

Veiling glare effects were compared for these 5 lenses with the intention of observing the impact that lens construction has on veiling glare effects. All targets were centered in the middle of the image under the three surround conditions described previously (no mask, white mask, and black mask). Two lenses were fixed distance, and the other two were zoom lenses. The radiometer lens was also a zoom lens. The targets for this experiment were the achromatic patches in the center of the ColorChecker DC chart. These images and measurements were repeated for all 4 camera lenses and the radiometer.

4.2 Effect of Lens Construction on Veiling Glare

In Figure 4.1, Figure 4.2, and Figure 4.3 below, the four DSLR lenses used the green channel response of the camera to estimate light intensity while the radiometer measured luminance (cd/m²). The relative response of each lens was plotted under each surround condition.

Under the black mask, sensor responses were lower than the other two surround conditions for all achromatic patches. For the camera lenses, sensor responses were higher than responses under the white mask for high brightness patches. For low brightness patches, the camera sensor responses were lower for no mask surround compared to the white mask surround. The reason for
white mask responses not being consistently higher than the no mask responses is due to the thickness of the cardboard mask casting a shadow as discussed in CHAPTER 3:

![Figure 4.1: No Mask Lens Comparison.](image)

![Figure 4.2: Black Mask Lens Comparison.](image)
4.3 Comparison of Lens Construction

To determine lens performance, the percentage difference between measurements made with no mask and the black mask were plotted, as shown in Figure 4.4. It should be noted that the difference in measurements with the white and black masks is larger than originally measured due to shadow cast from the mask as discussed previously in CHAPTER 3:. For this reason the comparison is between the black mask and no mask, to show the amount of glare in a full color image compared to an image with minimal light reflectance. The effect of the black mask is apparent in reducing the light intensity that reaches the sensor by 12-24% depending on the lens. The two zoom lenses experienced the largest change in intensity when glare was reduced by the black mask. This is because those lenses have more elements with surfaces that light can reflect from, which in turn contribute to increased veiling glare effects. Finally the 35mm lens showed the best performance with an average percentage difference of 14.2%. Thus, among the lenses examined the 35mm lens is the better choice for light measurement.
Figure 4.4: Percentage Difference between No Mask and Black Mask.
CHAPTER 5: CHARACTERIZING SURROUND EFFECTS ON VEILING GLARE

5.1 Gradual Change in Surround

The previous chapters show that the surround brightness does have an effect on the brightness of a target, so this next experiment aims to observe the effect a gradual change in surround would have by gradually changing from a white surround to a black surround. The measurement setup remained the same as previous experiments. The target for this study was a black cardboard made of the same material as the black mask. On top of the black target a white mask with laser cut concentric circles. The center of the black target was measured, and after each measurement the centermost layer of the surround was removed. A diagram of the laser cut mask is given in Figure 5.1 and each circle increases in radius (Rn) by 1cm.
The initial circle diameter was 1 cm and a total of nine concentric circles were cut, as shown in Figure 5.2, for a total of 10 measurements. The uniformity of the black and white boards was measured by a radiometer to determine the variation in the boards being used. The variation in luminance of the two boards is depicted in Figure 5.3 and Figure 5.4. Measurements were taken in a rectangular 5 × 10 grid pattern to obtain an even distribution across the board. All measurements were taken within the same location in the Digieye unit. A scatter plot was used to show the variability in the boards rather than a surface plot to avoid interpolation of the points. The black cardboard showed more variability between the max and minimum luminance compared to the painted white cardboard. The small signal from the black cardboard would experience a greater percentage change from non-uniformity than the white board would from the same luminance changes.

Figure 5.2: Images of the surround radius increasing.
Figure 5.3: Black Cardboard Radiometer Uniformity.

Figure 5.4: Painted White Cardboard Radiometer Uniformity.

Figure 5.5 and Figure 5.6, show a decrease in relative light intensity for the 35mm DSLR lens and the radiometer lens when the white surround decreased. For the digital camera, this change
in light intensity fits a power curve, while the radiometer experienced a linear change in light intensity.

