THE RELATIONSHIP BETWEEN MACULAR PIGMENT OPTICAL DENSITY, VISUAL RANGE, AND BRIGHTNESS PERCEPTION

by

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(Under the Direction of Billy Hammond Jr.)

ABSTRACT

Yellow intraocular filters, such as the macular pigment (MP) of primates, are found throughout the natural world. A variety of hypotheses have been proposed to explain the prevalence of these filters, many regarding the advantages they may confer. One optical benefit is that under specific conditions MP and other filters will improve the contrast of visual targets from their background. Thus potentially enhancing important visual functions, including visual range and brightness perception. The purpose of the present investigation was to assess if individuals with higher densities of macular pigment (MPOD) can see farther in the distance, and perceive natural world scenes as brighter. A sample of young, visually healthy adults were recruited from the University of Georgia and assessed psychophysically on the previously described functions. MPOD was significantly and positively related to visual range, but not the perceived brightness of natural-world scenes.

INDEX WORDS: Macular pigment, visual range, brightness perception, contrast, contrast sensitivity

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DEDICATION

For my father, were you to read this, I hope you would be proud.

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INTRODUCTION

Macular Pigment

Many vertebrates possess colored intra-ocular filters, which absorb light before it reaches the photoreceptors. These filters range from oil droplet mosaics common in birds to the macular pigment of primates (Walls & Judd, 1933). A common feature of these filters is that they are yellow and derived from dietary carotenoids. This is the case for macular pigment, which is the blue-absorbing, yellow intraocular filter present in the human eye. Macular pigment (MP) is composed of the dietary xanthophylls lutein, and zeaxanthin (L+Z). These pigments are commonly found in colorful fruits and green leafy vegetables (Sommerbug et al., 1998; Abdel-Aal et al, 2013). When consumed in sufficient quantities, L+Z can cross the blood-retina barrier. Once in the eye, L+Z preferentially concentrate in and around the fovea, with highest densities in the fiber of Henle and the inner plexiform layer (Snodderly et al., 1984a). The density of these pigments' decline exponentially with retinal eccentricity (Snodderly et al, 1984b). The spatial distribution of MP ensures that it screens incoming light before it reaches the central photoreceptors. MP preferentially absorbs shortwave light, with peak absorption at approximately 460 nm. This area of the spectrum is commonly identified as “sky-blue”. There are significant individual differences in the amount of L+Z present in the eye, ranging from 0.0 to greater than 1.5 log units (Hammond et al, 1997). Individuals with an exceptionally high density of these pigments (approx. 1.5 optical density units), will filter about 97% of incoming short-wave light before it reaches the photoreceptors. Reducing the amount of short-wave light incident upon the photoreceptors has many benefits, from reducing glare and photostress, to protecting the retina from photo-oxidative damage (Beatty et al., 1999; Stringham et al 2003; Stringham & Hammond 2007; Stringham et al. 2011). It has also been suggested that MP can improve vision outdoors by filtering out short-wave light scattered by the atmosphere (Walls & Judd 1930; Wooten & Hammond, 2002).

Visual Range

Discriminating a target from its surround/background is one of the more basic functional requirements of the human visual system. Increasing distance between the eye and a target reduces the ability to discriminate due to both changes in relative size and contrast. Not all targets, however, are affected by distance in the same way (Bennet et al. 1933). Moderating factors include, the inherent contrast between an object and its surround, the wavelength composition of a target/surround, the presence of veiling luminance, etc. (Bennet, 1933). Taken together, these conditions determine the distance a given individual can correctly identify a visual stimulus and is referred to as their visual range.

Many of the factors that determine visual range are external and stable features of a given scene (size, atmospheric turbidity, etc). Others, however, are intrinsic and differ across individuals. Some of the latter are obvious (e.g., acuity), others are likely less obvious and may be amenable to change (like increasing MP density).

A key environmental limiter of *visual range* is the veiling luminance of the atmosphere (Bennet, 1933). In naturalistic settings, this veiling luminance takes on a bluish hue and is often called *blue haze* (Went, 1960). Blue haze gets its distinctive color from the scattering of light by air particles and other substances suspended in the atmosphere. Scattering in the atmosphere is related to both particle size and wavelength (Went, 1960). The dominant molecules in the atmosphere (oxygen and nitrogen) are small. These small particles scatter light in a way that is inversely proportional to its wavelength. Thus, short-wavelength light is scattered significantly more than other wavelengths, making the sky blue. The relationship between wavelength and scatter was described by Lord Rayleigh in his famous equation: scatter is equal to the inverse of wavelength to the fourth power.

Although air molecules contribute significantly to blue haze, they are not the only source of the phenomenon (Went, 1960). An important contributor is volatile organic compounds (VOCs) exuded by trees and other plants. These compounds, which include terpenes, are small, and preferentially scatter short wavelengths. Other contributors to blue haze include dust, sea-salt, volcanic ash, and products of combustion.[1] These particles and VOCs are called *haze aerosols.* The interaction between haze aerosols and oncoming sunlight creates what we perceive as blue haze. This haze is most prevalent over heavily forested areas and is most dramatically apparent from mountains[2] or airplanes. The added aerial perspective of standing on a mountain's summit illustrates how with increasing distance blue haze begins to blur contrast borders between sister peaks before completely obscuring far off mountains into the horizon. Refer to Figure **1** for an example of this phenomenon.

The preponderance of short-wave light (Earth appears very blue from space) often poses a challenge for the visual system. Short-wave light yields the lowest monochromatic visual acuity, and highest photophobia (Luckiesch 1911, as cited in Walls & Judd, 1933; Stringham et al., 2003). Furthermore, this portion of the spectrum radicalizes oxygen species which leads to the degradation of ocular tissue. It has been suggested (Walls and Judd, 1933, Hammond, 2012)

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[1] Human industrial activity, mostly based on plants that emit sulfur dioxide, is greatly expanding the ubiquity of blue haze as a factor effecting visual outdoors. This was exemplified by the "Blue Haze incident" in Kanawha Valley, West Virgina (1-25-2008) where an industrial accident caused intense blue haze for months.

[2] Blue haze in mountainous areas often serves as the motivation for naming the area: for example, the Blue Ridge Mountains (extending from the town of Blue Ridge GA to Pennsylvania) and the Blue Mountains in Oregon/Washington, Jamaica, Australia, Canada, New Zealand, Southern India, and the Congo.

that primates have evolved colored intraocular filters to combat these effects (i.e., improving acuity and preventing damage).

Brightness Perception

Brightness perception is often described as the subjective experience of the intensity of light that is emitted by a surface (Gregory, 2015; Kindom, 2011; Murray, 2021). Given the physiological process of phototransduction (i.e., a single photon of light isomerizes a photopigment molecule producing excitation) it is reasonable to assume that the perceived brightness of a stimulus is directly proportional to its intensity. This is, however, not the case. The relationship between the intensity of a stimulus and its apparent brightness is not linear. Stevens (1957) demonstrated that under specific conditions it is well described by a power function of 0.33. Subsequent psychophysical research supported Stevens' conclusions, showing a strongly curvilinear relationship between intensities and apparent brightness (e.g., Bartelson & Breenamen, 1967). Brightness perception is thus a complex process influenced by more than simply the number of photons reaching the photoreceptors.

Similar to the perception of color, apparent brightness remains fairly constant under varying levels of illumination (referred to as brightness constancy; Cornsweet, 1970). This effect is dependent upon the illumination of both the stimulus and its background. If only the stimulus is illuminated perceived brightness will largely become a function of intensity (Cornsweet, 1970). This highlights the importance of contrast in apparent brightness. Heinemann (1955) assessed the effect of contrast on apparent brightness by presenting subjects with a circular stimulus super-imposed on a large disc background. Increasing the intensity of the background relative to the target decreased its perceived brightness. Jameson & Hurvich (1964) demonstrated the bidirectionality of this effect by reducing the luminance of a target's surround, thereby increasing its apparent brightness (termed brightness induction). The effect of contrast on brightness is further evidenced by White's effect (White, 1979; White 1981): where identical grey squares are overlaid on or between contrast gratings. The squares that are overlaid between the gratings are perceived as darker than those on top of the gratings. Shapley and Reid (1985) argued that the visual system associate's brightness with reflectance rather luminance. Thus, contrast is an effective cue for apparent brightness as it is directly related to the reflectance of an object and its background, and remains constant under varying levels of illumination.

Contrast is not the only cue utilized by the visual system in the perception of brightness. Further studies have demonstrated that assimilation (summing the brightness of a target and background; Leeuwenberg, 1982) also impacts the apparent brightness of a target (e.g., Shapley and Reid, 1985). Brightness is also impacted by saturation, so that more saturated colors are perceived as brighter (known as the Helmholtz-Kohlrausch effect; Corney et al., 2009). Additionally, a stimulus' apparent brightness is impacted by temporal factors. In studies of brightness pulse perception it has been demonstrated that pulse duration significantly affects the perceived brightness of a pulsing stimulus (e.g., Bowen et al., 1981). This temporal brightness enhancement is known as the Broca-Sulzer effect.

It is important to note that although brightness perception has been extensively studied, many investigations have used stimuli unlikely to be encountered outside of the laboratory. For example, it is doubtful that individuals will encounter discs pulsing at 50 msecs outside of a vision science experiment. Consequently, there is a need for an ecologically valid assessment of brightness perception in outdoor natural scenes.

Macular Pigment and Visual Range

Given the absorption profile of MP and the spectral characteristics of blue haze, the question arises: would a higher concentration of lutein and zeaxanthin (L+Z) improve visual range by filtering out blue haze? This relationship was initially proposed by Henning (1920) and further elaborated by Walls & Judd (1930), who hypothesized that yellow intraocular filters might enhance long-distance target discrimination by filtering out shortwave light. Luria (1972) observed that yellow filters increased the visibility of a long-wave target against a short-wave background. This effect occurs because the filter selectively reduces the amount of shortwave light reaching the photoreceptors, while the amount of long to mid-wave light remains constant. Consequently, the contrast between the target and its surroundings is enhanced. This contrast enhancement was not observed with other filters and was significantly reduced when using a yellow filter on mid and long-wave backgrounds. A subsequent study by Wolffsohn et al. (2000) found that yellow-tinted lenses (ytls) increased the contrast between a white on blue sinewave grating target and a short-wave background. Importantly, the spatial frequency of the target played a role in contrast enhancement. The lenses used in this investigation closely resembled the absorption profile of MP (ytl: 450-nm, MP: 460-nm).

