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Progress in Retinal and Eye Research 21 (2002) 225–240

Progress in
RETINAL AND EYE RESEARCH

www.elsevier.com/locate/prer

# Macular pigment: influences on visual acuity and visibility

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**Abstract**

There is increasing evidence that the macular pigment (MP) carotenoids lutein (L) and zeaxanthin (Z) protect the retina and lens from age-related loss. As a result, the use of L and Z supplements has increased dramatically in recent years. An increasing number of reports have suggested that L and Z supplementation (and increased MP density) are related to improved visual performance in normal subjects and patients with retinal and lenticular disease. These improvements in vision could be due either to changes in the underlying biology and/or optical changes. The optical mechanisms, i.e., preferential absorption of short-wave light, underlying these putative improvements in vision, however, have not been properly evaluated. Two major hypotheses are discussed. The *acuity hypothesis* posits that MP could improve visual function by reducing the effects of chromatic aberration. The *visibility hypothesis* is based on the idea that MP may improve vision through the atmosphere by preferentially absorbing blue haze (short-wave dominant air light that produces a veiling luminance when viewing objects at a distance). 

**Contents**



## 1. Overview

The macular pigment (MP) is composed of the yellow, blue-absorbing carotenoids lutein (L) and zeaxanthin (Z) and found primarily in the retinas of some primates, including humans. Although trace amounts are distributed throughout the retina, it is heavily concentrated in the central fovea. Since light must pass through the MP before reaching the receptors, it screens out significant amounts of short-wave (SW) energy. Individual variation in peak absorbance is large ranging from 0.0 up to 1.5 log units. Several important functions for MP have been proposed. It may serve to protect the retina from damage by absorbing actinic SW light or by inactivating highly reactive free radicals and reactive oxygen species

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1350-9462/02/$ - see front matter 
PII: S1350-9462(02)00003-4

that are the by-product of light driven cellular activity. MP may also serve, as proposed over a century ago, to improve acuity by removing much of the blurry, SW light that results from the eye's chromatic aberration.

In addition to blur from chromatic aberration, there is another source of optical degradation that has been overlooked and that MP could serve to reduce. It has to do, not with the eye, per se, but with the optics of seeing in the outdoors. The earth's atmosphere through which we view objects almost always contains small suspended particles from both natural and man-made sources. This *haze aerosol*, as it is called, scatters SW light more than other wavelengths and results in a bluish veiling luminance. *Blue haze*, as it is sometimes called, is a major factor that degrades *visibility*, i.e., how well and how far we can see targets in the outdoors. The MP may improve vision through the atmosphere by preferentially absorbing the SW energy produced by blue haze and, thereby, increasing both the contrast within targets and the contrast of targets with respect to their backgrounds. We call this proposed role of MP the *Visibility Hypothesis*.

Based upon the literature to date, acuity and/or contrast sensitivity improvements from blur removal might be expected to be small and of little practical importance. Earlier work, however, did not take into account the MP present in the eyes of the subjects, i.e., additional yellow filtration would be superfluous in most cases. When individual MP levels are taken into account, the results could be visually significant for observers with moderate or low concentration. Potentially, the results from the tests of the Visibility Hypothesis could also be quite large and significant. We know that haze is blue, frequently very blue. We know that MP or equivalent yellow filters will definitely improve contrast relations. Experiments must determine the size and significance of potential improvements in vision. Positive results for either hypothesis would suggest that individuals whose profession involves highly demanding visual tasks, especially in the outdoors, should have their MP distribution measured. If low, by a criterion yet to be determined, they should be put on a diet rich in L/Z in order to increase MP levels or use appropriate yellow goggles, or both.

## 2. Macular pigment

Primate foveas have a distinctive yellow macular pigment (MP) that is one of their recognized specializations. MP was originally identified as being composed of xanthophyllic carotenoids by Wald (1945). The primary pigments were later more specifically identified as lutein (L) and zeaxanthin (Z). (Bone et al., 1985) These carotenoids are absorbed in the gut and ultimately deposited throughout the tissues of the eye. The highest concentration, however, is within the inner layers of the fovea. Compared to other bodily tissues, the concentration of carotenoids at this site is very high (Landrum et al., 1999) and deposition is highly regulated. Of the 30–40 carotenoids available within the circulation, with very similar molecular configurations, only L and Z are absorbed within the tissues of the eye.

