

Macular Pigment: A Test of the Acuity Hypothesis

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PURPOSE. Schültze, in 1866, originally proposed that macular pigment (MP) could improve acuity by reducing the deleterious effects associated with the aberration of short-wave (SW) light. Although proposed well more than a century ago, the hypothesis has never been empirically tested. The authors chose to begin evaluating the acuity hypothesis by measuring MP levels, gap, and hyperacuity in the same observers.

METHODS. Eighty healthy young subjects were assessed. Forty subjects were assigned to the gap acuity experiment and 40 to the hyperacuity experiment. Peak MP optical density (MPOD) was measured using heterochromatic flicker photometry (HFP). Resolution and hyperacuity were measured as the minimum perceivable gap between two solid black lines (1" width) vertically separated and as a vernier offset, respectively. These targets were presented on a 0.5° circular diffusing background that appeared either white (17 cd/m²) or yellow (16 cd/m²). The yellow background was produced by using light-emitting diodes (LEDs) with a peak $\lambda = 570$ nm. The white background was produced by combining the yellow with a blue LED (peak $\lambda = 460$ nm). The subject's head (5.33 m from the stimulus) was stabilized with a head-rest assembly, and the adaptive state was controlled with the use of a constant white surround (11 cd/m²). Thresholds were determined based on probit analysis of psychometric functions generated using a two-alternative forced-choice procedure.

RESULTS. MPOD ranged from 0.14 to 1.00 measured at 30' eccentricity. Gap and hyperacuity measures each varied by a factor of approximately 5 to 6. Average gap acuity ($N = 38$) for the white condition (filtered by MP) was 31.2" (SD = 9.4) and did not differ from the average ($N = 38$) for the yellow condition (not filtered by MP), which was 32.1" (SD = 10.9). Similarly, average hyperacuity for the white condition (7.0"; SD = 2.9) did not differ from that of the yellow condition (6.8"; SD = 3.5).

CONCLUSIONS. MPOD did not correlate significantly with gap or hyperacuity measured in the yellow or white conditions. These data, therefore, do not support the predictions of the acuity hypothesis. (*Invest Ophthalmol Vis Sci.* 2007;48:2922-2931) DOI:10.1167/iovs.06-0883

Macular pigment (MP) is composed of xanthophyll carotenoids, primarily lutein and zeaxanthin,^{1,2} and is concentrated in and around the central fovea anterior to the cone outer segments. The high accumulation of the pigments between incoming light and receptors results in significant filtering of light (~400–500 nm) before that light is processed by

the foveal cones. Such a significant filter, in a functionally critical area, has led many to question whether the pigments might serve to influence visual performance, either positively or negatively. If such an influence exists, it might be expected to be variable because variation in peak absorbance (460 nm) is large, ranging from approximately 0 to 1.6 optical density (OD) units in the very center of the retina.³

Speculations regarding possible optical functions of MP began at a time of considerable debate concerning whether the pigments actually existed in the living eye or were simply postmortem artifacts.⁴ Schültze,⁵ taking the former view, was the first (circa 1866) to describe what has often been referred to as the acuity hypothesis of MP function. This hypothesis is based on the fact that MP selectively absorbs short-wave (SW) light, which is known to be poorly focused on the retina because of chromatic aberration. For example, when accommodating to 580-nm light (as would be typical when viewing a broadband target), light at 460 nm would be approximately -1.2 diopters (D) out of focus.⁶ The basic premise of the hypothesis is that by absorbing this poorly focused SW light before it reaches the receptors, visual acuity would be improved. Limited empirical and theoretical studies, up to the present, have reached inconsistent conclusions regarding the validity of the acuity hypothesis. The key problem with previous work is that visual acuity and MP have never been evaluated in the same subjects.

The first quantitative attempt to evaluate Schültze's theory was made by Reading and Weale in 1974.⁷ Using known parameters related to chromatic aberration and visual thresholds, they calculated that an average amount of MP was sufficient to reduce the violet (SW) penumbra of a white disc to below detectable levels, thus potentially improving visual acuity. McLellan et al.⁸ challenged these conclusions by showing that various other ocular aberrations (mainly wavefront) tend to wash out the deleterious effects of chromatic aberration and, therefore, that MP would not improve acuity. It is difficult, however, to generalize their conclusion beyond the specific conditions used in their experiment. For instance, McLellan et al.⁸ dilated their subjects' pupils to 7 mm, which maximized the optical blurring caused by spherical aberration and increased the number of contributing wavefront aberrations. A more realistic pupil diameter, of say 3 mm, which would apply to typical daytime vision, yields considerably less spherical aberration and fewer wavefront defects but a similar degree of chromatic aberration (approximately 1 D). These factors, even when combined with the smaller depth of field that results from a smaller pupil (e.g., approximately 0.3–0.4 D),⁹ would still be consistent with the effects predicted by the acuity hypothesis. Davies and Morland¹⁰ also argued that the conditions used by McLellan et al.⁸ to prevent accommodation were insufficient. If, in fact, subjects were able to focus on individual wavelengths, then the measured effects of chromatic aberration would obviously be reduced.

Campbell and Gubisch¹¹ compared acuity for two subjects measured using broadband versus monochromatic light (for pupils smaller than 4 mm). They found slight improvements for one subject but not in the other when acuity was measured under monochromatic conditions. Yoon and Williams,¹² also testing only two subjects but under more careful conditions, found that acuity and contrast sensitivity (beyond approxi-

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Supported by National Science Foundation Grant 0350992.

Submitted for publication July 28, 2006; revised February 2, 2007; accepted April 20, 2007.

Disclosure: **M. Engles**, None; **B. Wooten**, None; **B. Hammond**, None

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mately 6 cyc/deg) measured when using narrow-band light was improved for both subjects by a factor of 1.2 to 1.5. These relatively small improvements in spatial resolution, however, must be put in context: neither Yoon and Williams¹¹ nor Campbell and Gubisch¹² measured MP, so we can only assume that the MP optical densities (MPOD) of their subjects were average or nearly so. If so, as argued by Reading and Weale,⁷ any additional reduction of SW energy would be largely superfluous in that further improvements in acuity would be negligible or nonexistent. Thus, the reports of small improvements in acuity comparing white with narrow-band light could simply be attributed to the absorption provided by the subject's MP and cannot be taken as evidence against the acuity hypothesis. The same interpretation¹³ applies to the large number of studies that have found yellow filters generally do not improve spatial vision. Given that no previous study has measured MP and the effects of chromatic aberration in the same subjects, an empirical evaluation of the acuity hypothesis cannot be made.

