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The effect of macular pigment on heterochromatic luminance contrast

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ABSTRACT

Macular pigment (MP) selectively filters short-wave light and may improve visual performance via this mechanism. This study was designed to test the hypothesis that MP alters contrast between an object and its background, and thus alters the object's detectability. In order to test this hypothesis, participants of a variety of ages were recruited into two groups. Group 1 consisted of 50 healthy elderly subjects ($M = 72.7$, $SD = 7.3$ years). Group 2 consisted of 28 healthy younger subjects ($M = 22.7$, $SD = 3.6$ years). For all subjects, contrast thresholds were assessed in Maxwellian-view. For subjects in Group 1, a circular grating target (600 nm, 1°; not absorbed by MP) was surrounded by a 10°, 460 nm field (strongly absorbed by MP). Subjects in Group 2 were measured using identical conditions with the exception that the surround was changed to 425 nm in one condition and to a broad-band (xenon) white in another. All subjects adjusted the intensity of the surround until the target was no longer visible. Finally, for a subsample of subjects in Group 2, a 1° bipartite field was used and wavelength was varied on one side to minimize the appearance of the border with the 460 nm reference side, foveally and parafoveally between 420–540 nm, with 20 nm steps, using the minimally distinct border (MDB) technique. MP density was assessed psychophysically. MP density was related to the amount of energy in the surround (at 425 and 460 nm, and for broad-band white) needed to lose sight of the central target. When the MDB technique was used to measure spectral sensitivity, the differences in the two curves yielded a spectrum that closely matched MP's *ex vivo* spectrum. Our data suggest that MP modifies an object's contrast against a short-wave background via simple filtration.

1. Introduction

The extent to which yellow-tinted lenses impact visual performance has been a long-standing, unresolved issue in vision science (e.g., Clark, 1969). Consideration of the data as a whole is difficult, as many of the studies that have investigated the relation between yellow filters and visual performance have differed with respect to the variety of yellow lens used, the location of the lens (i.e., intraocular vs. extraocular lenses), the transmittance of the lens and the visual tasks used to assess "performance." Nevertheless, a few generalizations can still be made from the confluence of past data. If the yellow lens in question reduces luminance significantly, that yellow lens can lead to reductions in visual performance under scotopic conditions. Given the clear positive relation between luminance and spatial vision (e.g., Johnson and Casson, 1995), reducing light input under low light conditions is obviously negative. Light can, however, be lost to the viewer's advantage when light levels are high. Indeed, yellow lenses can effectively brighten the visual field under normal photopic conditions, presumably due to increasing rod input to the chromatic pathways (Kelly, 1990). Of all the effects of yellow lens filters on visual performance, however, one relation seems most clear: the effect of yellow filters on contrast (e.g., Wolffsohn et al., 2000).

Contrast can be defined quite easily with homogeneous targets and surrounds as, simply, the Weber fraction, where contrast equals the increment or decrement in the luminance of a target divided by the luminance of a uniform surrounding field. The vision system, due in large part of the anatomy of the neural retina, is particularly apt at highlighting these luminance differences via detection of, and at time creation of, edges (e.g., Shapley and Tolhurst, 1973). For example, it is commonly known that bipolar cells in the retina alter firing rates depending on which portion of the receptive field is activated, with maximal firing rates being achieved when a luminance difference occurs over only part of the receptive field (e.g., Kuffler, 1953). Given the fact that the neural retinal relies heavily upon the existence of edges in the visual field, any mechanism that optically enhances the appearance of edges, such as by filtering a portion of the visible spectrum at an edge, should amplify the difference between target and background and, consequently, enhance contrast.

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As early as Luckiesh, 1915 reviewed the idea that yellow filters would improve visual performance by enhancing contrast. Luria (1972) later demonstrated this effect by showing that the threshold for a yellow increment flash on a blue background is reduced when viewed through a yellow (blue absorbing) filter. Others have confirmed this effect (Yap, 1984; Hovis et al., 1989; Leat et al., 1990; Leguire and Suh, 1993; Zigman, 1990). The mechanism for contrast enhancement is straightforward: extraocular yellow filters reduce the luminance of the background relative to the target (or vice versa), which increases contrast and, consequently, the target's detectability.

The test scenarios used commonly in laboratory studies of contrast probably generalize well to many ecological situations. Yellow intraocular filters are relatively ubiquitous in nature, and it has been argued that their relative ubiquity is due to their important roles in visual performance in everyday vision (Walls and Judd, 1933). For example, birds concentrate yellow carotenoid pigments in the oil droplets that are anterior to their photoreceptors (e.g., Thomson et al., 2002; Toyoda et al., 2002), and these yellow filters sharpen the spectral sensitivities of their cones and improve their ability to discriminate color differences (e.g., Bowmaker, 1977, 1980; Young and Martin, 1984). Oil droplets such as those described in birds are also present in turtles and other amphibians (e.g., Walls, 1942; Kennedy and Milkman, 1956) and seem to serve the same filtering functions in these diverse species. Other species have adapted yellow lenses (e.g., squirrels, tree shrews; Walls, 1942; Kennedy and Milkman, 1956) or occlusable yellow corneas that appear clear in dim light and become yellow following pigment migration in bright light (e.g., puffer fish; Appleby and Muntz, 1979). The end result of these optical structures is the reduction of short-wave light transmission to the retina and an overall improved ability to discriminate color differences.