Despite the fairly ubiquitous presence of L and Z throughout the tissues of the eye, it is only within and around the fovea that L and Z are optically dense. Hammond et al. (1997a) showed that at this site, absorption of short-wave light can be very significant, ranging from a maximum in some individuals of 1.5 optical density units at 460 nm (3% transmission) to a minimum of near zero density (100% transmission). Thus, MP represents a significant, and variable, filtering element in the short-wave processing of light by the visual system.

## 3. Macular pigment. The protection hypotheses

There have been at least two varieties of protection hypotheses advanced to account for the presence of MP within the primate fovea. These hypotheses are based on the spectral absorption and spatial distribution of L and Z, as well as the biochemical properties of the pigments. Short-wave light is exceptionally damaging to retinal tissue (Ham et al., 1978). The location of MP in the inner Henle fiber layer (Snodderly et al., 1984) is optimal for screening vulnerable receptor outer segments from actinic short-wave light (Junghans et al., 2001). In addition to screening, carotenoids are effective quenchers of reactive oxygen species. The identification of oxidized by-products of lutein and zeaxanthin within the human retina is consistent with a function as retinal antioxidants (Khachik et al., 1997).

There is a large confluence of data that support the possibility that MP protects the retina from light-initiated oxidative damage (Beatty et al., 1999), such as experimental studies on rats (Li and Tso, 1995), quail (Dorey et al., 1997) and primates (Neuringer et al., 1999). Data from humans have shown that the central fovea, where MP is most dense, is also the most resistant to degenerative change (Haegerstrom-Portnoy, 1988; Weiter et al., 1988). Observational studies have suggested that MP is lower in patients with AMD (Beatty et al., 2001; Bone et al., 2001). Concomitantly, epidemiological data has shown that L and Z may be lower in the plasma (EDCC, 1993) and diet (Seddon et al., 1994) of patients with AMD. Lutein supplements are now being actively marketed for promoting retinal health and are available in a number of preparations that can contain as much as 25 mg of lutein per unit. This is in sharp contrast to the average intake of most Americans, which is approximately 1–1.5 mg/day.

Dietary modification (Hammond et al., 1997b) or supplementation with purified supplements (Landrum et al., 1997; Bone et al., 1998) have been shown to increase MP density. Moreover, there is some evidence, albeit anecdotal, that suggests that supplements could improve the vision of patients with inherited retinal degenerations (e.g., retinitis pigmentosa; Dagnelie et al. (2000), AMD (Richer, 1999; Olmedilla et al., 2001), and cataract (Olmedilla et al., 2001). Whether such potential improvements in vision result indirectly from a protective metabolic function or result directly from the absorptive properties of MP is an important question and harkens back to the earliest thinking about MP's role in human vision.

## 4. Macular pigment. The acuity hypothesis

The original description of the spectral absorption characteristics of MP was made by Max Schültze in 1866. At that time, he theorized that MP might improve visual acuity in broadband illumination by filtering out SW energy before absorption by the photoreceptors. The surprising argument that less light is better was based upon the well-documented fact that the eye's focal length is proportional to the light's wavelength. Thus, when the emmetropic eye is in focus for middle-wave light (as it typically would be given the photopic luminosity function and most phases of natural sun light), it will be myopic for short-wave light and slightly hyperopic for long-wave light (Gilmartin and Hogan, 1985). This effect is known as longitudinal chromatic aberration. For 460 nm light (the dominant wavelength of typical phase of daylight and peak absorption of MP), the magnitude of the focus error is approximately –1.2 diopters (Howarth and Bradley, 1986). Given optimal focus at 550 nm, much of the SW region would be seriously out of focus. In addition to the focus problem, the wavelength dependency of the eye's focal length means that retinal image size is proportional to wavelength, i.e., the longer the wavelength the larger the retinal image. This effect is known as lateral chromatic aberration. Thus, if a disc of white light is imaged on the fovea, violet-blue penumbra will result. Together, longitudinal and lateral chromatic aberration are known simply as chromatic aberration. Clearly, both kinds of chromatic aberration degrade the retinal image of any potential target. Schültze's Acuity Hypothesis predicts that retinal images are sharpened by MP's SW absorption and that visual acuity is consequently improved. Although the Acuity Hypothesis has never been directly tested, a large number of studies have examined the use of yellow lenses or filters that roughly approximate the blue-absorbing properties of the MP.