In this report, we measured MPOD and acuity in a group of healthy young adults. More specifically, two types of acuity were assessed: gap detection, which is a form of resolution acuity (RA), and vernier acuity, which is a form of hyperacuity (HA). We measured RA as the minimum perceivable angular separation (smallest visible gap) subtended between the ends of two thin dark bars against a bright background. This stimulus setup is comparable to the reverse case in which the smallest visible separation (gap) is found between a pair of point sources.¹⁴⁻¹⁷ In either case, our arrangement was similar to a task whereby an observer is asked to judge the presence or absence of a gap between two dark surfaces, such as in eye charts using an arrangement of Tumbling-E, Landolt-C, or square-wave gratings. Spatial resolution tasks of this type have been shown to provide average thresholds on the order of 30" to 60" (Hecht, 1927¹⁸; Wilcox, 1932¹⁹; Shlaer, 1937²⁰; Haegerstrom-Portnoy, 1997²¹) using a variety of test patterns.

Although 30" to 60" is easily within an area in which MP might be expected to operate, another type of spatial task is available that provides an even finer threshold and that may be more sensitive to detecting smaller changes. Westheimer²² originally used the term *hyperacuity* to describe these extremely detailed visual discriminations. A number of various stimulus configurations can generate thresholds of the HA type.²³ One example, originally described by Wülfing in 1892²⁴ and called *vernier acuity*, is essentially two vertically oriented and abutting edges (or lines). One line is adjusted horizontally such that an offset from perfect alignment is introduced and the threshold is determined as the minimum offset required to obtain a just noticeable difference. In an HA task, offsets as small as 2" to 4" of arc can be detected reliably²² using bright bars on a dark background or dark bars on a bright background.^{22,25,26}

Although HA was not specifically included in the original formulation of the acuity hypothesis, it is included here because it represents the finest spatial discrimination achievable by the human visual system. Although extensive discussion of the underlying mechanisms for HA is beyond the scope of this article, a few important aspects are worth mentioning (e.g., contrast and blur). It is often stated that HA is resistant to blurring (e.g., DeValois and DeValois²⁷ citing Westheimer²⁸). Such generalizations, however, appear not to hold for all examples of HA. For example, Westheimer²⁸ did not evaluate vernier hyperacuity but rather evaluated motion displacement thresholds, which is a different task requiring a different kind of judgment. A careful study by Krauskopf and Farell,²⁶ specifically using vernier tasks, have found that vernier thresholds measured under various contrast levels and subjected to increasing levels of Gaussian blurring were negatively affected (increased blur resulted in increased thresholds). Similarly,

Williams et al.²⁵ found that the deleterious effects of blurring were only reduced for gaps that were relatively large. HA tasks (line tilt, two dot, and line vernier) consistently showed increasing thresholds with increasing blur. Collectively, these studies show that, although the effect of blur on HA can be influenced by stimulus conditions and individual differences, HA is clearly degradable by blur under conditions similar to our own. It can then be used, as can RA, as a dependent variable for testing the predictions of the acuity hypothesis.

RA and HA were measured using two different spectral conditions, achromatic light and chromatic light. The achromatic condition contained significant portions of SW light and therefore would be filtered by MP. The acuity hypothesis predicts that performance on this task with an achromatic background will be proportional to MPOD. In contrast, the chromatic condition contained no SW light and therefore was unaffected by MP absorbance. This latter condition evaluates visual performance as if each observer has an infinite amount of MP; results should not be proportional to MPOD. All the measures were conducted on healthy young subjects with good vision to minimize confounding from age-related changes.

SUBJECTS AND METHODS

Subjects

Data collection took place at two sites, the University of Georgia ($n = 73$) and Brown University ($n = 7$). RA was measured in 39 young subjects (age range, 18-30 years) recruited from the student population at the University of Georgia and one 40-year-old staff member. HA measurements were obtained from 33 undergraduate students recruited from the University of Georgia (age range, 18-28 years) and 7 undergraduate students recruited from Brown University (age range, 18-19 years). MP measurements were obtained for all the subjects. The densitometers used to measure MPOD and the acuity apparatuses (both from Macular Metrics, Corp., Providence, RI) were the same at both sites. Care was taken to use precisely the same psychophysical procedures at both sites. All participants were in good ocular health, had no color deficits or past eye trauma (self-report), and had Snellen acuity of at least 20/40 (corrected to 20/20) either by prescription or by trial lens. Participants were treated ethically and were briefed before and after experimentation, in compliance with the tenets of the Declaration of Helsinki.

Apparatus for Measuring Resolution and Hyperacuity

Stimuli in both experiments (RA and HA) consisted of a pair of black, vertically oriented bars shown in Figure 1. These bars were 1' wide by 14' high and were separated by a 1' gap. This stimulus was placed on a rectangular background that subtended a vertical angle of 30' and a horizontal angle of 15' and was viewed through a hole cut in the center of a baffle fitted with a manually operated shutter. This shutter was closed during configuration changes. The background itself was formed by using a diffusing plate that was backlit by two light-emitting diodes (LEDs). Spectral characteristics of these diodes are shown in Figure 2 and were used to create the two lighting conditions used in our experiment, an achromatic condition (a white background absorbed by MP) and a chromatic condition (a yellow background not absorbed by MP). The latter condition was created by simply using the yellow LED (peak $\lambda = 570$ nm) shown in Figure 2. The former condition was created by mixing the blue (peak $\lambda = 460$ nm) and yellow LEDs. To mix the light, we placed the LEDs as close as possible (approximately 0.125' apart) and embedded them in epoxy. A lens was then used to collimate the combined light, and the background diffuser was placed in the path of the overlapping beams. The intensity of the two LEDs could be controlled separately to vary the mixture to create a perceptual white. Intensities used for this mixture (our achromatic