The proposed relationship between MP and visual range was revisited by Wooten and Hammond (2002); who referred to it as the *visibility hypothesis* of MP. The authors modeled the relationship between the density of MP, also known as macular pigment optical density (MPOD), and visual range. Their modeling predicted a positive relationship between MPOD and visual range, meaning that with increases in the density of pigment, targets would be lost at a greater distance. According to the model, all things being equal (e.g., basic acuity), individuals with high MPOD (1.0-log unit of density) would experience a 30% increase in their visual range compared to individuals with low MPOD. The mechanism behind the visibility hypothesis, the selective reduction of a shortwave background, was investigated by Renzi et al. (2010). This study examined the relationship between MPOD and heterochromatic contrast. The authors found that individuals with higher MPOD required more energy to lose a long-wave target against its short-wave background, indicating that MP produced a contrast enhancement similar to those shown with yellow-tinted lenses by Luria (1972) and Wolffsohn et al. (2000).

The first empirical assessment of the visibility hypothesis was conducted by Hammond and colleagues (2012). Their investigation utilized an artificial MP filter cell, allowing the researchers to adjust the density of MP. Under simulated blue haze conditions, added MP density reduced contrast thresholds for an 8-cpd sine wave grating. The strongest effect was observed after 0.25-log units of density were added, and eventually the effects plateaued with increased MP. A similar experiment was conducted by Fletcher et al. (2014), correlating increased visual range with in vivo measurements of MPOD. Importantly, subjects in Fletcher et al. (2014) were tested in broadband, simulated blue haze, and short-wave deficient conditions. MP had no effect on contrast in the short-wave deficient condition, demonstrating that improvements in visual range are dependent on the selective reduction of short-wave light.

Brightness Perception and Macular Pigment

The effects of filtering on contrast raise a corollary question, do yellow filters also increase perceived brightness? Ytls are widely used by outdoorsmen, skiers, hunters, and hikers. It has been noted that these groups often report an increased subjective perception of brightness in natural scenes. Despite these reports, the literature describing the effect of ytls on brightness perception is mixed (Yap, 1984; Kelly, 1990; Luque et al., 2006).[3] There are two theoretical mechanisms that could explain how ytls increase brightness. The first to consider is contrast enhancement contributing to brightness perception. As discussed earlier, most natural scenes have a short-wave background. A yellow filter will improve contrast in these scenes by reducing the amount of short-wave light reaching the photoreceptors. This contrast enhancement could boost the overall perception of brightness. Hence, although the overall amount of light reaching the retina is reduced, selective filtering may have the paradoxical effect of making a scene appear brighter. Kelly (1990) suggested a different mechanism. In their experiment researchers found that ytls enhanced brightness by as much as 40% when the stimulus exceeded the fovea. This effect was not observed when rods were exposed to a bleach. Kelly (1990) hypothesized that luminance reduction from the ytls caused the rods to become active and contribute to the overall brightness signal (analogous to the beginning of the Purkinje shift from photopic to mesopic vision).

Another important distinction is that only anterior lenses, like spectacles and contact lenses, have been tested. Anterior filters screen the entire retina (both rods and cones). In contrast, MP is in the posterior section of the eye (inner retinal layers of the macula) and screens mostly cones. If MP does improve brightness, it seems much less likely to do so by inducing the Purkinje shift effect described by Kelly (1990). MP does, however, improve chromatic contrast (Renzi et al. 2010). Toscani et al (2013) argued that lightness judgements (perceived reflectance) are based on the brightest parts of the image sampled by eye movements. The visual system scans an image (aligning salient features with the fovea) and then stitches these representative

[3] Although, it should be noted that the studies are hard to consider together. Often the filters and/or stimuli are not precisely specified. For example, many studies describe the filter they used as simply yellow but a lens can appear yellow while having dramatically different filtering profiles.

pieces into a whole. If MP is screening these samples, it could also influence the brightness of the entire image (despite only filtering a small portion at any given time).

Hypotheses

Macular Pigment and Visual Range

The relationship between MPOD and visual range has been well studied. Data from Hammond et al. (2012) and Fletcher et al. (2014) demonstrate that higher MPOD leads to increased visual range. Given these findings one of the main aims of this study was to replicate the relationship between MPOD and visual range. The specific hypotheses for the MP and visual range measures were: H_0 = MPOD has no relation to contrast sensitivity under blue haze conditions; H_1 = MPOD is inversely related to contrast sensitivity under blue haze conditions.

Through the use of more effective and user-friendly devices, this study aimed to address unanswered questions from Fletcher et al. (2014) and Hammond et al. (2012). Two specific questions of interest were:

I) What is the effect of blue haze on different spatial frequencies? Fletcher et al. (2014) investigated this issue on 12 subjects and found a uniform reduction in the CSF curve. For this reason, she conducted her primary investigation using only one spatial frequency (7.5-cpd). The optical system used in this study allowed for a much quicker assessment of contrast sensitivity. Thus, it was feasible to test subjects at multiple spatial frequencies.

II) Why did improvements in visual range plateau in Hammond et al. (2012) but not Fletcher et al. (2014)? The primary difference between the two studies is that the artificial MP filter cell used by Hammond and colleagues (2012) was an extrinsic filter: which was not adapted to in the same way as a stable internal filter.

Macular Pigment and Brightness Perception

A much less studied area is the effect of MP on brightness perception. In our brightness testing, we used images which covered a wide region of the visible field. MP, which is most densely concentrated in the fovea, cover about 6 to 7-degrees at most. Since, the visual inspection of a scene involves rapidly moving the fovea over the visual area, it is possible filtration by MP may have a significant effect on scene perception. If MP improves brightness via contrast enhancement, it would be due to the effects of contrast as aggregated over the visual scan. The second mechanism, also possible, is due to boosting the brightness signal by engaging rods. Kelly (1990) originally suggested that yellow filtering could increase brightness by bringing more rods online (i.e., they are not bleached out by unfiltered light). Although MP is most dense in the fovea, it still absorbs a significant amount of short-wave light in areas with high concentrations of rods (e.g. Snodderly 1984b, Hammond et al. 1997). Given the high number of rods in the retina (~100 million) relative to cones (~6 million), it would take a relatively small number of rods to boost the much smaller population of cones.

Hence our hypotheses regarding MPOD and brightness perception were: H_0= MPOD has no relationship with the perceived brightness of complex stimuli; H_2= MPOD is positively related to the perceived brightness of complex stimuli.

Figure 1

Figure 1 demonstrates the occluding properties of haze: note that both the borders become less distinct as the target (the mountains) is lost to its background (the blue sky). (Unsplash.com)

METHODOLOGY

Participants

Sixty-two participants were recruited from the student body at the University of Georgia and from the Athens-Clarke county community. The sample size was selected based on a power analysis done in RStudio (Version 4.3.3) using the "*pwr*" package. For this analysis, Pearson's *r* was set at .35, the significance level at .05, and power at .80. The results of this analysis suggested that a sample size of 60 would be sufficient to detect an effect of that size.

In order to control for individual differences in resolution acuity, which could have affected the visual range measure, those with uncorrected visual acuity worse than 20:40 were excluded from participating in the experiment. Additionally, to control for the yellowing of the crystalline lens and other age-related confounds, study participation was limited to individuals between the ages of 18 and 32 years. Further inclusion criteria included good ocular health and fluency in spoken and written English. Exclusionary criteria included any eye or medical conditions, extreme light sensitivity, and failure to meet the inclusion criteria described above.

Of the 62 participants enrolled in the study, 2 were discontinued during their visit. Both participants were discontinued because they did not meet the visual acuity requirements of the experiment. After removing these subjects from the study, the final sample was 60 healthy young adults.

Measurement of Macular Pigment Optical Density.

MPOD was measured using flicker photometry and the macular densitometer (Macular Metrics Corp., Providence, RI) described by Wooten et al. (1999). Results from this method have been shown to be both highly reliable and valid (Hammond et al., 2005). The method is explained in detail in Wooten et al. (1999) and Snodderly et al. (2004). A brief description of the procedure is as follows: participants were measured in free view using their dominant eye with the non-dominant eye covered. The device contained an optical system that was housed within black, metal baffling. The entire system was occluded from view with the exception of a 1-inch (radius) circular aperture through which participants peered to view the stimulus. Participants were first assessed at a foveal location (30-arcmin) followed by a parafoveal reference (7-degree). Once properly aligned, participants viewed a 1-degree circular test stimulus superimposed on a 6-degree background (470-nm). The wavelength of the test stimulus alternated in a square wave between a measuring wavelength (460-nm) and a reference wavelength (570-nm), creating the perception of flicker. The measuring wavelength is strongly absorbed by MP while the reference wavelength is not. The rate at which the measuring and reference wavelengths alternated was determined by the participant's critical flicker fusion threshold (CFF) and the test location (foveal vs. parafoveal). The overall output of the stimulus remained constant throughout the MPOD measurement (2.75 cd/m^2); however, the yoked intensities of the measuring and reference wavelength were adjustable. The experimenter modified the intensity of the measuring wavelength (in turn affecting the reference) until the participant indicated flicker fusion. The log radiance of the measuring and reference wavelengths were then recorded by the experimenter. Five measurements were conducted in the foveal and parafoveal locations respectively. In the parafoveal condition, the test stimulus was enlarged to 2-degrees and a tiny (5-arcmin) fixation point was added 7-degrees to the left of the test stimulus. At this retinal eccentricity, the amount of measurable MP is negligible, therefore it can be compared to the foveal measure. At this location, subjects were instructed to focus their gaze on the fixation point and use their peripheral vision to monitor the test stimulus for flicker. The experimenter adjusted the intensities of the yoked wavelengths until no flicker was perceived. The log radiance of the measuring wavelength was then recorded. A participant's MPOD was derived from the difference of the log radiances in the fovea and parafovea.

Measurement of Experimental CFF

CFF was measured centrally using the 1-deg test stimulus, prior to the assessment of MPOD. To measure CFF, the experimenter turned off the measuring wavelength so that the test stimulus was only composed of the 570-nm light which continued to flicker in a square wave at 100% modulation[4]. The rate of flicker was first set to approximately 10-Hz so that the test stimulus was obviously flickering. The experimenter then increased the flicker rate until the participant reported the test stimulus appeared solid. The flicker rate was then set at approximately 35-Hz (well above threshold for this sample and these conditions) and decreased until the participant reported that flicker had returned. Two ascending and descending trials were conducted, and all scores were averaged to yield an approximate CFF.

Measurement of Visual Range

The assessment of visual range was conducted using a two-channel optical system. This system is shown in Figure **2**. The "visual target channel" consisted of the optical device used in Hammond et al. (2023). The contrast stimulus consisted of sine-wave gratings on glass that were back-illuminated with green (520-nm) light by two highly stable lasers (Model DS20X90-520-

[4] The 470-nm background was not turned off and variations in participant's pupil size were not controlled for; thus, the CFF value obtained may have been confounded. The fact that only younger subjects were used and that CFF is not overly influenced by the off-phase being completely black suggests, however, that those effects were likely minimal..