The efficacy of improving some aspect of vision (not just acuity) with colored filters was, and continues to be, of practical as well as theoretical interest (e.g Fowler et al., 1991). Over the years, indeed over the centuries, various claims have been made for better vision when viewing the world through green windshields, red visors, rose-colored glasses, etc. In 1969, Clark (1969) reviewed nearly 100 studies of colored sunglasses and concluded that generally no evidence supported claims of improved vision through tinted as opposed to spectrally flat lenses. In fact, for obvious reasons, some filters can even harm color discrimination. With respect to yellow lenses improving visual acuity, Clark concluded that the empirical observations were largely negative. We should emphasize, however, that there were some positive studies and that even the negative ones reported significant improvements in some observers.

Historically, spatial vision has been evaluated by acuity measures, i.e., determining the finest discrimination possible using very high contrast targets. In most clinical settings this is still the practice. Modern views of spatial vision, however, consider acuity as merely the upper limit of the more general contrast sensitivity function (CSF). In an early study using both measures, Campbell and Gubisch (1967) showed that they sometimes yield different conclusions, i.e., a significant result for mid-spatial frequencies, but a null effect for acuity. As DeValois and DeValois (1988) point out, in naturalistic conditions the mid- and low-spatial frequencies are certainly as important as the high-spatial frequencies, sometimes more so. Thus, Schültze's original hypothesis linking MP, chromatic aberration, and acuity has been extended to any measure of spatial vision where a sharpened retinal image could improve performance. This certainly includes the entire CSF.

Studies examining contrast sensitivity with yellow filters have reached contradictory conclusions. Campbell and Gubisch (1967) were the first to measure the CSF in broadband (2600°K) light versus SW-free light and they found about 15% higher contrast sensitivity for the mid-spatial frequencies. Kinney et al. (1983) found a significant, but small (7%), reduction in reaction time for low contrast gratings viewed through yellow filters compared to luminance-matched, spectrally flat filters. Zigman (1990) found improved contrast sensitivity for yellow filters at high-spatial frequencies, contradicting Gubisch and Campbell to some extent. Kelly et al. (1984), in a well-controlled study, found no significant differences. Wolffsohn et al. (2000) recently reviewed all papers that have examined contrast sensitivity with yellow filters: out of 9 papers, including their own, 5 reported positive and 4 reported negative results. Thus, while the results are somewhat more positive than for acuity, there is little agreement when all of the CSF studies looking at yellow filters are considered. Importantly, a common thread running through these papers is that they all report large individual differences in improvement with yellow filters.

Why these mixed results and large individual differences? The Acuity Hypothesis provides a likely answer. SW light in natural illumination is severely out-of-focus and MP is ideally suited to remove this blurred light. On the other hand, acuity is positively related to luminance; therefore improved acuity may be offset by the luminance reduction. Reading and Weale (1974) have shown (using a model which is based upon known psychophysical parameters) that MP absorption based upon estimated average values is sufficient to reduce the violet penumbra of a white disc to a sub-threshold value, i.e., when all relevant factors are quantitatively considered, the Acuity Hypothesis is quantitatively plausible. The authors point out, as did Walls and Judd in 1933, that additional SW absorption from more MP or yellow filters would not significantly improve acuity for those subjects with average (or greater) concentrations, i.e., more would be superfluous for the average person. In fact, for subjects with abnormally high levels of MP further increases in blue absorption could lead to a decrease in acuity and/or contrast sensitivity due to the consequent fall in luminance. In contrast, for observers with low levels of MP, adding SW absorption with MP or yellow lenses could improve spatial resolution as predicted by the Acuity Hypothesis. Thus, unaccounted natural variations in individual's MP, which we know varies in peak absorbance from near 0.0 to over 1.0 OD units (Hammond et al., 1997a, b), could account for the wide range of empirical results.

This possibility is best illustrated by quoting a study that assessed the use of yellow filters to aide visual acquisition.

> The use of yellow filters to enhance visual performance has been proposed for more than 75 years. Many users, including some military aircrew members, are absolutely convinced that the yellow filters improves target acquisition performance; yet others are just as certain that they provide no improvement or even degrade performance. (Provines et al., 1992)

Provines' study was designed to determine whether yellow ophthalmic lenses enhanced visual threshold acquisition performance when viewing approaching aircraft. The study had a null outcome, but the individual variability in results was large. Yellow filters apparently helped some individuals, harmed some, and did nothing for others.