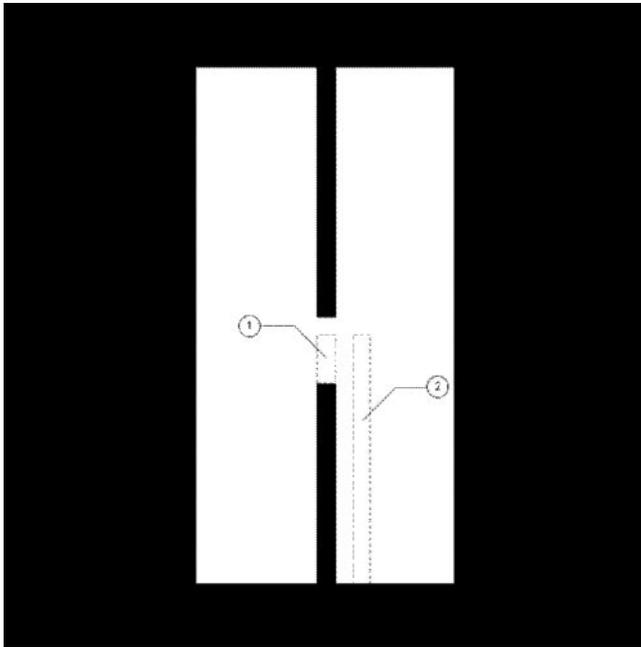


FIGURE 1. Diagram of the stimulus used to measure both types of spatial vision. As indicated by 1, the lower bar could be lengthened or shortened to adjust gap size and measure resolution acuity. As indicated by 2, the lower bar could also be adjusted laterally to measure vernier acuity.

condition: CIE coordinates $x = 0.32$, $y = 0.32$) for all subjects were based on preliminary testing of five subjects. The achromatic background was displayed at a luminance of 17.0 cd/m^2 . The yellow (CIE coordinates $x = 0.46$, $y = 0.54$) background was displayed at a luminance of 15.7 cd/m^2 (using only the yellow LED).

When making spatial judgments, participants sat 5.3 m from the stimulus in a dimly lit room behind a white screen back-illuminated (11.7 cd/m^2) by two warm white fluorescent bulbs. A 5.83° -diameter hole was cut through the center of the screen to allow for viewing of the display. Each subject's head was held steady by a chin and head rest assembly. All testing took place under monocular (right eye only, left eye patched) viewing conditions.

Resolution Acuity Procedure

Gap detection thresholds were determined according to the method of constant stimuli. Pseudorandom offsets were made by displacing the bottom bar in increments of $10''$ within the range of $0''$ to $90''$. In some instances (approximately 10%), this step size was larger than optimal. For example, subject performance on neighboring points was too close (e.g., within approximately 20%) to random and 100% detection. In such cases, subincrements of $5''$ were used. Ten trials were used for each configuration. If a subject's responses were interpreted as excessively noisy (e.g., a separation of $20''$ that was neither clearly detectable nor undetectable), 10 additional trials were added. To ensure that subjects were correctly responding to perceived gaps, a large number of catch trials was also used. These catch trials consisted of a condition in which no gap or a very obvious gap was present. These trials were presented approximately 25% to 30% of the time with feedback (indicating correct or incorrect performance). Psychometric functions were generated using probit analysis,²⁹ and thresholds were defined as the 60% correct point.

Hyperacuity Procedure

HA was assessed using a two-alternative, forced-choice paradigm. Participants were asked to judge whether the bottom line appeared laterally displaced to the left or to the right relative to the top line (Fig. 1). This was done in $2''$ arc increments up to a maximum offset of $20''$ arc, plus one centrally aligned configuration. The lines were always separated by a $1'$ gap during testing. Ten presentations were made for each configuration (total average number of presentations, 215). Psy-

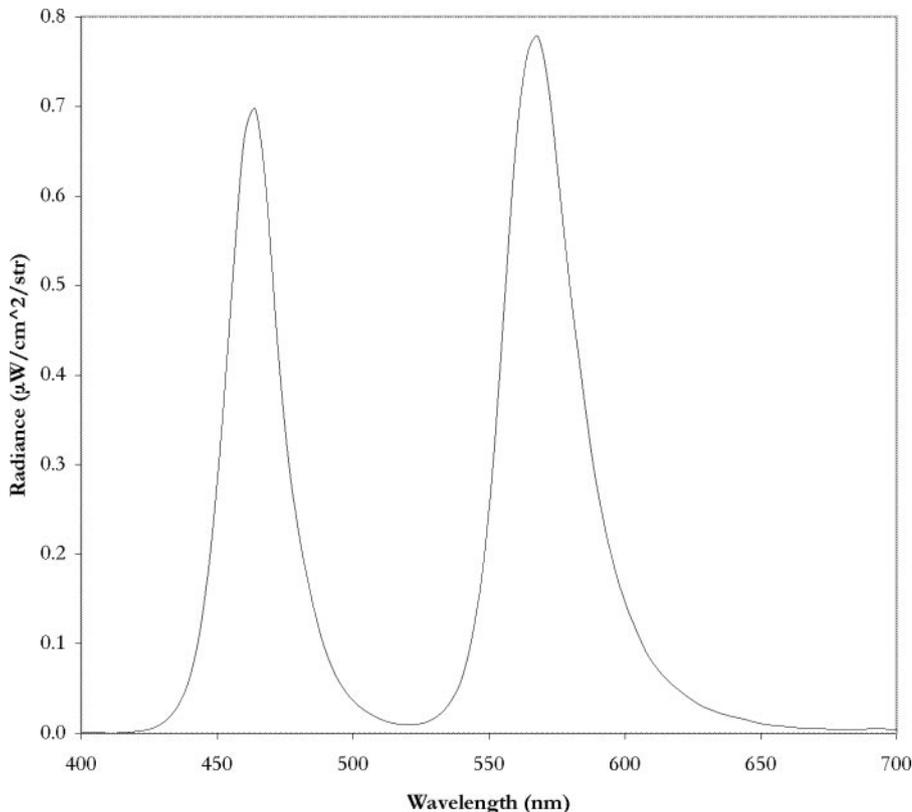


FIGURE 2. Radiometric output of the achromatic background. Notice that the achromatic condition included both the short-wave (peak output, 460 nm; maximum absorbance by MP) and long-wave (peak output, 570 nm; no absorbance by MP) components. The blue LED was turned off to generate the chromatic light condition.

TABLE 1. Descriptive Statistics for the Resolution Acuity Experiment

	N	Minimum	Maximum	Mean	SD
White RA	38	16.4"	55.4"	31.2"	9.37"
Yellow RA	38	15.5"	55.9"	32.1"	10.91"
MPOD 30'	38	0.14	1.00	0.45	0.20

chometric functions were generated using probit analysis,²⁹ and thresholds were taken as the average of the 25% and 75% correct points. It is well known that HA, in general, increases as a function of feedback³⁰⁻³⁵; therefore, no feedback was given during this phase of the experiment. After data collection, we evaluated whether there was an effect of learning on our HA measures. Because the presentations were counterbalanced, we compared the difference between the thresholds of the observers who were tested in the achromatic condition first with those who were tested in the achromatic condition second. No significant differences between the two groups of observers were found ($P < 0.25$). A similar comparison was made for the chromatic yellow condition, but no significant difference was found ($P < 0.14$). This suggests that our HA thresholds were not influenced by order effects.