Figure 5.5: Gradual Surround Change with DSLR.

Figure 5.6: Gradual Change in Surround with Radiometer.
5.2 Constant Image Scene with Change in Distance from White Area

In addition to gradually changing the surround, the follow up question was to quantify how far glare spreads from the source to a target measurement. For this setup, the same black cardboard was used for half of the measurement area while the second half contained a cardboard that had been painted white with a white spray paint. Along the vertical center of the boards, measurements were taken horizontally at equal intervals starting from the white and black border and moving outwards towards the far edge of the board as shown in Figure 5.7. Similar measurements points were used with the radiometer, however there were limitations in how far away could be measured due to the limit size of the DigiEye unit. This experiment looked at veiling glare effects combined with vignetting and then used corrections for vignetting to reveal how glare spreads from the bright portion of an image.

Figure 5.7: Diagram of pixel locations used for DSLR Images.
In addition, a set of measurements was made at the same locations with the camera on the black cardboard, and a white uniformity board. This was done to determine what changes in intensity were due to non-uniformity of the black cardboard, and those that occur due to vignetting towards the edge of an image. Those two sets of measurements were used to compare the edge study and better understand the changes that occurred from glare effects. A uniformity correction would not have perfectly corrected for non-uniformity of the DigiEye unit as described in section 1.4 DigiEye Illumination Chamber) and 3.2 Effect of Sensor Location on Veiling Glare). In Figure 5.8 below, the uniformity of the black cardboard and a white uniformity board is compared. Decreases in the green channel response towards the edge of the image are due to a combination of vignetting and lighting of the DigiEye unit [2, 20]. The uniformity board showed a smooth curve with a high R² fit, while the black cardboard showed variation due to non-uniformity of the board itself. Most of the black cardboard non-uniformity is due to a lower signal-to-noise ratio that occurs in measurement of darker colors. Overall the general curve shape produced by the black cardboard and uniform whiteboard were the same as shown in Figure 5.8.
Figure 5.8: Uniformity of Black Cardboard Compared to Uniformity Board.

In Figure 5.9, the effect of the distance from the white/black edge to the measured green channel pixels is shown. Veiling glare effects combined with vignetting demonstrate that for low brightness targets, there is a much larger difference between the center and edge when veiling glare from the white half of the image brightens the dark parts of the image. This causes a difference of 20% from the center to the edge rather than a difference of 10% when there is no veiling glare effect on the black cardboard. The painted white board does not show changes in relative green channel response because its signal is much higher than the black board. This can be seen in Table 5.1 that compares the center and edge green channel response with and without the white board present. The absolute response from the green channel of the DSLR increases for areas closer to the border of the white board.
Figure 5.9: Relative Intensity of Half Black, Half White Image.

Table 5.1: Edge and Center Green Channel Values.

<table>
<thead>
<tr>
<th>Pixel Location</th>
<th>Green Channel Response With Glare</th>
<th>Green Channel Response Without Glare</th>
<th>Absolute Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>108.5</td>
<td>102.8</td>
<td>5.8</td>
</tr>
<tr>
<td>150</td>
<td>110.5</td>
<td>106.3</td>
<td>4.3</td>
</tr>
<tr>
<td>200</td>
<td>112.7</td>
<td>108.3</td>
<td>4.4</td>
</tr>
<tr>
<td>950</td>
<td>128.6</td>
<td>116.0</td>
<td>12.6</td>
</tr>
<tr>
<td>1000</td>
<td>132.8</td>
<td>115.8</td>
<td>17.1</td>
</tr>
<tr>
<td>1050</td>
<td>135.2</td>
<td>115.4</td>
<td>19.8</td>
</tr>
</tbody>
</table>

To better understand how veiling glare is causing changes separate from vignetting, the results above were corrected for non-uniformity using the image of a uniform white board.
white board is assumed a constant reflectance so as to adjust for any spatial non-uniformity due to either camera vignetting or lighting non-uniformity within the DigiEye unit. The curves for both the white and black halves of the image change after vignetting corrections as shown in Figure 5.10 below. The white board gradually increases as it moves away from the center, while the black board experiences a sharp drop off in relative intensity before leveling off. This means that veiling glare spread has a sharp drop off at a certain distance and very little effect after that point.