In summary, the 140-year-old Acuity Hypothesis (as expanded to include contrast sensitivity) has never been properly evaluated. Past studies that have explored the relation between SW absorption and acuity or contrast sensitivity have used various yellow filters that resemble MP, i.e., none has actually duplicated its spectral absorption. Maybe some of these yellow filters were close enough to effectively mimic MP; maybe they were not. We simply cannot evaluate the issue with precision. The more fundamental problem with past studies, however, is that subjects were not tested for their MP levels. Without knowing the spectral transmission of an individual's MP, the spectral energy of the target at the receptor level is indeterminate, even knowing the properties of the illuminant and the filter. A lesser but still significant unknown is the spectral transmission of the human lens, which we know is not flat in the SW region. Together these problems are devastating to past studies because the relation between visual performance and relative spectral energy at the receptor level is clearly required for any valid conclusions regarding the efficacy of yellow filters in improving human vision.

Granted that the potential of MP improving visual performance by reducing the deleterious effects of chromatic aberration remains open, a related question can be posed: could the pigment, or yellow extrinsic filters, improve vision by means of some other optical effect? One possibility has to do with intra-ocular light scatter. If scatter within the eye is wavelength dependent in the same way as in the clear atmosphere, i.e., proportional to the inverse of wavelength to the fourth power as described by Lord Rayleigh (1871), then the MP could improve the retinal image by selectively screening the severely scattered SW light (e.g., Rosenberg, 1984; Leat et al., 1990). The parallel to the Acuity Hypothesis is obvious. There are, however, two major problems with this proposal. First, accepted models of the physics of intra-ocular scatter rule it out (e.g., Hemenger, 1992). Second, recent empirical studies of light scatter within the eye clearly show independence of wavelength (Wooten and Geri, 1987; Whittaker et al., 1993). Thus, there seems to be no excessive SW, intra-ocular scatter for MP to absorb. To our knowledge, no other hypotheses regarding optical effects of MP have been systematically developed. An early paper by Henning (1920), however, suggested the possibility that macular pigment could improve vision in the atmosphere by improving contrast relations (as cited in Walls and Judd, 1933). In the following section, we have developed this idea as a major new hypotheses concerning how MP may improve visibility in the outdoors.

## 5. Macular pigment. The visibility hypothesis

Luria (1972) originally demonstrated an effect of yellow filters that at first seems trivial: the threshold for a yellow increment flash on a blue background is reduced when viewed through a yellow (blue absorbing) filter. (Wolffsohn et al., 2000, confirmed this effect using contrast measures.) This is perfectly predictable from an analysis of the physics of the stimulus array, i.e., the blue background is selectively reduced by the yellow filters and the known behavior of increments on backgrounds. Thus, the increment threshold is reduced when the background is reduced. In addition, a suprathreshold yellow target on a blue background is more visible (or more apparent) when the blue background is reduced. Put simply, a yellow filter reduces the luminance of blue backgrounds which results in yellow targets being more visible. At first, this effect appears trivial in that it seems to be too specific, i.e., it does not apply to many examples of everyday vision. Upon adequate consideration of vision in the atmosphere, however, Luria's finding leads to a new theory for an optical function of MP.

Before we develop the main hypothesis, an important term should be clearly defined

> …visibility is the clearness with which objects in the atmosphere stand out from their surroundings (Bennett, 1930, cited in Middleton, 1952).

### 5.1. The physics of light scatter

There are several ways in which a light ray can be diverted from a given path, e.g., absorption, reflection, and scatter. By far the most important process, as related to vision at the earth's surface, is scattering.

> Scattering is the process by which a particle—any bit of matter—in the path of an electromagnetic wave continuously (1) abstracts energy from the incident wave, and (2) reradiates that energy into the total solid angle centered at the particle. Scattering only occurs when the particle's refractive index differs from the surrounding medium.
>
> (from McCartney, 1976).