Common Experimental Procedures

The resolution and hyperacuity experiments shared the same experimental procedure, so the following description applies to both. During configuration changes, the baffle was closed and participants fixated on a small cross located 12.85° below the acuity target. This cross was drawn onto the white screen and ensured that the subjects maintained a relatively constant state of adaptation throughout the experimental session. Subjects were informed when the stimulus change was complete and the baffle was opened. Participants then viewed the stimulus

until a judgment was made and the baffle was closed again. A typical judgment was made in 1 to 3 seconds. Judgments taking longer than 3 seconds were discarded, and that trial was reintroduced later during testing. Testing took place across a 2- to 3-hour period. This period was broken up into 20- to 30-minute testing blocks with short breaks that were used to prevent problems resulting from fatigue. During breaks, the room lights were turned on and the participants were allowed to move about freely until comfortable or otherwise sufficiently rested. After each break, the testing conditions were returned to their original settings and the measurements continued. To prevent order effects, the achromatic and chromatic conditions were counterbalanced across subjects.

Macular Pigment Measurement

MPOD was assessed only in the right eye (because of the high interocular agreement in MP density [e.g., Hammond and Fuld³⁶]) using heterochromatic flicker photometry (HFP). The apparatus (Macular Metrics Densitometer, Providence, RI) and the specific procedure are described by Wooten et al.³⁷; a brief description follows. Test stimuli were presented near the center of a 6°, 2.75-cd/mm², 470-nm circular background. The test stimulus was composed of a 458-nm measuring field (peak MP absorbance) alternating with a 570-nm, 3.0-cd/mm² reference field (no MP absorbance). Light for the measuring and reference fields and the background was produced by 20-nm half-band-pass LEDs (Nichia Corp., Mountville, PA). The radiance of the LEDs was controlled by constant-current, high-frequency electronic pulses. Measuring and reference fields were superposed and presented out of phase at an approximate alternation rate of 11 to 12 Hz in the foveal condition and 6 to 7 Hz in the parafoveal condition. This alternation rate was carefully optimized for each subject to create a narrow (e.g., equivalent to approximately 0.10 OD) null zone. Once optimized, subjects adjusted the radiance of the 458-nm measuring field (which

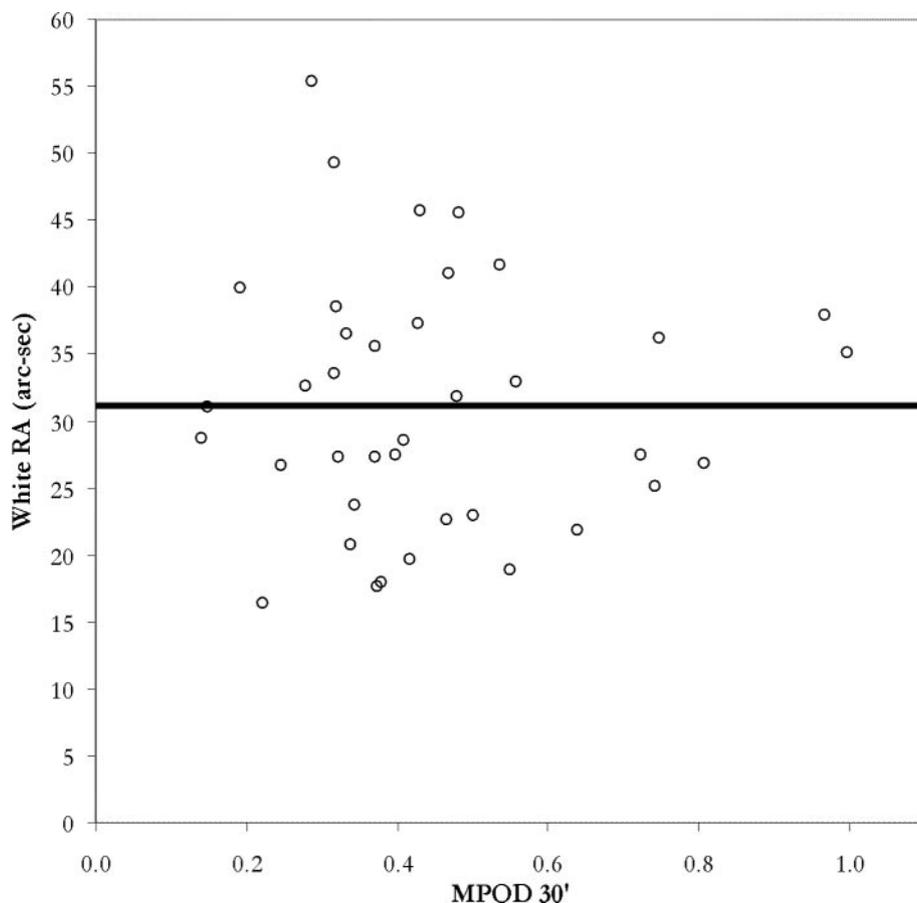


FIGURE 3. Relation between MP and RA for the achromatic condition ($y = 0.16x + 31.1$, $r = 0.003$, $P = 0.98$).