120L; Apinex; apinex.com). Light from both sources was spatially diffused through two 15.24-cm circular integrating spheres. Each integrating sphere had a circular exit port that subtended 3.5-degrees of retinal eccentricity through which the homogenized green light passed. Light from L1 traversed a 5.08-cm glass sinewave grating. For the purpose of this investigation, the spatial frequencies 3.2, 8, and 16-cpd were used. A slow revolving flicker vane placed between L1 and the integrating sphere was used to provide intermittent exposure (~1-sec exposures) of the grating stimulus to prevent subject adaptation. Light from L1 and L2 were combined by a beam splitter before being made circular by an iris diaphragm. The intensities of L1 and L2 were adjusted by two independent, circular, neutral wedges (CS_{w1} & CS_{w2}). Adjustments in the position of CS_{w1} & CS_{w2} allowed continuous variation in the modulation of sine waves.

The other channel, the "haze channel", utilized a 150-W xenon arc lamp (T_x) as a light source (Thorlabs, Newton, NJ). Light passed through a collimating lens (L_{c1}), a specialized chromatic "blue haze" filter (B_f). This filter was selected based on past research (Wooten et al., 2002) and with the purpose of creating a light veil that matched the known spectrum of blue haze as measured in the atmosphere (the CCT of our source was 9424). A neutral density filter (ND_{f1}), a pinhole aperture paired with a neutral density wedge (BH_w,) and a focusing lens (L_{f2},) were used before being projected onto a diffusing screen (Ds)[5]. Haze from this channel was integrated with the contrast target by a beam splitter placed 91.44-cm from the eye of the observer. BH_W allowed the experimenter to adjust the amount of haze obscuring the contrast grating. The Thorlabs lamp was selected as a light source because the output of xenon arc bulb closely matched that of sunlight (Refer to Figure 1 in Hammond et al., 2013 for the spectrum of sunlight

[5] The exact distances for the haze channel are as follows: L_{c1} at 18 cm from T_x.. B_f 10 cm from L_{c1}. The pinhole and BH_w would respectively be located 7 and 10 cm from B_f. The distance between the wedge and D_s would be set at 11 cm.

and xenon). Previous studies investigating the visibility hypothesis (e.g., Fletcher et al., 2014; Hammond et al., 2012) have paired 1000-W xenon arc bulbs with specialized glass filters to simulate blue haze. This pairing produces a spectrum that is nearly identical to blue haze (refer to Figure **3**).

To obtain visual range thresholds, participants first aligned their gaze with the test stimulus. An adjustable forehead/chinrest assembly stabilized their view of the 3.18-degree stimulus. The three contrast gratings were presented in the following order: 3.2, 8, and 16-cpd. To ensure that the gratings were easily visible without the introduction of haze (e.g. 80% modulation for the 3.2-cpd grating), the position of CS_{w1} & CS_{w2} in the visual target channel remained fixed. With output at approximately 200-mcd/m^2 and 3.00-cd/m^2 respectively. Optical baffling was employed throughout both channels to prevent crosstalk and interference from stray light. After confirming that the subject could easily resolve the grating, the experimenter introduced blue haze via adjustments in BH_w. The intensity of light in this channel was increased until the grating was no longer visible. Three measurements (all ascending) were obtained using the method of limits and averaged for each spatial frequency. The position of wedges in the visual target and haze channel were recorded from a wedge readout. Prior to data collection, the corresponding log relative energy (LRE) values for each position on the wedge were obtained and used to create a formula in Microsoft Excel (2021). After each experimental session, participant's average wedge positions for each spatial frequency were entered in Excel to obtain the corresponding LRE value. A UDT5370 Optometer (Artisan Technology Group, Champaign, IL) with a photometric lens (Artisan Technology; artisantechnology.com) was used to ensure a constant luminance output in the contrast channel. A digital radiometer (Industrial Fiber Optics Inc, Tempe, AZ) was also used to monitor the output of the haze channel.

In the early stages of the investigation (participants 001-032) participants experienced difficulty resolving the 16-cpd grating without the presence of haze. This was likely due to the low luminance of the visual target channel (approximately 3.00-cd/m^2). When these participants did lose sight of the grating to haze, it was often in a region of the wedge that had minimal filtration, so the derived LRE values were not meaningful. Therefore, beginning with participant 033, an additional neutral density filter (ND_{f2}; .50 optical density) was added to the haze channel on an as needed basis. The addition of the filter decreased participant burden for the 16-cpd task and increased the interpretability of the derived LRE values. The experimenter determined if inclusion of ND_{f2} was necessary by presenting the 16-cpd grating at a specified cut-off point; specifically at 1100 on the wedge readout which corresponded to a derived LRE value of 2.80. Above this point on the wedge readout, the derived LRE values became unreliable; briefly plateauing before incorrectly indicating more energy. If the participant could not resolve the grating then the extra filter was added, and .50 was subtracted from their derived LRE value. Participants who completed the study prior to this change and whose LRE values were below the 2.80 cut-off for the 16-cpd target where either re-measured (n = 1) or their data for that frequency was excluded from analysis (n = 9).

Measurement of Brightness Perception

Brightness perception was measured using a brightness-matching technique where participants matched the intensity of a comparison field (a broadband, short-wave deficient circular target) to projected natural-world scenes. The apparatus included two optical channels and is shown in Figure **4**. The optical channel producing the comparison field consisted of a 1000-W xenon arc lamp (Oriel Instruments, Newport, CA), a collimating lens (L_{c1}), a focusing lens (L_{f1}), a pinhole aperture and neutral density wedge (ND_w), a Voltmeter (Greenlee, Rockford, IL), a circular yellow filter, another collimating lens (L_{c2}), and a focusing lens (L_{f2}). Light from the xenon lamp traveled 12-cm before becoming collimated by L_{c1}, then focused by L_{f1} through the pinhole aperture on ND_W. The distance between L_{c1}, L_{f1}, the pinhole aperture and ND_W was set at 12-cm, 14-cm, and 5-mm successively. Following ND_W, light passed through the yellow filter, became re-collimated by L_{c2} and then was focused onto a white projector screen by L_{f2}. These distances were set at 1.5-cm, 21-cm, and 16-cm respectively. To produce a representation of an outdoor-world scene, we utilized a xenon-slide projector (Navitar Inc., Rochester, NY). The second optical channel consisted of the projector and a neutral density filter fixed 4-mm from the projector lens in the path of the light. Six slides ranging in content from chromatic natural scenes to a blank monochromatic (yellow) filter were used. Refer to Figures **5** and **6** to review the slides used. The filters were presented in identical order to all participants.

To obtain a brightness measurement, the experimenter presented the participant with the 17.8-degree test slide and the 14-degree comparison field. The brightness of the comparison channel was set at an intensity unlikely to be matched to the slide (either significantly brighter or dimmer). The experimenter then adjusted the position of ND_W to increase the intensity of the comparison field. Participants were instructed to notify the experimenter when the perceived brightness of the comparator matched that of the test slide. The position of ND_W given by the voltmeter was recorded. Three measurements (alternating ascending and descending) were obtained using the method of limits and averaged for each slide. The values from the voltmeter were averaged, entered in Microsoft Excel (2021) and transformed into LRE values. Prior to data collection, experimenters obtained a range of wedge readout values with corresponding energy levels. These data were used to create a formula in Excel which gave the LRE for each wedge readout value. The LRE of all 6 slides was then averaged to derive an overall measure of participant's brightness perception throughout the experiment.

To ensure the stability of the system and all measurements, a digital radiometer (Industrial Fiber Optics Inc., Tempe, AZ) was used to calibrate the slide projector and the comparison field. Prior to every experimental session, the researcher confirmed that the radiometer readout was ~400-mW for the comparator at 6.00 on the wedge readout and ~18.00-μW for Filter 1.

Measurement of Skin Carotenoid Score

The Skin Carotenoid Score (SCS) was obtained using the LifeMeter™ (MacuHealth, LLC, Bloomfield Hills, MI, USA). The device utilized a pressure-mediated reflection spectroscopy method which is described in detail in Ermakov & Gelllerman (2012). A brief overview of the procedure is as follows: participants first disinfected their non-dominant index finger using a sterile alcohol prep pad. After a brief, drying period, they were instructed to place their finger over a convex lens housed within the device. Then, moderate pressure was applied to the participant's finger using a spring-loaded cover within the device. The pressure was applied in order to temporarily squeeze the blood out of the tissue of interest. After sufficient time had passed for blood to leave the tissue, a broad-band white light (350 to 850-nm) irradiated the finger. In order to derive a measure of carotenoids in the skin, the device computed the absorption difference between 480-nm and 610-nm. Individual differences in absorption at 610-nm are negligible and carotenoids do not strongly interact with this wavelength; whereas, carotenoids strongly absorb 480-nm light. Once the scan was completed, participants removed their finger from the device. This process was repeated three times for every participant with a 5-second break in between measures. After all three scans were completed, the device averaged the absorption differences from the three scans to yield the density of carotenoids in the skin. This density value was then transformed by the device so that possible values ranged from 0 (almost no skin carotenoids) to 800 (exceptionally high skin carotenoids). Additionally, the device also produced a histogram of the distribution of scores in the general population, with the bin most closely aligned with the participant's carotenoid levels highlighted.

Overall Procedure Description

Participants first provided verbal and written informed consent prior to participation. The tenets of the Declaration of Helsinki were adhered to during this step and throughout the duration of study. Good Clinical Practice (GCP) guidelines were followed regarding the storage and usage of participant data and information. The protocol and all study materials were approved by the University of Georgia's Institutional Review Board (PROJECT00009382).

After providing written and verbal informed consent, participants had their Snellen binocular visual acuity measured using a wall-mounted chart. Participants stood 20-ft away from the chart and were instructed to read the lowest line possible with both eyes open, upon successful completion of the task, their Snellen visual acuity was recorded. Participants who did not meet the acuity requirements for the study (20:40 or better) were discontinued. Demographic information (age, gender, ethnicity, and race) were then provided by the participant. Following the collection of demographic information, participant's iris lightness and hue were obtained using an iris color scale (refer to Figure **7**).

Participants typically completed the experimental portion of the study in the following order: SCS, brightness perception, visual range, MPOD. This order was preferred due to the perceived difficulty of the MPOD measurement, specifically the parafoveal condition. However, there was variability in the order in which some participants completed the study tasks. Each experimental session took approximately 60-minutes.

All data was recorded on an IRB approved case report form (CRF). Upon completion of the study visit, data were averaged and inputted into Microsoft Excel. Researchers also recorded any concerns with specific participants reliability or the validity of the collected data on their CRF. After the conclusion of the study, research assistants verified that all CRF calculations were correct and that there were no transcription errors in the online database. Data checking revealed no systematic errors. Once data collection and checking were completed, statistical analyses were performed.