![Vignetting Corrected Edge Experiment](image)

**Figure 5.10:** Edge experiment adjusted for vignetting.

Under the radiometer, measurements were taken by keeping the radiometer in a stationary position above the DigiEye unit and the black and white boards were shifted 0.5 cm for each measurement. It was not possible to measure the entire length of the boards under this set up. Figure 5.11 shows that the white edge did increase the luminance of the black cardboard
measurements, but the non-uniformity of the black cardboard had a large impact on the variation of luminance measured. There is a large variance in these measurements from board non-uniformity, and human error from moving the boards in a controlled manner. Due to limitations from the radiometer setup within the DigiEye, it is difficult to determine the effect glare spread has on the radiometer lens.

Figure 5.11: Radiometer Edge Experiment.
6.1 Conclusions

The final conclusions are summarized below, with longer explanations provided in the following sections of this chapter.

- Surround brightness has a direct effect on the amount of light that reaches the camera sensor. Surround noise will affect the light intensity of a target by 24% - 63% depending on the ratio between the noise and the signal size.

- To reduce veiling glare noise, a lens construction with fewer elements perform better than lenses with more elements. Each element contributes to more reflection so fixed lenses are preferred to zoom lenses.

- The 35mm Nikon lens performed the best out of the observed lenses.

- Gradually changing the area of a bright surround showed a change in sensor intensity due to veiling glare.

- Veiling glare effects decreases in intensity further away from the source of higher intensity light.

- Veiling glare is dependent on the conditions of the surround and scene being observed. Both radiometers and DSLR cameras are affected by veiling glare from either a bright or dark surround.

- Color measurement with optical devices should take into consideration the influence of surround brightness, illumination and any changes in those conditions.

- Future veiling glare work could look into the influence that surround color has on measured and observed color.
6.1.1 Effect of Veiling Glare on Measurements

When white and black masks were used to isolate achromatic patches, veiling glare effects were clearly affected as demonstrated in Figure 3.6. Patches with lower brightness (Y) exhibited a larger percentage change in green sensor intensity than higher brightness patches. The percentage difference between the white mask and black mask were 24% for the highest brightness patch and 63% for the lowest brightness patch. The black mask represents an image measurement with reduced veiling glare, and the white mask represents increased veiling glare. The differences between the bright and less bright patches under each condition show the difference between the signal-to-noise ratios caused by veiling glare. Low brightness patches will have a smaller signal-to-noise ratio than high brightness patches since the surround remains constant.

Under the white mask, there is more light reflected from the scene and from the elements’ surfaces. These reflections increase the response in the green sensor for the target patch. The black mask reduces the light reflected from the scene and the green sensor response is accordingly lower.

6.1.2 Veiling Glare Variation Based on Lens Construction

Fixed lenses with fewer elements are less affected by veiling glare than zoom lenses with a high number of elements. Each element in the lens reflects small amounts of light, which means when a lens has more elements, it will cause more veiling glare. This is why the zoom lenses showed a larger difference in green sensor intensity when the black mask was used to reduce veiling glare, as shown in Figure 4.4. The performance of the radiometer was in between the performance of the camera with zoom and fixed lenses. Since information pertaining to the radiometer’s lens was not available, it is speculated that the construction of its lens is related to its performance. The fixed lenses contained 7 and 8 elements, while the zoom lenses contained 11
and 17 elements as shown in Table 1.1. The relation between the type of lens and the amount of veiling glare shows that fixed lenses are preferable for reducing veiling glare, but predicting the lens construction based on the veiling glare does not appear possible from this experiment.