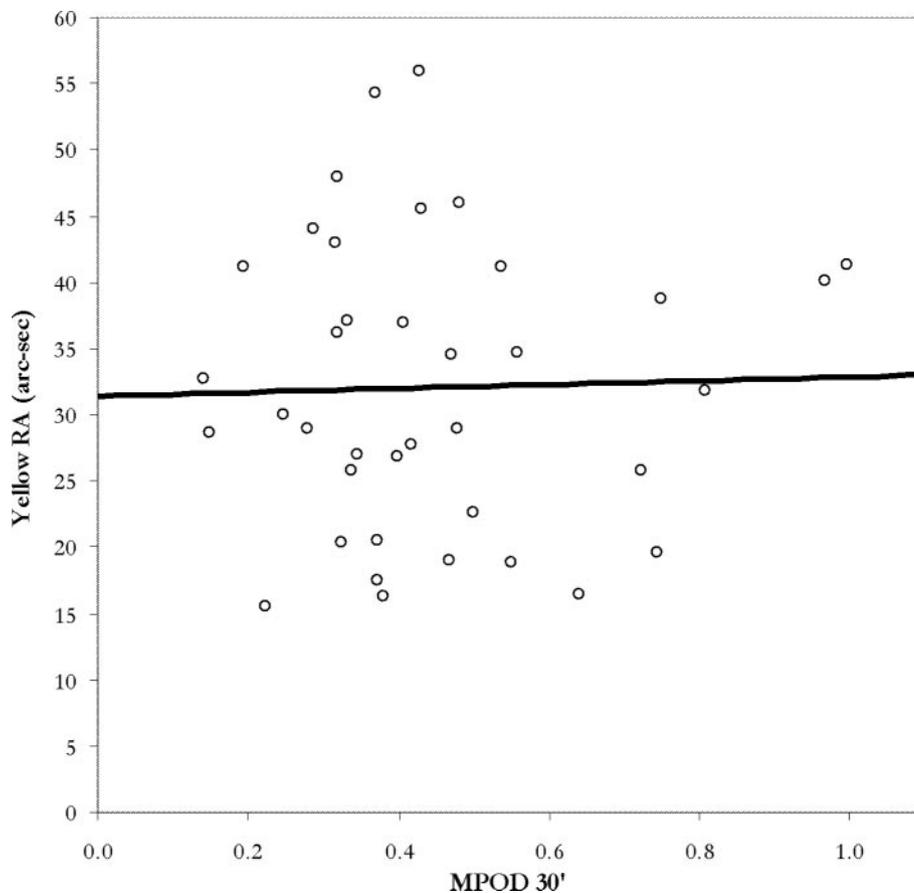


FIGURE 4. Relation between MP and RA for the yellow condition ($y = 1.65x + 31.3$, $r = 0.031$, $P = 0.85$).

was counterbalanced with the 570-nm reference to maintain constant luminance) until a no-flicker point was achieved. This measurement was made in the fovea (where MP is most dense) and 7° in the parafovea (where light absorption by MP is negligible).

RESULTS

A summary of the descriptive statistics for the RA experiment can be found in Table 1. Two subjects were excluded from further analysis because their acuity thresholds were more than 5 SD from the mean. As shown in Table 1, measures for the large sample still varied widely across subjects. For example, MP ranged from 0.14 to 1.00 OD, and RA in the white and yellow conditions ranged from $16.4''$ to $55.4''$ and $15.5''$ to $55.9''$, respectively. As can also be seen in Table 1, the average RA in the white condition ($31.2''$) did not significantly differ from the average RA in the yellow condition ($32.1''$; $P = 0.82$). Indeed, the average across the two conditions differed by less than $1''$ of arc. Thus, although the light source used in the white condition was strongly filtered by MP, this filtering did not change the average acuity when compared with the light source used in the yellow condition that was not filtered by MP. The acuity hypothesis predicts that acuity in the white condition improves as MP increases. As shown in Figures 3 and 4, however, RA in either the white or the yellow condition was not significantly correlated with MPOD (slope = 0.16, $r = 0.003$, $P = 0.98$; slope = 1.66, $r = 0.03$, $P = 0.85$, respectively).

A summary of the descriptive statistics for the HA experiment can be found in Table 2. As with the subjects tested in the resolution experiment, a wide range of MP densities was found (range, 0.06–0.77). HA thresholds also varied widely between participants in both the white and the yellow conditions

(ranges, $2.6''$ – $13.5''$ and $2.0''$ – $15.5''$, respectively). As also shown in Table 2, average HA in the white condition did not differ from average HA tested in the yellow condition ($P < 0.53$). Figures 5 and 6 show the relation between HA in the white and yellow conditions, respectively. As can be seen in Figure 5, HA in the white condition was not significantly correlated with MPOD (slope = -3.88 , $r = -0.226$, $P = 0.161$). As can be seen in Figure 6, chromatic yellow HA was also not significantly related to MPOD (slope = 3.09, $r = 0.147$, $P = 0.36$).

DISCUSSION

Schülte⁵ first proposed what is commonly called the acuity hypothesis, which posits that MP improves acuity by screening some unfocused SW light that would otherwise degrade the retinal image. We tested this hypothesis by measuring resolution acuity and hyperacuity under two different illumination conditions (as illustrated in Fig. 2). One was composed of mid-wave yellow light not absorbed by MP, whereas the other was a perceptual white light with a SW blue portion absorbed by MP and, hence, subject to chromatic aberration. As can be seen in Figures 3 to 6, we found no relation between MP and RA or between MP and HA in either the white or the yellow

TABLE 2. Descriptive Statistics for the Hyperacuity Experiment

	<i>N</i>	Minimum	Maximum	Mean	SD
White HA	40	2.60''	13.51''	7.0''	2.87''
Yellow HA	40	2.00''	15.5''	6.8''	3.53''
MPOD 30'	40	0.06	0.77	0.42	0.17