Statistical Analysis

All statistical analyses were conducted in RStudio (Version 4.3.3), and the graphing software Origin (7.0). Data was first cleaned and recoded for ease of analysis. The following variables were numerically recoded: gender, race, ethnicity, iris hue, iris lightness, and binocular visual acuity. Histograms and scatter plots were then generated to assess the data for skew or outliers (refer to Figure **8** and **9**). During this step, experimenters identified two participants as outliers and removed them from the analyzable sample (N = 58). Importantly researchers had previously noted that both participants struggled with the visual range and MPOD measures during their study visit. Data were further assessed for non-normality using the describe function from the "*psych*" package which gives skew and kurtosis values for each variable. Bivariate Pearson's product moment correlations were computed to assess the relationship between continuous variables (e.g., MPOD and visual range at 3.2-cpd). When appropriate, multiple regression analysis was used to determine the amount of variance accounted for by one variable while holding another constant. Regression analyses were also used to model the relationship between visual range and its covariates. T-tests and ANOVAs were conducted to determine the effect of categorical variables, such as binocular visual acuity, on visual range and brightness perception. Data visualization was done in RStudio using the "*ggplot2*" package, as well as in Origin.

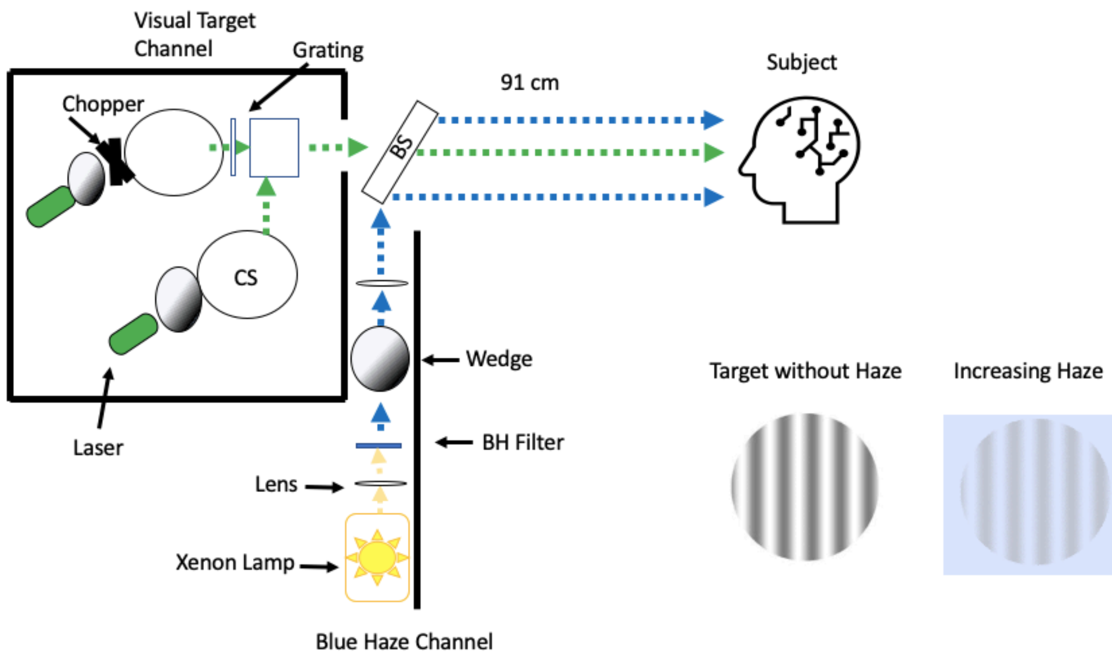

Figure 2

Figure 2 is a conceptual schematic of the device that was used to assess visual range. Refer to the Measurement of Visual Range subsection of Chapter 3 for a detailed description of the light path in both channels.

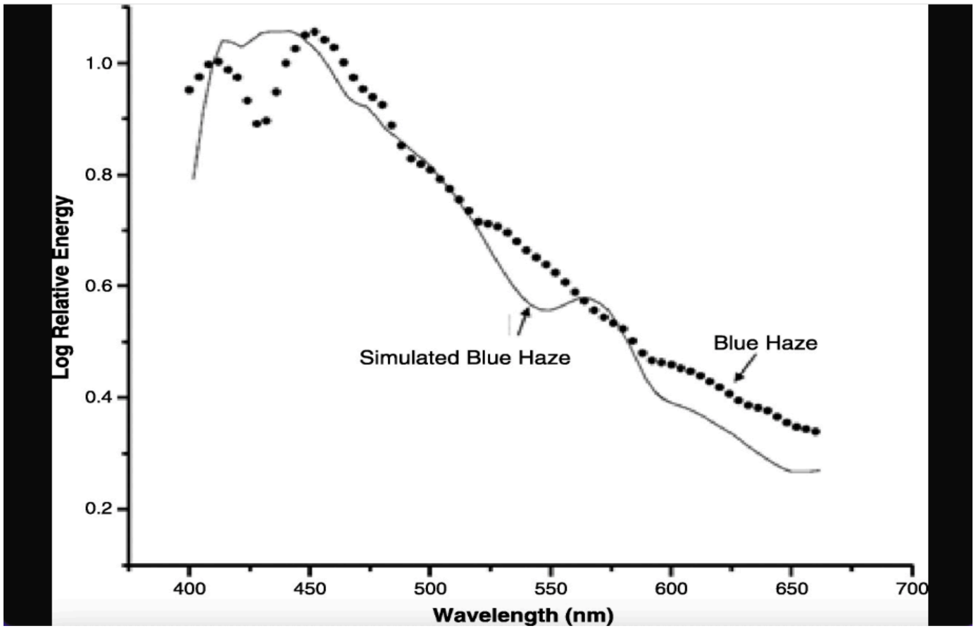

Figure 3

Figure 3 shows the spectrum of haze in the atmosphere compared to that of xenon light paired with the specialized blue haze filter this study would utilize (Fletcher et al., 2014).

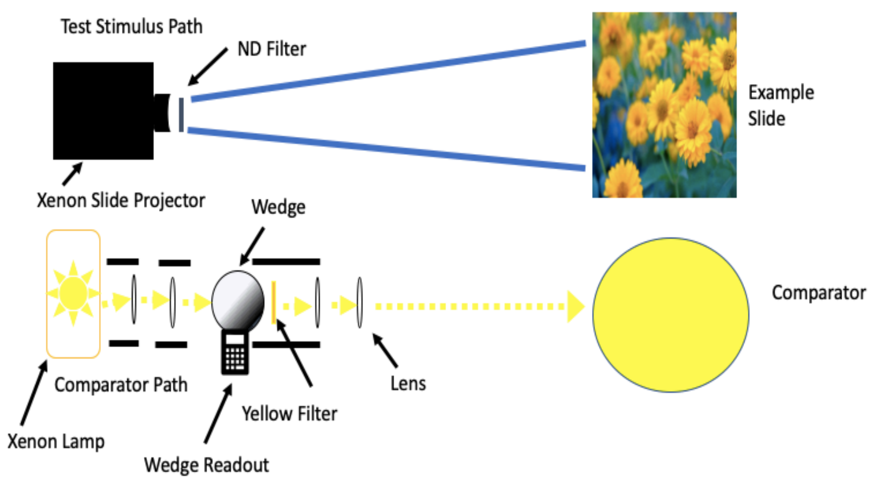

Figure 4

Figure 4 is a conceptual schematic of the apparatus that was used to asses brightness perception. Refer to the Measurement of Brightness Perception section of Chapter 3 for a detailed description of the light path.

Figure 5

Figure 5 shows the five real-world scenes used to asses participants brightness perception. The slides were presented in the order shown (left to right) to all participants.

Figure 6

Figure 6 shows the mid-wave control slide, referred to as Filter 1, that was used to asses participants brightness perception in non-complex scenes.

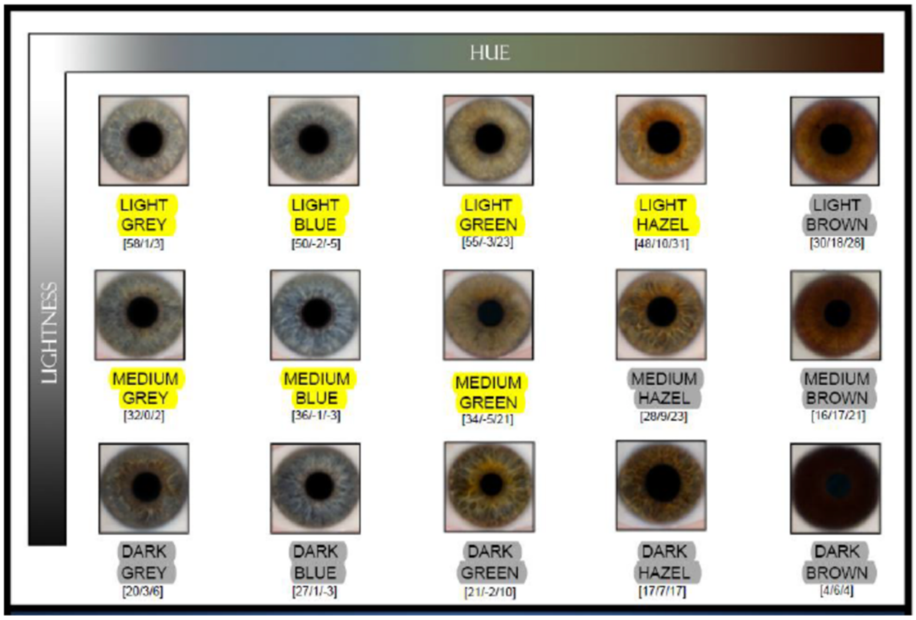

Figure 7

Figure 7 shows the iris color scale used to identify participants iris hue and lightness.

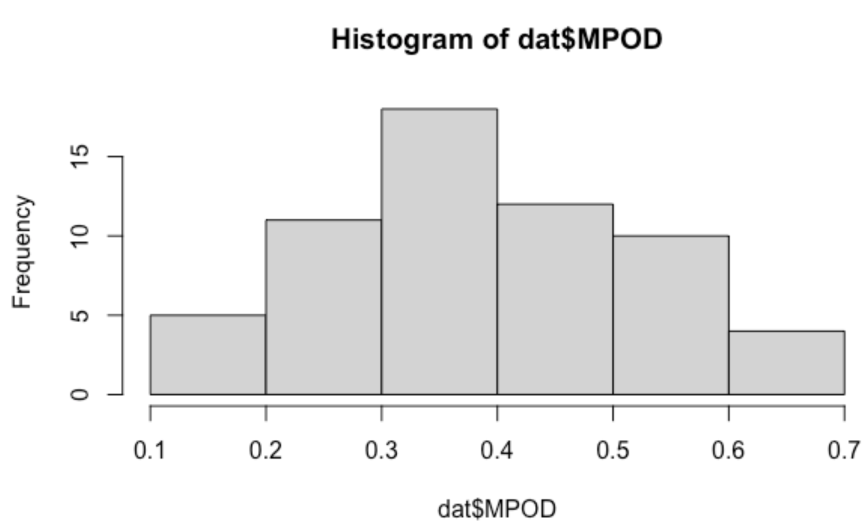

Figure 8

Figure 8 shows the distribution of MPOD in the sample. Similar histograms were generated for experimental variables to ensure a normal distribution.