Primate species have adapted to an arboreal world, in which mid-to-short- wave foliage is commonly viewed against a short-wave sky, and in which mid-to-long- wave fruits are commonly viewed against mid-to-short- wave foliage (e.g., Mollon and Regan, 1999). Consequently, survival depends on the ability to detect edges between fruit and foliage, foliage and sky, and, often, fruit and sky. In other words, primates have the need to detect fruit and foliage as distinct objects from their short-wave dominant backgrounds. Primate cone types are tuned to the wavelengths that dominate this arboreal environment (e.g., Mollon and Regan, 1999). In addition to detecting objects that are relatively close, yellow filters might also aide in the detection of distant objects that could be obscured due to short-wave veiling caused by "blue haze" conditions (e.g., Wooten and Hammond, 2002). Yellow-tinted lenses (e.g., amber goggles) are often used by individuals needing to view objects at a distance (pilots, sharp-shooters, etc.).

Based purely on the optics of yellow filters and their resulting reduction in short-wave light transmission to the retina, a number of immediate visual effects can be predicted. These purely optical hypotheses were originally summarized by Walls and Judd in 1933:

1. "To increase visual acuity by reducing chromatic aberration.
2. To promote comfort by the reduction of glare and dazzle.
3. The enhancement of detail by the absorption of 'blue haze.'
4. The enhancement of contrast."

Nussbaum et al. (1981) argued that macular pigment (MP) serves these same optical functions proposed by Walls and Judd in human and non-human primate vision. MP is composed of the yellow, dietarily derived carotenoids lutein (L) and zeaxanthin (Z) and their stereoisomer meso-zeaxanthin (MZ), which is converted from L within the retina itself (e.g., Bone et al., 1993; Johnson et al., 2005). These pigments are concentrated in the inner layers of the fovea and screen foveal cones from short-wave light. Many have argued that their presence in the area of the retina most responsible for our highest visual acuity is not incidental. Further, since MP density varies so strongly between subjects (e.g., Bone and Sparrock, 1971; Pease et al., 1987), MP's effects on visual function should vary accordingly. Given the above-described arboreal environment in which primates must exist, reduced glare, enhanced detail (visibility) and enhanced contrast provided by an intraocular yellow filter, such as MP, would be advantageous to survival.

To date, only the first three predictions by Walls and Judd have been tested (Wong et al., 2009; Engles et al., 2007; Stringham and Hammond, 2007, Stringham and Hammond, 2008). The fourth prediction, that MP is capable of enhancing contrast by adding luminance contrast information to an edge, has not been empirically tested. The purpose of the present study was to evaluate the hypothesis that MP density can enhance luminance contrast by differential absorption of chromatic edges.

2. Methods

2.1. Participants

A total of 78 participants were recruited at two separate time periods for studies on visual function. A total of 50 subjects from the Athens – Clarke County region who were participating in a vision and aging study ($M = 72.7$, SD = 7.3 years), were tested under the first round of contrast experiments. These participants were given an ophthalmic examination and were determined to possess no obvious sign of pathology, such as age-related macular degeneration, glaucoma or diabetic retinopathy, from a dilated fundus examination. Twenty-nine of these subjects had intraocular implants (IOLs), and the rest retained their natural lenses. After the data from the first group of participants were evaluated, a second group of participants was recruited for further contrast testing. This group consisted of 28 younger subjects ($M = 22.7$, SD = 3.6 years), who were assessed in three control experiments designed to test how MP affected contrast under varying spectral and border conditions. Younger subjects all had acuity of 20:40 or better (Snellen notation) and reported good ocular health. The study was approved by the Institutional Review Board at the University of Georgia and the tenets of the Declaration of Helsinki were followed.

2.2. Macular pigment measurement

MP density was measured with a retinal densitometer (Wooten et al., 1999) (Macular Metrics Corp., Providence, RI) using a standardized method (Snodderly et al., 2004) based on heterochromatic flicker photometry (HFP). This method, including optimizing for assessment of elderly or diseased subjects, has been extensively described and validated (e.g., Stringham et al., 2008). The basic measurement procedure involves presenting a small test stimulus (one-degree diameter) that alternates between a measuring wavelength strongly absorbed by MP (460 nm) and a reference wavelength not absorbed by the pigments (550 nm). This stimulus is presented in the center of the fovea and at an eccentric location (7 degrees), which is used as a reference. In effect, the subject perceives a test light that appears to flicker. The subject is then instructed to adjust the intensity of the measuring light until the flicker is eliminated. The log difference in the measurement and reference settings (ten trials of each) yields a measure of MP optical density at the test locus.