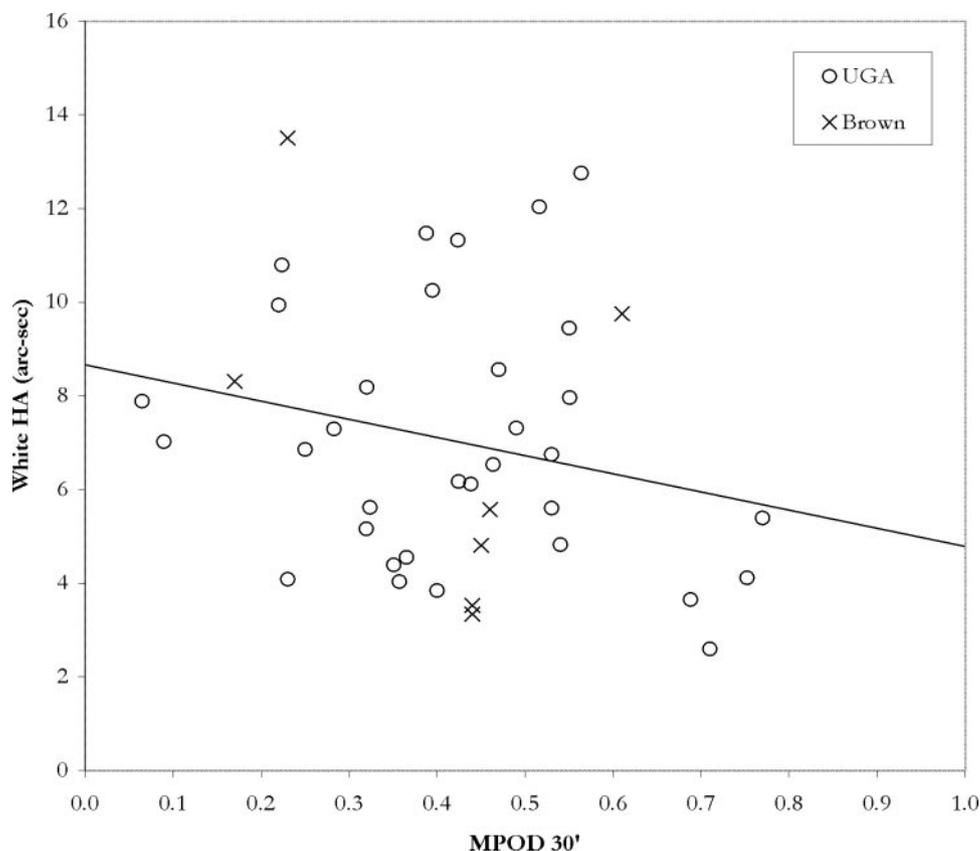


FIGURE 5. Relation between MP and HA in the achromatic condition ($y = -3.88x + 8.66$, $r = -0.226$, $P = 0.161$). Data collected at the University of Georgia are indicated by *open circles*. Data collected at Brown University are indicated by *x*s.

condition. As shown in Tables 1 and 2, the means across chromatic conditions were essentially identical. Average RAs in the white and yellow conditions were 31.2" and 32.1", respectively. Average HAs in the white and yellow conditions were 7.0" and 6.8", respectively. The fact that the two conditions yielded essentially identical results, despite the fact that the white condition was strongly filtered by MP whereas the yellow was not, clearly does not support the fundamental prediction of the acuity hypothesis.

An image-forming optical system is said to exhibit chromatic aberration if its focal length is not independent of wavelength. In the case of the human eye, focal length is proportional to wavelength. Thus, if the eye is in focus in the mid-wave region of a broadband light, as would be the case with sunlight, then shorter and longer waves would be out of focus. This is illustrated in Figure 7A, which is adapted from the Wyszecki and Stile³⁸ summary of relevant literature. For example, when the eye is in focus at 560 nm, the defocus at 460 nm is approximately -1.0 D; at 650 nm it is approximately -0.30 D. Wavelength-dependent refractive error affects the retinal image quality of a polychromatic stimulus in several ways, primarily in the region below 500 nm, where the defocus may reach -1.3 D by 425 nm. One way is by wavelength-dependent blurring, sometimes called longitudinal chromatic aberration. Another way is by wavelength-dependent image position, sometimes called lateral chromatic aberration. Yet another way is by wavelength-dependent image size. Although each of these manifestations of chromatic aberration degrades the retinal image, the blurring effect is the dominant factor for the normal eye with a well-centered pupil (as discussed in Bradley³⁹). Thus, the relation between focus and wavelength shown in Figure 7A is a good indicator of the degree to which chromatic aberration degrades the retinal image. Empirical studies have shown that for every diopter of blur, acuity decreases by a factor of about two.⁴⁰⁻⁴² Of course, if one views a stimulus

illuminated by any monochromatic light, including SW light, accommodation can be complete, resulting in a crisp image. In contrast, if one views a target illuminated by a broadband source (that provides an effective accommodation signal at approximately 560-580 nm), which is more common, the question is whether there is enough unfocused SW light to degrade acuity.

This question can only be answered by considering both the degree of longitudinal chromatic aberration and the amount of MP. As discussed in the Introduction, Reading and Weale⁷ calculated the blur circle resulting from chromatic aberration for typical sunlight. They then derived the spectral transmittance of an ideal filter that would reduce the bluish penumbra to threshold while minimizing light loss. Such a filter closely resembles the average OD and the spectral absorption of MP, albeit without the characteristic carotenoid cusps. Bradley,³⁹ however, modeled the effects of chromatic aberration on the modulation transfer function (MTF) and concluded that image degradation is small. The MTF for broadband light is similar to that for monochromatic light, with approximately 0.15-D defocus. His conclusion suggests that the filtering effect of MP would have an insignificant effect on spatial discrimination tasks. We performed an analysis similar to that of Bradley³⁹ by evaluating the effects of different levels of MP on the spectral energy distribution of our white stimulus at the receptor level. First, we modeled photopic spectral efficiency functions for hypothetical subjects with zero, average, and high levels of MP by simply correcting the standard V_λ function, with MP levels corresponding to maximal spectral absorbance values of 0.0, 0.50, and 1.0, respectively. (No correction was made for lens absorption, thus implicitly assuming an average value.) We then multiplied, wavelength by wavelength, our hypothetical V_λ functions with the measured spectral energy of our white light (Fig. 7B). The resultant three product curves indicating relative sensation luminance to wavelength are shown in Fig-