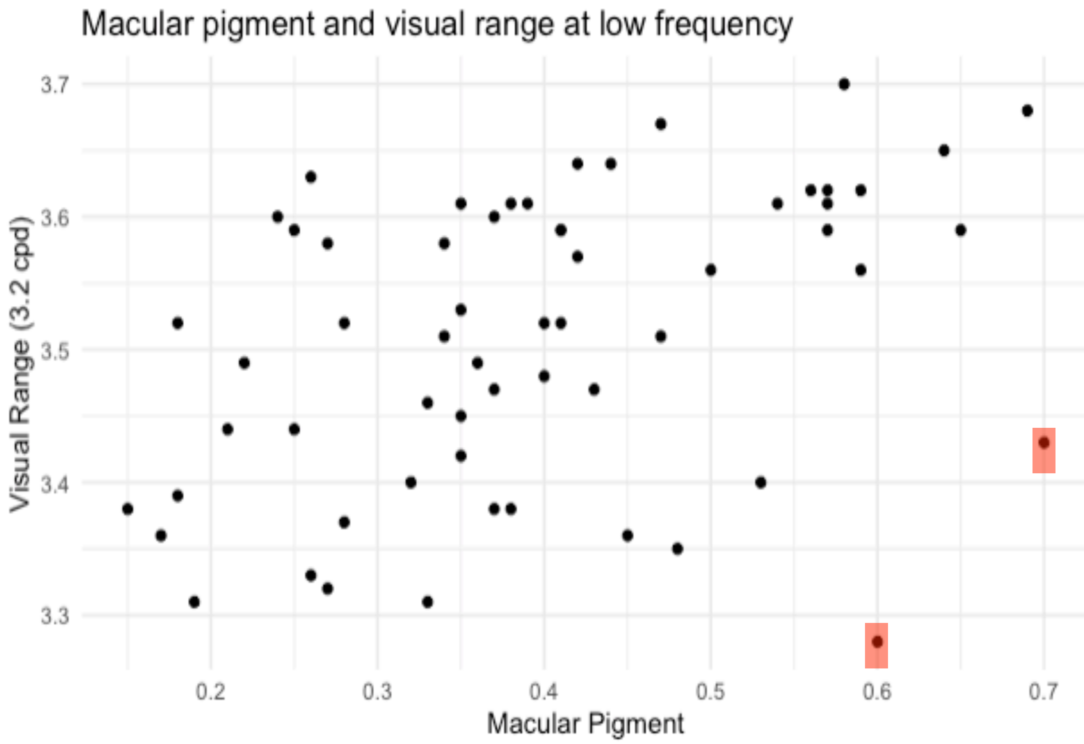

Figure 9

Figure 9 is a scatter plot showing participants visual range at 3.2-cpd on the y-axis and their MPOD on the x-axis. The two outliers who were removed are highlighted in red. Similar plots were generated to assess for skew in the data.

RESULTS

Macular Pigment and Visual Range

Bivariate Pearson's correlations revealed that MPOD was significantly and positively related to participant visual range for the 3.2-cpd ($r(56) = .54$, $p < .001$), and 8-cpd ($r(56) = .36$, $p < .01$) contrast gratings. MPOD was not significantly related to visual range for the 16-cpd contrast grating ($r(47) = -0.03$, $p = .86$). Refer to Figure **10-12** for a graphical representation of these relationships.

To assess if the relationship between MPOD and visual range plateaued in individuals with high concentrations of L+Z, participants were sorted into three groups based on MPOD status (low > .25; .25 > medium < .50; high > .50). The relationship between MPOD and visual range was then plotted. Refer to Figure **13** for a visual representation of these relationships.

Macular Pigment and Brightness Perception

Despite the previously reported positive association between yellow filters and brightness perception (e.g., Kelly, 1990), no significant relationship was detected in this study. Bivariate Pearson's correlations were conducted to assess the relationship between MPOD and Filter 1 ($r(56) = -.25$, $p =.06$), Filter 2 ($r(56) = -.10$, $p = .20$), Filter 3 ($r(56) = -.11$, $p =.42$), Filter 4 ($r(56) = -.02$, $p = .88$), Filter 5 ($r(56) = -.06$, $p = .65$), Filter 6 ($r(56) = 0.18$, $p = .17$). An additional Bivariate Pearson's correlation detected no relationship for the average log relative energy LRE of all slides ($r(56) = -.07$, $p = .58$). Refer to Figure **14** for a graphical representation of the relationship between MPOD and average brightness perception for all slides.

Pos-Hoc Analyses

Skin Carotenoid Score

Further analyses were conducted to assess the relationship between SCS and the variables of interest in the study. Initial inspection of SCS in the sample revealed a significant right skew in the data. In order to meet the assumption of normality required for the planned analysis, a natural log transformation was applied to the data. After this transformation, the data showed reduced skewness (refer to Figure **15**). Bivariate Pearson's correlations were conducted to assess the relationship between the transformed SCS variable (tSCS) and visual range for the 3.2-cpd ($r(56) = .33$, $p = .01$), 8-cpd ($r(56) = .34$, $p=. 01$), and 16-cpd ($r(47) = .22$, $p = .13$) contrast gratings. Additional bivariate Pearson's correlations revealed that tSCS was significantly positively related to MPOD ($r(56) = .38$, $p < .01$) and CFF ($r(56) = .36$, $p < .01$). To investigate if tSCS significantly contributed to the variance in CFF beyond that accounted for by MPOD, a hierarchical regression analysis was conducted. CFF was regressed onto MPOD in the first step followed by tSCS in the second step. Results indicated that tSCS accounted for an additional 6.26% of the variance in CFF beyond that accounted for by MPOD, $R^2 \Delta = .06$, $F(1,55)=4.21$, $p = .05$.

Critical Flicker Fusion Frequency

During the data collection process, experimenters noted that participant's CFF appeared to strongly predict visual range. For this reason, post-hoc bivariate Pearson's correlations were conducted to assess the relationship between CFF and visual range. These correlational analyses revealed that CFF was positively and significantly related to visual range for the 3.2-cpd ($r(56) = .55$, $p < .001$), 8-cpd ($r(56) = .57$, $p < .001$), and 16-cpd ($r(47) = .40$, $p < .01$) contrast gratings. Refer to Figure **16** for a graphical representation of CFF and visual range. To investigate if CFF significantly contributed to the variance in visual range beyond that accounted for by MPOD, a hierarchical regression analysis was conducted. Visual range at the 3.2-cpd was selected for this analysis, as it demonstrated the strongest relationship with MPOD. Visual range was regressed onto MPOD in the first step, followed CFF in the second step. Results indicated that CFF accounted for an additional 15.27% of the variance in CFF beyond that accounted for by MPOD, $R^2 \Delta = .15$, $F(1,55) = 14.77$, $p < .001$.

Gender and Brightness Perception

Welch's t-tests were used to assess gender differences in brightness perception. Slide 1 was selected for preliminary analysis because of its simplicity (e.g., no chromatic contrast). A significant effect of gender was detected $t(40)=2.55$, $p=.01$, with women ($n=42$, $M= 2.74$, $SD=.12$) requiring less log relative energy than men ($n=16$, $M = 2.81$, $SD=.08$) to achieve a brightness match. However, for the average of all slides, this effect was not significant $t(28)=1.70$, p =.10, despite women ($M=2.67$, $SD=.09$) requiring less log relative energy than men (M=*2.71*, $SD= .09$). Refer to Figures **17** and **18** for visual representations of these relationships.

Descriptive Statistics and Sample Characteristics

Descriptive statistics are provided for all experimental variables in Table 1. The sample of the study was relatively homogenous. Participants ranged in age from 18-28 (M = 20.45, SD = 2.90), and were majority (73.33%) women. The majority of the sample was White (73.33%; followed by 15% Asian, 6.67% Black, and 5% Multi-Racial.) and non-Hispanic (91.67%).

Table 1

Descriptive Statistics

Variable	Mean	Standard Deviation	Minimum	Maximum	Range
CFF	27.37	1.87	21.32	30.73	9.41
MPOD	.39	.13	.15	.69	.54
SCS	345.02	102.47	194	730	536
Visual Range (3.2-cpd)	3.51	.11	3.31	3.70	.39
Visual Range (8-cpd)	3.30	.17	2.91	3.64	.73
Visual Range (16-cpd)	2.88	.29	2.31	3.50	1.19
Brightness Perception Filter 1	2.76	.12	2.45	2.96	.51
Brightness Perception Filter 2	2.80	.12	2.57	3.05	.48

Brightness Perception Filter 3	2.47	.12	2.20	2.82	.62
Brightness Perception Filter 4	2.59	.14	2.24	2.97	.73
Brightness Perception Filter 5	2.69	.15	2.39	2.94	.55
Brightness Perception Filter 6	2.75	.14	2.38	3.02	.64
Brightness Perception All Filters	2.68	.09	2.49	2.93	.44

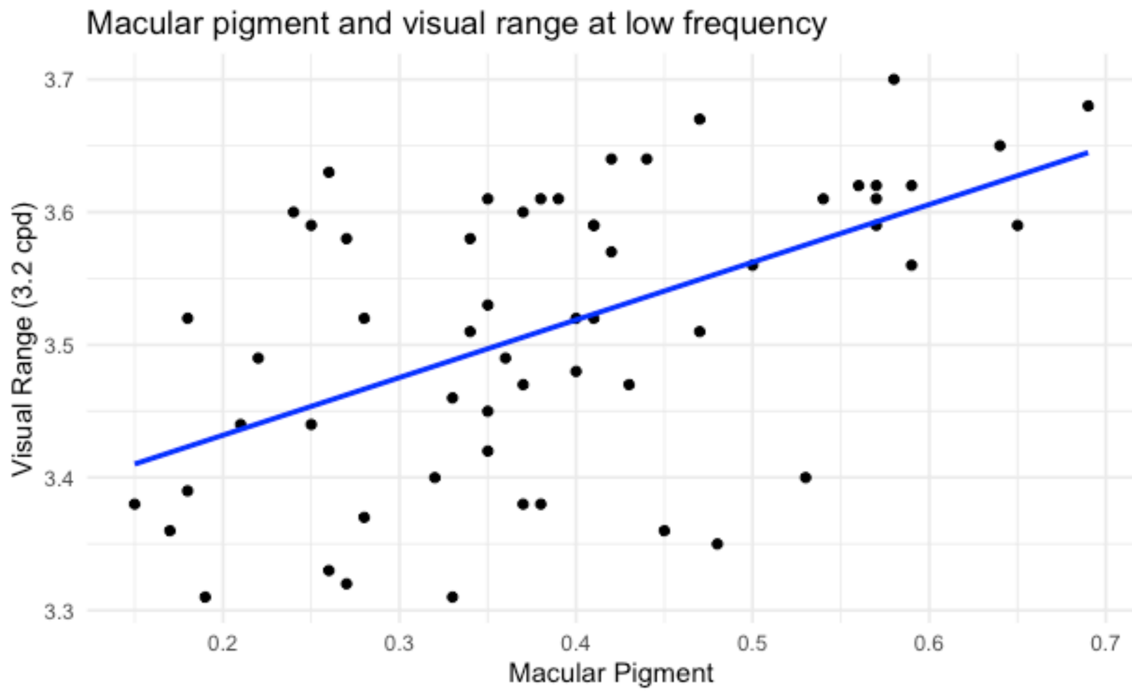

Figure 10

Figure 10 demonstrates the association between MPOD (x-axis) and visual range at 3.2-cpd (y-axis.