There is a broad range of particles that differ in size, usually given by the radius. The various types and their sizes are:

| Type | Radius (μm) |
|---|---|
| Air molecule | $10^{-4}$ |
| Aitken nucleus | $10^{-3}$–$10^{-2}$ |
| Haze particle | $10^{-2}$–1 |
| Fog droplet | 1–10 |
| Cloud droplet | 1–10 |
| Rain droplet | $10^{2}$–$10^{4}$ |

The actual particles that each type encompasses are many. For air, oxygen and nitrogen are the most important molecules. Aitken nuclei refer to huge range of small particles, such as sea salt that is suspended in the air by wave action, that are hygroscopic, i.e., they act as condensation nuclei. Haze particles include such substances as dust, smoke, pollen, and various industrial pollutants. When the ground air becomes very humid (saturated), water molecules condense around various nuclei forming complexes that vary in size and are termed fog, cloud or rain.

The amount of scatter depends upon the concentration and the type of particles. The obvious ubiquity of atmospheric particles means that the quality of vision out of doors is to a large extent determined by them. Scatter critically determines how far one can see and how well details can be resolved. Furthermore, and critical with respect to a possible role of the MP in visibility, the scatter is complexly dependent upon the light's wavelength.

The kind of scatter observed (the amount, the pattern, and the wavelength dependency) is determined principally by the size of the scattering particle. When the particle is smaller than about $0.1\lambda$ (much smaller than the wavelength of light), Rayleigh scattering occurs. Rayleigh (1871), using first elastic-solid theory and later the then new electromagnetic theory of Maxwell and Hertz accounted for virtually all aspects of scatter by very small particles. The most dramatic application was to the oxygen and nitrogen molecules of air. He deduced that such small particles scatter light proportional to the inverse of the wavelength raised to the fourth power:

$$\beta_{sc} = c\lambda^{-4}, \tag{1}$$

where $\beta_{sc}$ refers to amount scattered, $c$ is a constant, and $\lambda$ is the wavelength.

Thus, short-wave visible light (blue appearing) scatters much more than other wavelengths. Hence, a clear sky is blue, correlating with the predominance of SW energy that is scattered into our eyes.

When particle diameter is greater than about $0.1\lambda$, Rayleigh's theory does not explain the scattering. Larger particles scatter more and show a more complex spatial pattern and wavelength dependency. Mie (1908) is generally given credit for extending Rayleigh's use of electromagnetic waves and the electrical nature of matter to include scattering particles of all sizes. On the very small side, Mie's theory reduces essentially to Rayleigh's theory and on the large side (e.g., for fog droplets) converges onto simpler geometrical optics. Mie's application to large molecules and particles involves many complexities and interactions, making the issue that is important here of wavelength dependency difficult to generalize. (More about this later.) For fog droplets, i.e., for radii greater than about 3 μm, scatter is independent of wavelength; hence, clouds look white. Thus, the exact distribution of scattered light in the atmosphere depends upon many factors, an important one being the distribution of particle size.

### 5.2. Haze aerosols

Pure air, consisting of only gas molecules, is so rare as to be only of theoretical interest. Ground fog is unusual, but not rare. Between these two extremes exists a range of conditions called aerosols that constitute the overwhelmingly predominant set of factors that largely determine the quality of vision in the atmosphere:

> An aerosol is a dispersed system of small particles suspended in a gas; the term *haze aerosol* emphasizes the particle nature of haze. From the optical standpoint, haze is a condition wherein the scattering property of the atmosphere is greater than attributable to the gas molecules but is less than that of fog (from McCartney, 1976).

Haze virtually always exists near the earth's surface and is usually the determining atmospheric factor of visibility, i.e., how far we can see and how well we can resolve stimuli. Many particles make up the haze aerosol, including dust, volcanic ash, products of many kinds of combustion, sea salt, and exudates from trees and plants. Of particular interest are haze particles indirectly generated by foliage. In some cases dense forests or other heavy plant layers generate high concentrations of small particles that cause a distinctly blue, dense haze called *heat haze*. (Hence the explanation for the color term in Blue Ridge Mountains.) The mechanism is as follows: plants exude terpenes (aromatic hydrocarbon vapors) that sunlight and ozone causes to oxidize and condense into tiny droplets of resins and tars. Similar reactions probably occur in smog. The size of these various particles from all sources range over several orders of magnitude, from 0.01 to 10 μm. The size and concentration of these haze particles, according to Mie's theory, determine the amount and wavelength dependence of light scattered in the atmosphere.