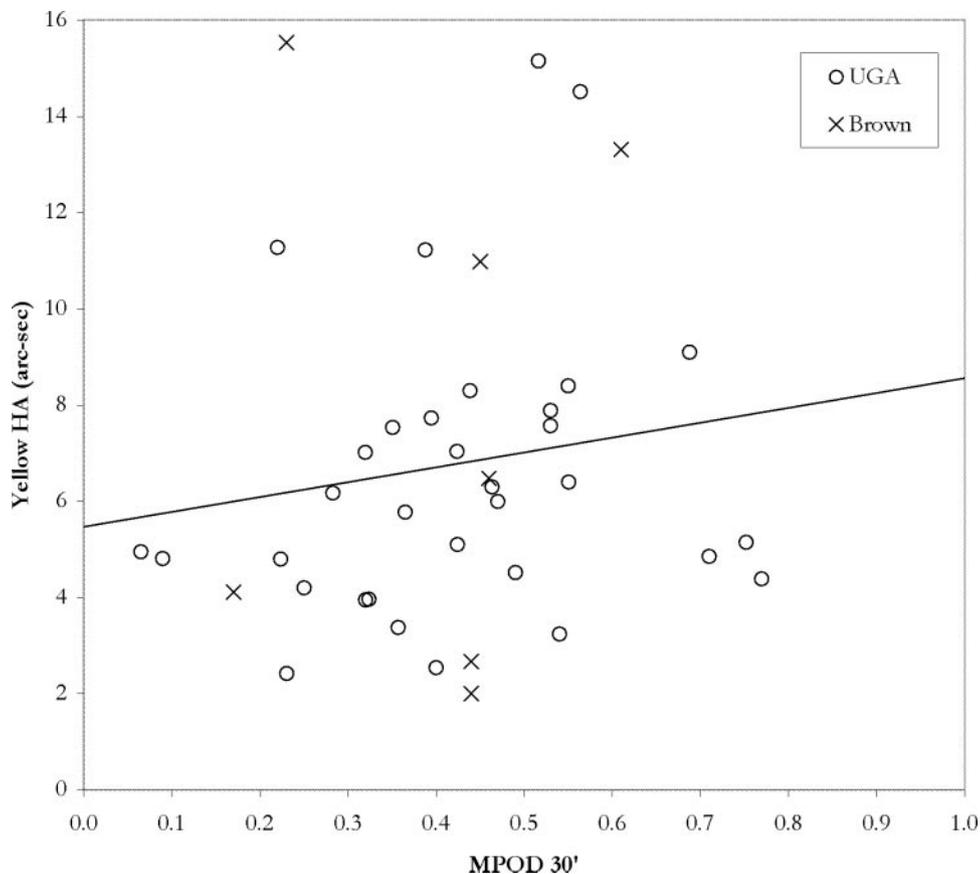


FIGURE 6. Relation between MP and HA in the chromatic yellow condition ($y = 3.09x + 5.47$, $r = 0.147$, $P = 0.363$). Data collected at the University of Georgia are indicated by *open circles*. Data collected at Brown University are indicated by *x*s.

ure 7C. (*Relative luminance* would be appropriate only for the 0.50-MPOD condition because the underlying luminance efficiency function is, in fact, the standard V_λ . The other two curves correspond to the 0.0- and 1.0-MPOD conditions and, therefore, are not identical to V_λ . Kaiser⁴⁰ introduced the term *sensation luminance* to refer to situations in which an individual observer's spectral sensitivity is used instead of V_λ , which refers only to the CIE standard observer.) Even a casual inspection of Figures 7B and 7C indicates that the SW lobe of the white light is drastically reduced compared with the long-wave lobe when correcting the energy distribution to sensation luminance (e.g., from 90% to 13% at the 460 peak for the zero MP condition). Thus, apart from MP absorption, lens absorption and receptor spectral sensitivity alone reduce the effectiveness of the corneal, SW component by a factor of almost seven. The addition of MP reduces the SW lobe even further (Fig. 7C, curve 0.5 and 0.0 MPOD), but a critical question remains: does the MP reduce the SW component enough to improve acuity or hyperacuity? Closer examination of the relevant factors suggests that, in agreement with Bradley,³⁹ little improvement would be expected.

The horizontal dashed line (Fig. 7A) shows the range of ± 0.25 D, with perfect focus (i.e., 0 D) aligned with the long-wave peak of our sensation luminance distribution. As can be seen from the vertical dashed lines, the ± 0.25 -D range corresponds to the wavelength region from approximately 530 to 620 nm. We calculate from Figure 7C that for a hypothetical person with 0 MP, 88.2% of the total relative sensation luminance is contained within a wavelength range corresponding to ± 0.25 D centered at the 565-nm peak. In other words, only 11.8% of the sensation luminance distribution is more than 0.25 D out of focus. Corresponding values for the 0.5- and 1.0-MP conditions are 6% and 3.9%, respectively. Thus, when comparing a person with average MP to one with no MP, we

see only a 5.8% difference in sensation luminance in the 430- to 510-nm region, which contains virtually all the out-of-focus sensation luminance. Even the extreme comparison of the 0- to the 1.0-MP condition yields only a 7.9% difference. Furthermore, these differences in SW sensation luminance occur in spectral regions with an average defocus for the low, average, and high MP conditions of only 0.79, 0.76, and 0.73 D, respectively. The reductions in SW luminance are modest and occur in a region in which the defocus is also relatively modest (approximately 0.75 D). One could argue that no or minimal improvement in spatial vision would be expected. A clear prediction, however, cannot be made in the absence of a quantitative model, which does not exist. In the absence of an accepted quantitative model, a firm conclusion cannot be reached. Our empirical results, however, also show no improvement. Taken together, we feel it is safe to conclude that MP is not related to RA or HA.

Of course, a larger sample might have allowed us to detect a difference that was statistically significant, but it is doubtful that such a small effect can be meaningful. A power analysis ($\alpha = 0.05$, $1 - \beta = 0.80$) indicated that our sample was sufficient to detect average differences in RA and HA of 10" and 5" to 6", respectively, when comparing subjects with low and high MPOD. In our judgment, if MP is related to improvements in RA that are smaller, such effects are too weak to be of interest.

Null effects may also be caused by noisy measurements. To obviate this possibility, we chose very careful psychophysical procedures and healthy young subjects with good acuity. The reliability and validity of our HFP method of measuring MP, for instance, are very high.^{41,42} Our RA values were derived from psychometric functions based on a rigorous psychophysical procedure and displayed high reliability across our conditions. Further, our acuity values were similar to those reported in earlier works. For example, our average RA was approximately