Of the DSLR camera lenses used, the 35mm lens demonstrated the least difference between the images without a mask and images with the black mask that reduced veiling glare. Using the black mask reduced green sensor intensity by 14.2% under the 35mm lens. For this reason, the 35mm lens would be the best choice, among the lenses examined, for measurements within the DigiEye unit.

6.1.3 Characterizing Surround Effects on Veiling Glare

Using the white and black masks, it was shown that veiling glare has an effect on green sensor intensity. The circle surround experiment shows that gradually changing the surround will change the veiling glare effect in a similar way. Figure 5.5 shows that glare does spread from the bright surround to the dark part of the image. It also shows that the veiling glare effect is related to the overall brightness of the image. Figure 5.6 shows that a similar effect occurs within the radiometer. The reason that the radiometer experienced a linear change and the camera lens did not could be due to lens construction and the device settings such as differences in aperture to block out stray light. The radiometer experienced less of an effect from veiling glare. It is possible that aperture size or other differences in devices caused that result.

A drawback of the glare spread function experiment (circular masks) is that it does not show if the decrease in green sensor intensity and radiometer luminance was only due to decreasing the amount of white surround or also due to the distance from the white surround to the target measurement. A future way of testing the effect of surround brightness independent of glare spread
could be by using a series of achromatic masks that start at white and gradually decrease in brightness to a black mask. By using a single scene, measurements can be taken at different distances from the white or dark part of the image. Figure 5.9 shows that veiling glare spreads into the dark portions of the image, but as seen in Table 5.1, the spread effect mostly affects the areas closest to the bright surround.

What both of these tests show is that veiling glare effects will depend on the overall surround of the scene being observed, as well as the immediate surround a target color has with other colors. Images with high contrast will be more susceptible to veiling glare effects. As a form of colorimetry, using a DSLR camera would be dependent on the scene being observed and may not be consistent in measuring the green sensor intensity (luminance estimate) in a manner similar to a spectrophotometer that measures a color in isolation. However, it should be noted that spectroradiometers that use optical systems are also susceptible to the same veiling glare effects and may provide inconsistency when measuring luminance from a colored patch that reflects light at its surface under different surround conditions. By isolating a color in a consistent surround, a DSLR camera and a radiometer would generate more consistent results. However, these lens based instruments are not designed for measuring a color in complete isolation like a spectrophotometer. The advantage of using a lens based system would be for objects that could not be easily measured by spectrophotometer such as a multicolored object.

Instances that DSLR cameras could provide useful color information include comparing scenes of similar brightness and surround conditions. For a multicolored object, such as textile patterns or printing, standards could be compared to batches because the veiling glare effects would remain the same due to the overall surround brightness remaining the same as well as the distance a target color would have with its surround effects. One of the potential drawbacks would
be that even within the same image, a pattern could have a color surrounded by low brightness in one area and high brightness in another, which would affect the green channel sensor intensity at those two different spots differently. While measuring color or light with a DSLR camera, care should be taken to consider the effects that the surround will have and when a camera is an appropriate instrument.

### 6.2 Recommendations for Future Work

This work examined the effect of veiling glare on data generated using DSLR cameras for scientific analysis. The conclusion is that veiling glare has an effect on the light intensity that reaches the sensor and that this effect is highly dependent on the surrounding scene. Future work that would build on this premise is to investigate whether veiling glare can affect the color of measurements by changing the color of the surround, but keeping brightness of the target and surround the same. If a red target were surrounded by green, would a camera or radiometer measure that the red target as having more green light than it reflects? Additionally, the next step for continuing this study would be to determine the effect glare has on color in terms of color difference. This study used white light as luminance and luminance estimates to understand quantify how much veiling glare light was affecting sensor measurements. Calculating these veiling glare differences within a color space in terms of CIEDE2000 would give a better idea of the accuracy color measurement using a digital camera.

For predicting glare, future work could seek to predict the effects veiling glare will have on an image due to the overall intensity measured by the sensor. Modelling the veiling glare effect in more complicated images could be used to create more accurate color images. This would also be a major step towards using optical devices to accurately measure color.
REFERENCES