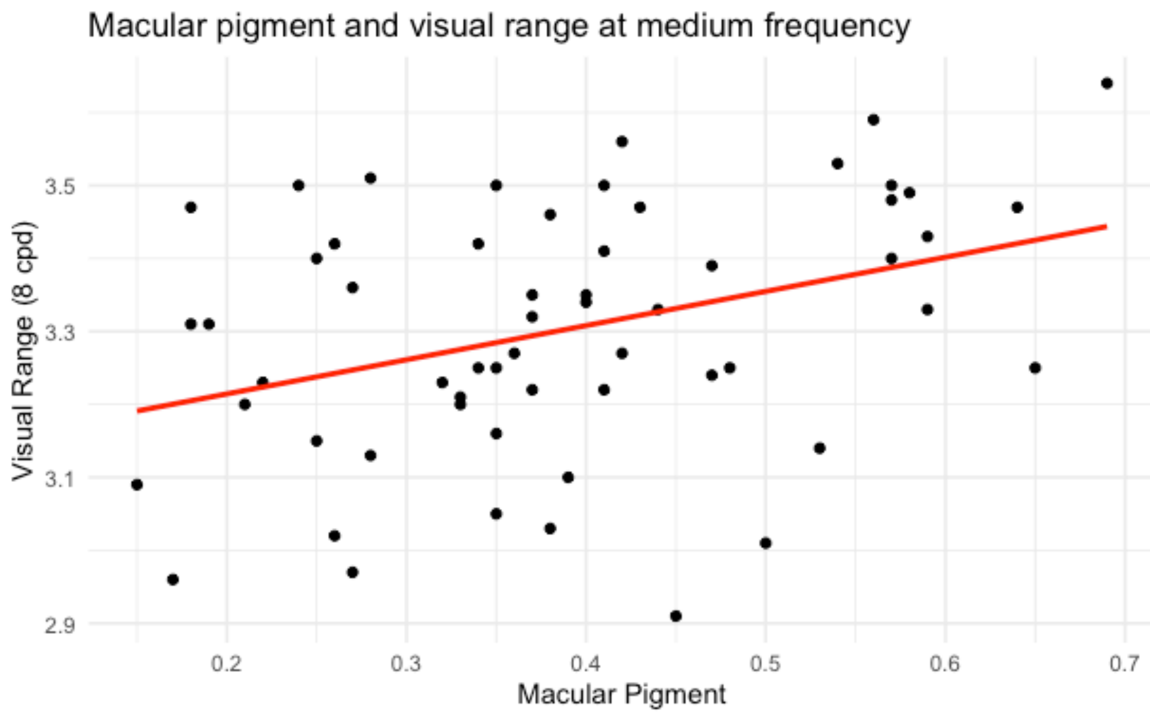

Figure 11

Figure 11 demonstrates the association between MPOD (x-axis) and visual range at 8-cpd (y-axis).

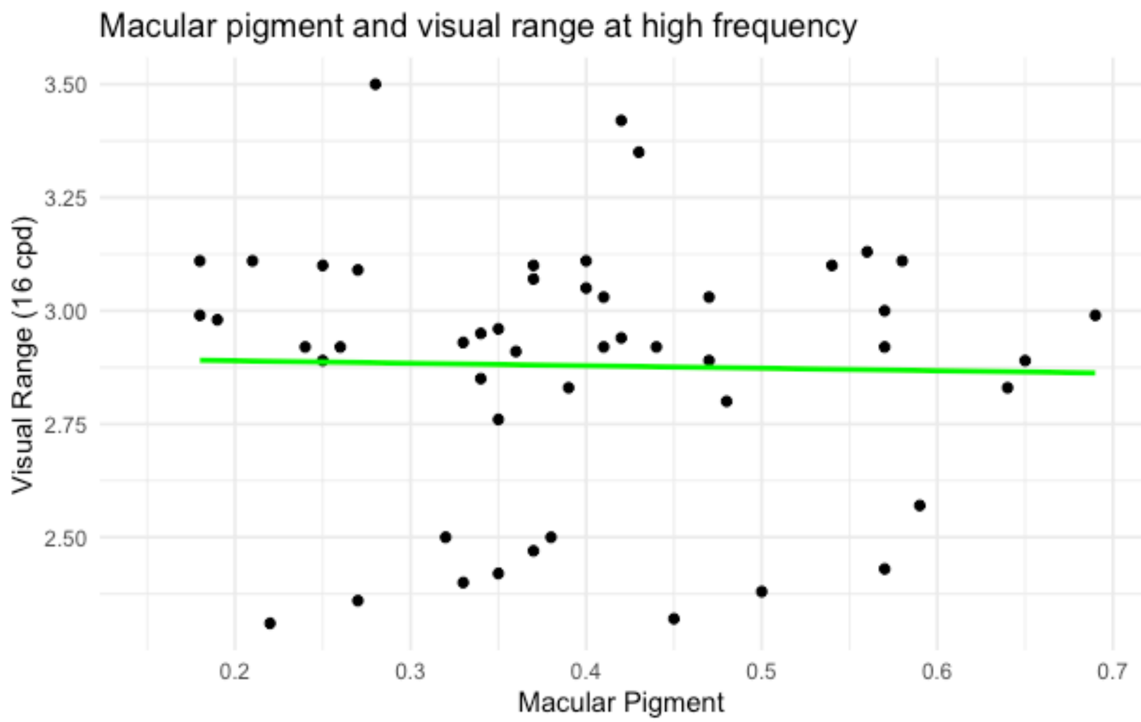

Figure 12

Figure 12 demonstrates the association between MPOD (x-axis) and visual range at 16-cpd (y-axis)

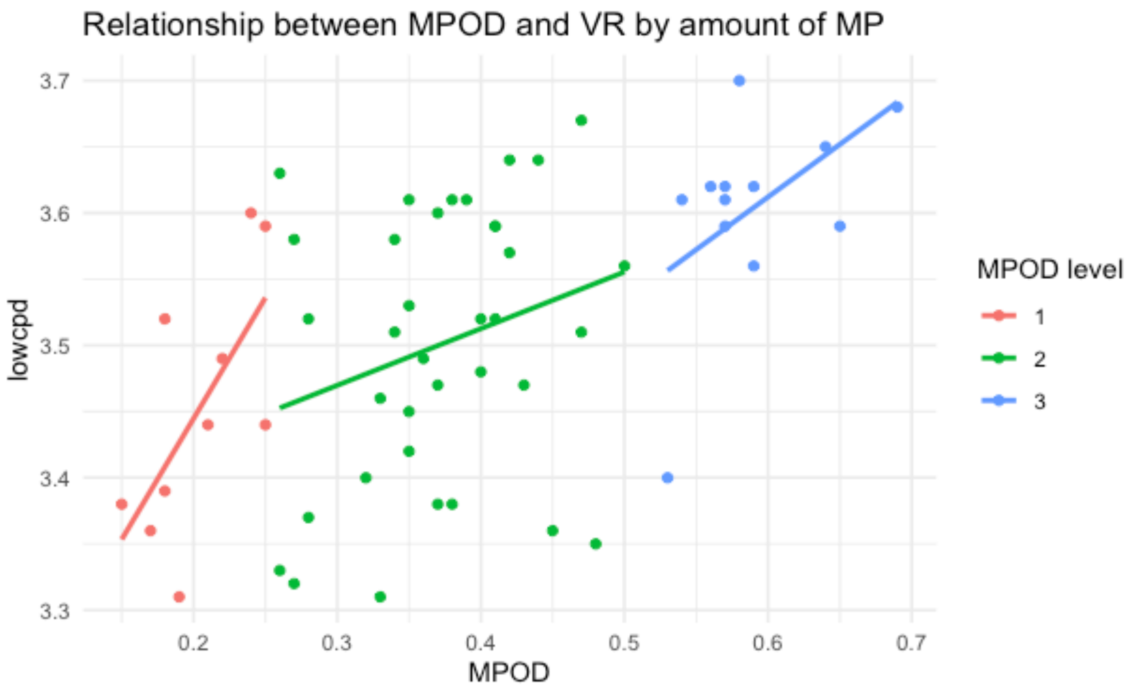

Figure 13

Figure 13 demonstrates the association between MPOD (x-axis) and visual range(y-axis) at different levels of MPOD. Visual range at 3.2-cpd grating was selected for this representation because it showed the strongest correlation with MPOD. The pink line ("MPOD level 1") represents participants with MPOD between 0 and .25. The green line ("MPOD level 2") represents participants with MPOD between .25 and .50. The blue line ("MPOD level 3") represents participants with MPOD above .50.