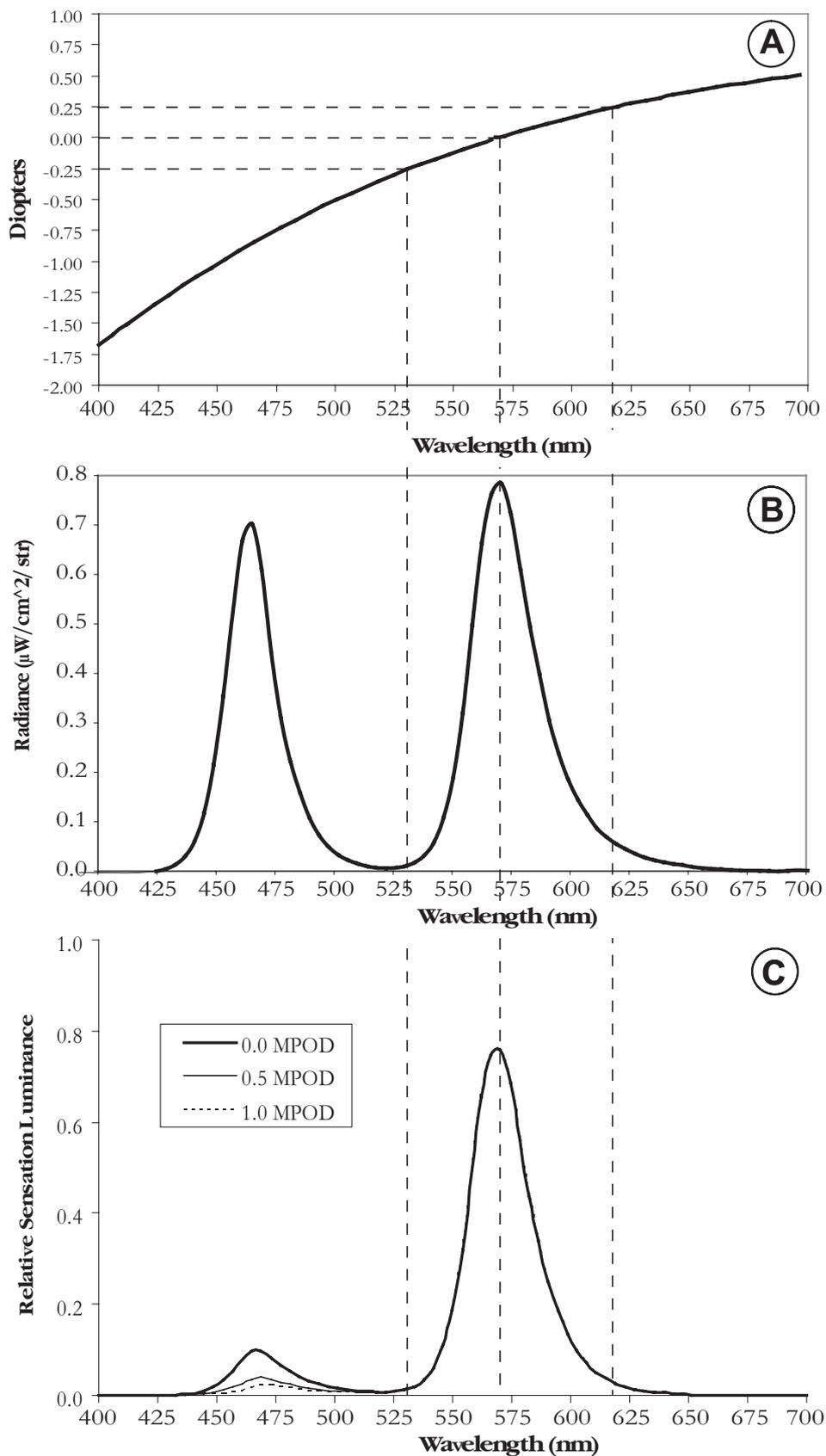


FIGURE 7. (A) Longitudinal chromatic aberration of the eye when focusing at 560 nm (*zero reference line*). (B) Spectral energy distribution for the white condition. (C) V_L corrected for low (0.0 MPOD, *dark solid line*), medium (0.5 MPOD, *light solid line*), and high (1.0 MPOD, *dashed line*) MP. Lines indicate a zone of defocused light (± 0.25 D) that would normally surround a point of perfect focus.

31.5". König (1897)⁴³ and Hecht (1927)¹⁸ found an average gap acuity of approximately 43". The empirical formulas provided by Danjon (1928) and Fortuin (1951) and reported in

LeGrand (1967)⁴⁴ predict acuity thresholds of approximately 42 to 43 seconds. Wilcox (1932),¹⁹ using stimuli that were more similar to ours (gap detection between two parallel bars)

but on only two subjects, found an average gap of 25". Shlaer (1937),²⁰ also using only two subjects who varied the dimension of a Landolt ring via magnification, found an average threshold of 36". More recent studies, using a variety of letters, numbers, and geometric symbols, have obtained a wider range of thresholds. For example, Haegerstrom-Portnoy et al.²¹ found an average gap threshold of 38" using the white Smith-Kettlewell Institute Low Luminance (SKILL) Card. With Sloan optotype letters (C, D, E, O, and S) viewed on a cathode-ray tube (CRT) monitor, Akutsu et al.⁴⁵ obtained an average threshold of approximately 1' at a luminance of 35 cd/m² in their subjects. In a study by Reich and Ekabutr⁴⁶ using Tumbling-E and Landolt rings, also viewed on a CRT monitor, at 105 cd/m² an average threshold of 40" was obtained. Westheimer et al.¹⁴ obtained an average threshold of approximately 36" in their younger (20–30 years) subjects using a Snellen eye chart at 60 cd/m². Radhakrishnan et al.,⁴⁷ using a Bailey-Lovie eye chart, observed an average threshold of 28" in their subjects; however, the background luminance during testing was not specified. Given the wide variety of stimuli and conditions known to influence acuity, particularly luminance, we regard our RA measures as consistent with those generally reported in the literature.

The acuity hypothesis, extended to include vernier acuity, was also not supported by our results. Recall that hyperacuity was chosen because it represents the finest spatial discrimination achievable. We reasoned it might, therefore, be most sensitive to the removal of the blurred components of the image. As shown in Figures 5 and 6, however, we did not find a relation with MPOD. Again, in our judgment, we do not think the lack of an effect is the result of too small of a sample. Based on our sample of 40 healthy young subjects, for instance, a power analysis ($\alpha = 0.05$, $1-\beta = 0.80$) showed that we should be able to detect an average HA difference of approximately 5" to 6" between persons with low and high MPOD. A smaller effect would not represent a meaningful validation of the hypothesis.

In sum, our data suggest that the predictions of the acuity hypothesis do not hold. Of course, other stimulus conditions (e.g., at different spatial frequencies or luminance levels) might yield different results. Moreover, MP could improve visual performance through other optical mechanisms (e.g., increased contrast resulting from differential absorption of a target with respect to its background¹¹) or through effects on the underlying biology. For example, in a recent double-blind, placebo-controlled study, Richer et al.⁴⁸ found that, after 12 months of 10-mg lutein or 10-mg lutein + antioxidant supplementation, visual acuity in 56 patients with atrophic age-related macular degeneration (AMD) improved by 5.4 and 3.5 letters, respectively, on the Snellen chart. Those receiving placebo showed no improvement in acuity. A similar result was reported by Olmedilla et al.,⁴⁹ who instructed cataract patients to consume 15-mg lutein supplement 3 times a week for up to 2 years and found that the visual acuity of the patients who took the lutein supplement improved nearly one line on the Snellen visual acuity chart compared with placebo controls. Careful study of optical mechanisms is necessary to interpret the results of such studies. If MP does not positively influence the optics of the eye, the effects seen in these patients would have to be biological in nature.

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