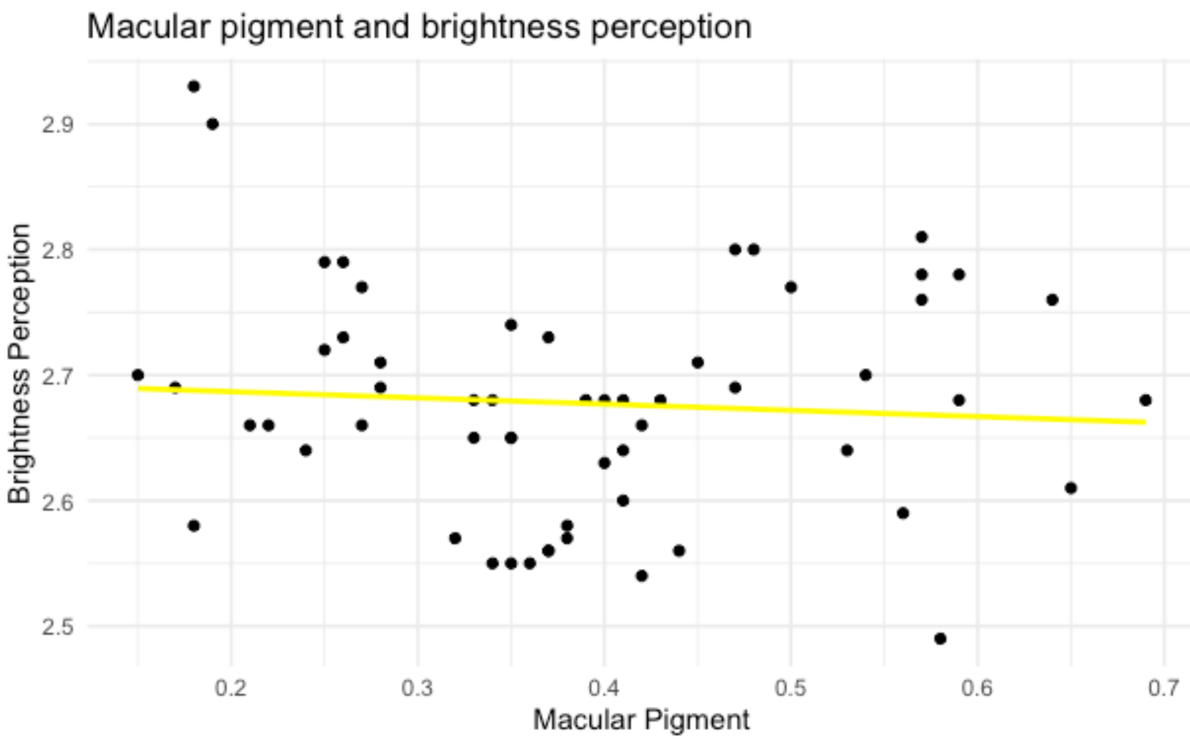

Figure 14

Figure 14 shows the relationship between average brightness perception for all filters (y-axis) and MPOD (x-axis)

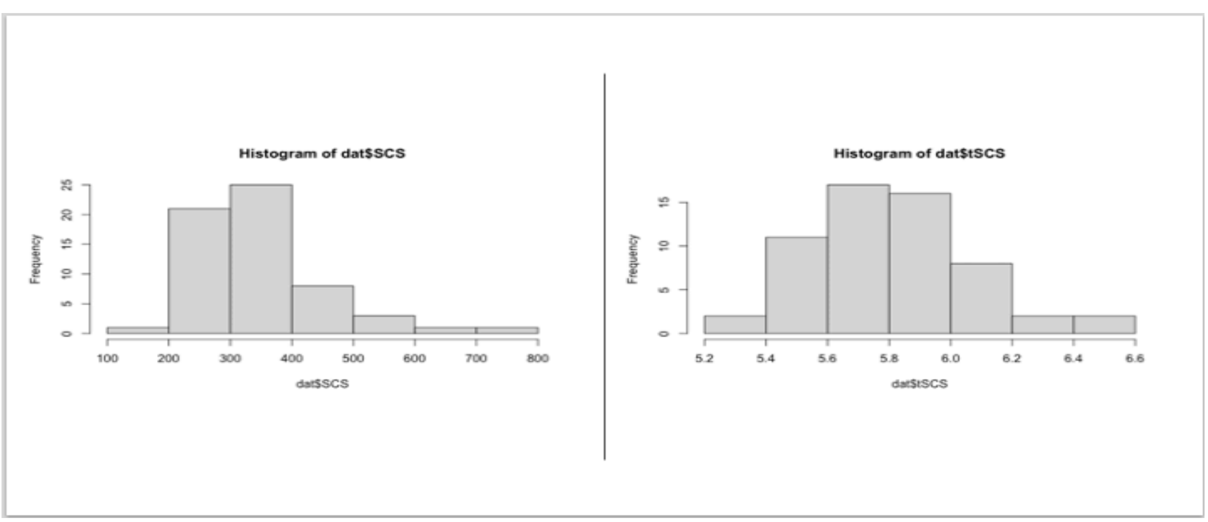

Figure 15

Figure 15 shows the SCS distribution, before (left) and after (right) the natural log transformation

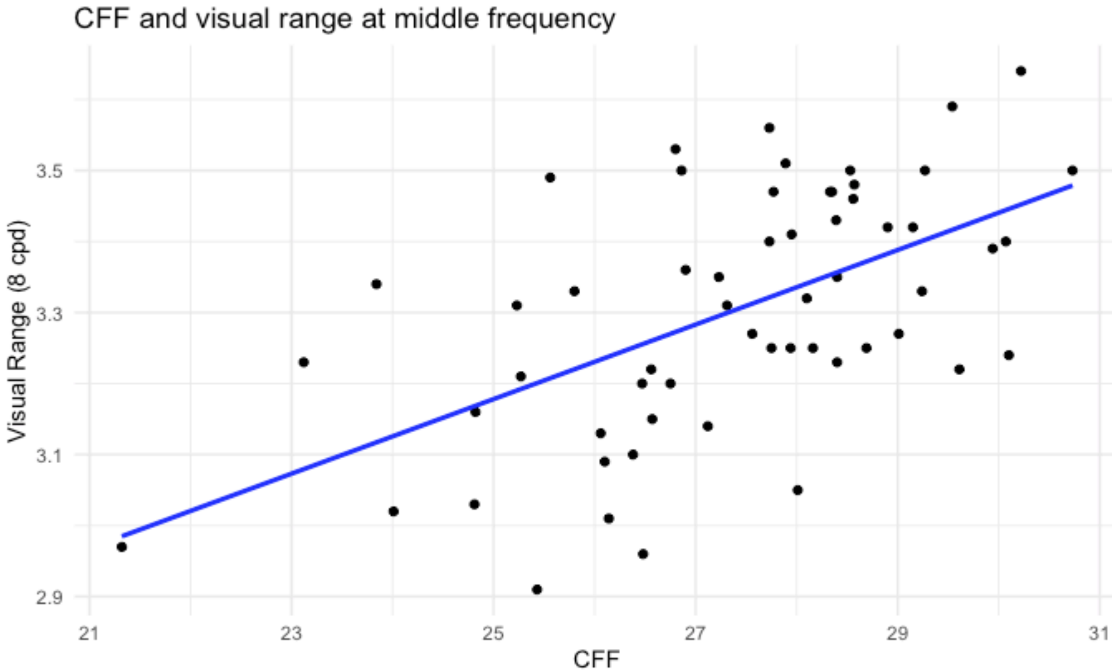

Figure 16

Figure 16 depicts the relationship between the experimental CFF(x-axis) variable and visual range at 8-cpd (y-axis). This spatial frequency was selected for visualization because it demonstrated the strongest relationship with visual range of all the gratings.

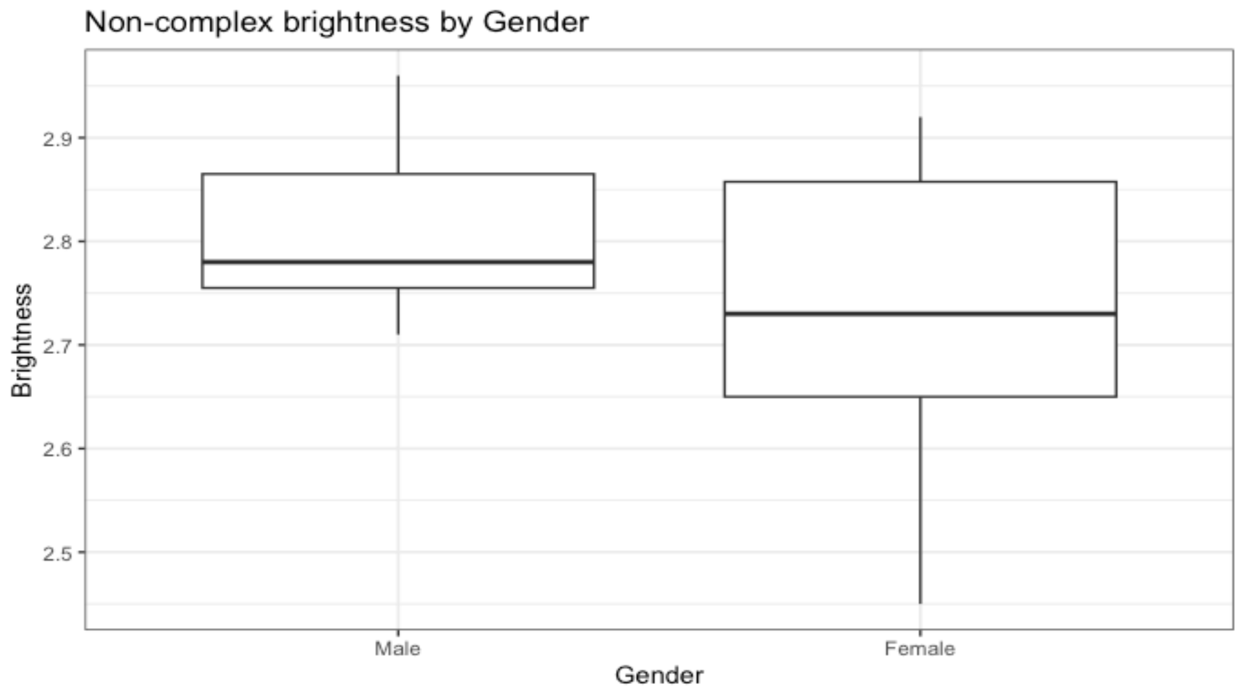

Figure 17

Figure 17 shows the significant gender differences in brightness perception in non-complex scene.

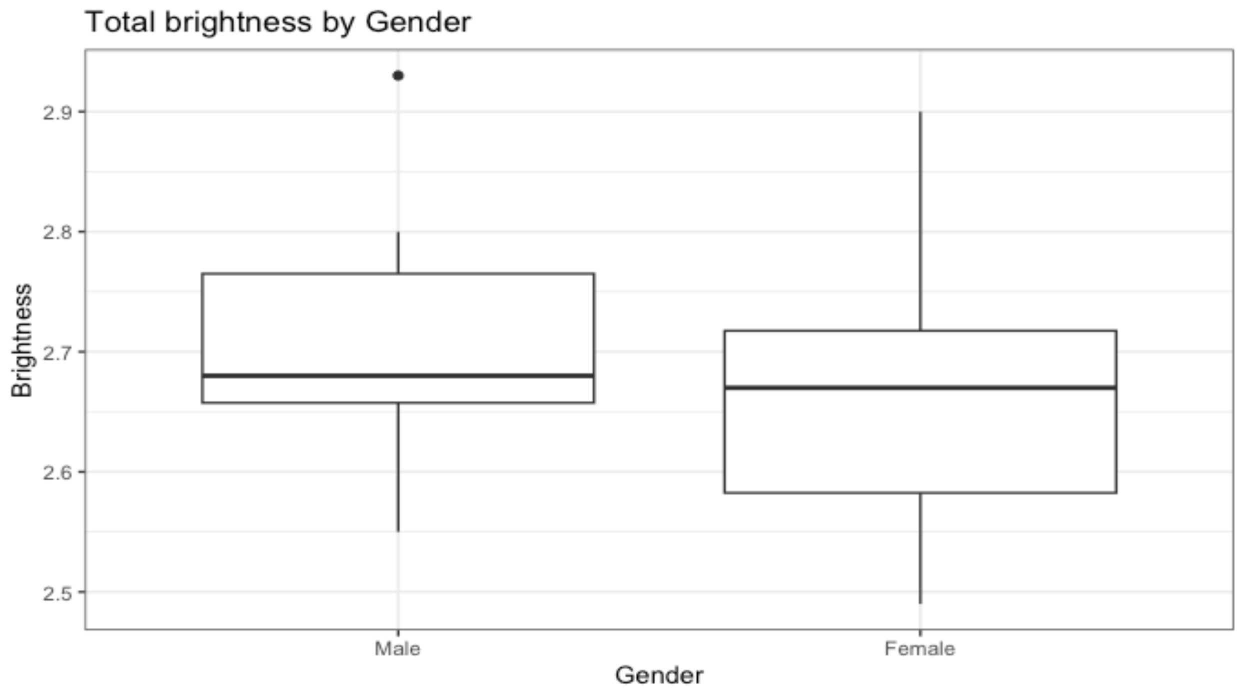

Figure 18

Figure 18 shows the nonsignificant gender difference in brightness perception for complex scenes

DISCUSSION

Macular Pigment and Visual Range

The effect of extrinsic and intrinsic filters on visual function and performance has been well studied (reviewed by Hammond & Buch, 2020). This investigation provides further evidence on the enhancement of real-world vision via short-wave filtering by MP. In the present study we detected a significant association between MPOD and the amount of simulated blue haze necessary to completely obscure high and medium spatial frequency targets. Interestingly, no significant relationship was detected for high spatial frequency targets.

There are a few possible explanations for why no significant relationship was observed for the 16-cpd target. First, the output from the target channel was relatively dim (~ 3-cd/m^2), which made it difficult to discriminate in the presence of haze. In a study defining mesopic contrast sensitivity in young healthy adults, Haughom and Strand (2011), found that approximately 10% of participants could not perceive 12 and 18-cpd contrast gratings at 3-cd/m^2. Somewhat surprisingly, the addition of broadband glare reduced this percentage to around 5% for a 12-cpd target (Haughom and Strand, 2011). It is possible, that a similar proportion of our participants could not perceive the grating at all. Which may have confounded the interpretation of the effect of haze on the 16-cpd target's visibility. It is also possible that no relationship was observed because at higher spatial frequencies individual differences in resolution acuity become more pronounced (National Research Council (US) Committee on Vision, 1985). For this reason, differences in acuity may have masked any effect from filtration by MP for the 16-cpd condition. Another factor to consider is that higher spatial frequencies correspond to smaller real-world objects when orientation and viewing distance are held constant (National Research Council (US) Committee on Vision, 1985). Given the set-up of our apparatus (where the only difference between conditions was spatial frequency) it could be the case that the visibility of smaller real-world objects is not improved by the filtering of atmospheric haze.

Our primary findings (3 and 8-cpd) are consistent with previous investigations on the relationship between MP and visual range (e.g., Hammond et al., 2012, Fletcher et al., 2014). Thus supporting the idea that MP and other intrinsic yellow filters (such as the oil droplet mosaics of birds) have been naturally selected for, in part, because they improve visibility in the atmosphere (referred to as the *visibility hypothesis* in Wooten and Hammond, 2002). Consistent with the results of Fletcher et al. (2014), we did not observe a "plateau" in the benefits conferred by MP as reported in Hammond et al. (2012). Suggesting that the effect was likely a biproduct of that study's experimental conditions (i.e., the use of an extrinsic filter, which covered the entire visual field). The most obvious future direction for this area of study is to assess the effect of MP on visual range outside of the laboratory (i.e., outside). However, such an experimental approach would face a myriad of difficulties, including, hourly changes in turbidity, cloud cover, humidity and angle of incident sunlight. Another more feasible future direction is to construct an atmospheric chamber, on a smaller scale to that described by Tai and colleagues (2017), wherein physical haze (e.g., filtered xenon light backlighting a fog machine) can be added. Utilizing such an apparatus would allow researchers to assess the effect of physical haze on target visibility.

Brightness Perception and Macular Pigment

In the present investigation we did not observe any relationship between filtration by MP and the perceived brightness of real-world scenes. This is inconsistent with previous research that has demonstrated that under specific experimental conditions yellow filters (like spectacles and contact lenses) can enhance the brightness of non-complex (e.g., Kelly, 1990) and complex (e.g., Renzi-Hammond, in-progress) stimuli. Across experiments this enhancement is dependent on an assortment of factors, including the size and chromatic composition of the stimulus (Luque et al., 2007) and the fact that these filters screen the entire retina (both rods and cones). For this reason, a variety of possible mechanisms have been proposed to explain the effect of yellow filters on perceived brightness. Kelly (1990) argued that yellow filters stimulate the activation of rods by reducing the amount of light reaching the photoreceptors. Thereby increasing sensitivity in the achromatic (luminance) channel (Kelly, 1990). In real-world settings, yellow filters could increase perceived brightness by reducing short-wave backgrounds (e.g., the sky) thus enhancing chromatic contrast. Given the spatial distribution of MP (i.e., most dense in the relatively rod-deficient fovea), we hypothesized that MP (through sampling) could improve brightness via this mechanism.

There is extensive evidence demonstrating that the visual system utilizes compensatory mechanisms in the yellow-blue (Y-B) opponent process channel to offset the loss of short-wave input from filtering by MP and the crystalline lens (reviewed by Stringham et al., 2013). For example, Stringham and Hammond (2007) showed that peak sensitivity in the short-wave visual pathway remains constant across the retina, despite large variations in MP density. Indicating a compensatory mechanism wherein sensitivity to short-wave light is increased in the Y-B pathway. It is possible that the increased gain in the Y-B pathway may offset any chromatic contrast related brightness enhancement via MP. Specifically, if compensatory mechanisms ensure that that sensitivity to short-wave light is not affected by MP, then it is unlikely that SW backgrounds will be perceptually reduced. Hence, those with high MPOD would not perceive real-world scenes as brighter compared to those with low MPOD.

An additional consideration is that our investigation did not directly test the hypothesis that MP enhances perceived brightness via a chromatic brightness induction mechanism. This is because we did not evaluate the optics of our test stimuli (gelatinous projector slides) for the presence of isoluminant edges. It is possible that the chromatic borders were not sufficiently sharp in terms of wavelength contrast (i.e., more of a gradient than a hard edge) to induce a brightness effect.

Post-Hoc Findings

A number of significant non-hypothesized relationships were detected during the data analyses stage of this experiment. A few which are conceptually interesting and could motivate future research. First, it appears that an individual's CFF threshold is highly predictive of their visual range across spatial frequencies. Our analyses demonstrate that this relationship is still significant while controlling for the effect of MP, which covaries with both variables (e.g., Hammond & Wooten, 2005; Fletcher et al., 2014). This finding indicates that an additional mechanism may be driving this relationship. One possibility is simply based on the stimulus characteristics. Both the visual range and CFF values were collected using short-wave stimuli (the 570 nm CFF stimulus was presented on a 470 nm background). This possibility seems unlikely since the effects should go in the opposite direction: high MP would improve visual range, but high MP should decrease CFF when measured using short-wave stimuli (reduced luminance causes reduced CFF as described by the Ferry-Porter law). CFF, even under our conditions, is likely post-receptorally determined at the visual cortex (Wells, et al, 2001). CSF, especially under light stress, is also likely determined by coordination between retina and visual cortex (Rahimi-Nasradbadi et al., 2021). Temporal and spatial areas within the occipital lobe are highly connected and constantly interact (spatio-temporal vision; Oliveri et al., 2009) and our observed correlation likely reflects this interaction.

Another finding of note was the observed relationship between CFF and SCS, which to date has not been shown in the literature. The significance of this association while controlling for MPOD indicates that there may be additional dietary antioxidants which contribute to visual processing speed independent of L+Z. Another possibility is simply that both are likely indicators of good health.

We observed a statistically significant association between MPOD and SCS in our data. This finding contributes to the complex body of results regarding this relationship. To date, three studies have been published which assess both variables. Two of those studies (Obona et al., 2020; Cannavale, et al., 2023) did not find a significant relationship. While the other, conducted by Conrady and colleagues (2017), found a robust and statistically significant association between MPOD and SCS. Importantly, these studies sampled from different populations, and used different measurement techniques. For example, Cannavale et al. (2023) studied 181 American children, whereas Obona et al. (2020) sampled 16 individuals recruited from a Japanese hospital. Additionally, Conrady and colleagues (2017) utilized an older raman reflectance spectroscopy technique while the other two studies used the LifeMeter™. Consequently, this is the first study to report a significant association between MPOD and SCS, measured with the LifeMeter™. Conceptually, it is intuitive that two variables would be related. The LifeMeter™ uses 480-nm as a measuring wavelength which is strongly absorbed by L+Z (e.g., Ermakov & Gellerman, 2012; Snodderly, 1984a). Hence, those with high concentrations of the pigments in their diet should see subsequently higher MPOD and SCS. Given the variability in results between investigations on this topic it is an area in need of further study. Future work should address these inconsistencies by sampling a large number of subjects, from a diverse set of backgrounds and ages.

Lastly, a significant but weak effect of gender on perceived brightness was detected for Filter 1 (the monochromatic yellow slide). Where men needed more log relative energy to achieve a brightness match. This finding is consistent with evidence demonstrating gender-related differences in visual perception (e.g., Shaquiri et al., 2018). For example, Chellapa and colleagues (2017) demonstrated that men had significantly higher brightness perception than women after exposure to blue-enriched light. This result is preliminary and tentative since our sample was largely female and small.

Conclusions

If everyone had a high concentration of MP, the issue of MP's effect upon visual performance would be only of scientific interest. We know, however, that a wide range exists in the normal population and that individual levels are usually strongly influenced by diet. Individuals with low concentrations of MP might be seeing at a level lower than their potential and less than is needed in their jobs (e.g., pilots) or personal life (e.g., athletes). The National Park Service stated a large series of visibility studies in the 1980s focused on improving visibility in American National Parks (National Park Service, 2019). These studies focused on extrinsic issues like human-made pollution as major factors limiting the ability of visitors to see in the distance and enjoy the beauty of the park. Our study suggest an additional possibility. That intrinsic factors (a decline in dietary intake of MP carotenoids) may play just as important a role.

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