The actual distribution of particle size varies widely depending upon obvious factors, such as amount of foliage, degree and type of pollution, and meteorological conditions (especially temperature and humidity). Fig. 1 shows the total scattering coefficient ($\beta_{sc}$) as a function of particle size (μm) for a typical sample of haze aerosol. Wavelength dependency is more complex as is shown in Fig. 2.

Fig. 2 shows the prediction of Mie's theory for relative total scattering ($\beta_{sc}$) as a function of wavelength (μm), with particle radii as the parameter. This graph is a bit difficult to interpret, but is the key to understanding the wavelength dependency (and amount) of scattering in the haze aerosol. For our purposes, the area of interest is, of course, the relatively narrow visible spectrum indicated at the top of the graph. Notice that for small particles (e.g., 0.2 μm) the curve has a large negative slope, i.e., SW's are scattered more than others. As particle size increases, the slope becomes less negative until at about 0.5 μm the slope is actually positive, i.e., longwaves scatter more than shortwaves. At about 3 μm and larger, the slope is 0.0 in the visible spectrum. The conclusion from these two graphs is that the actual spectral energy distribution of scattered light

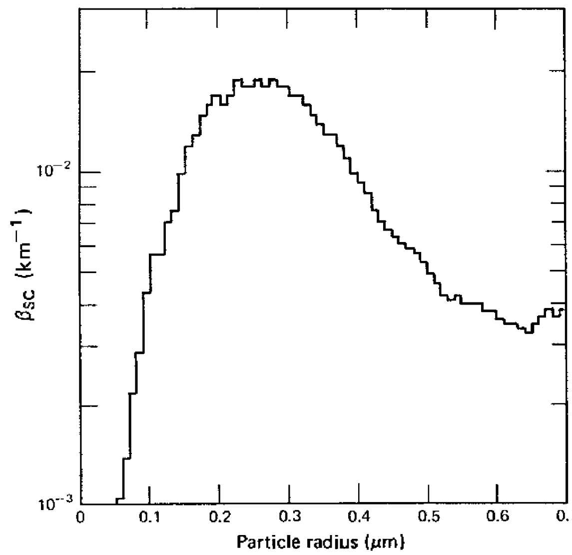



Fig. 1. Total scattering coefficient for a sampled size distribution of a haze aerosol in the Seattle region (Pueschel and Noll, 1967, as cited in McCartney, 1976).

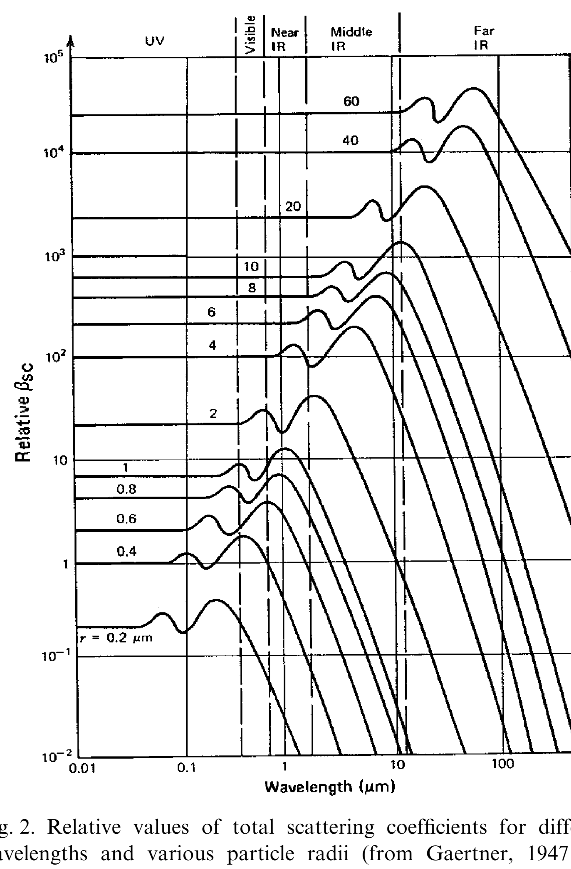



Fig. 2. Relative values of total scattering coefficients for different wavelengths and various particle radii (from Gaertner, 1947 and McCartney, 1976).

in the haze aerosol will vary, but in practice will almost always be dominated by SW light.

The wavelength dependence of scatter in the haze aerosol has been examined and summarized by

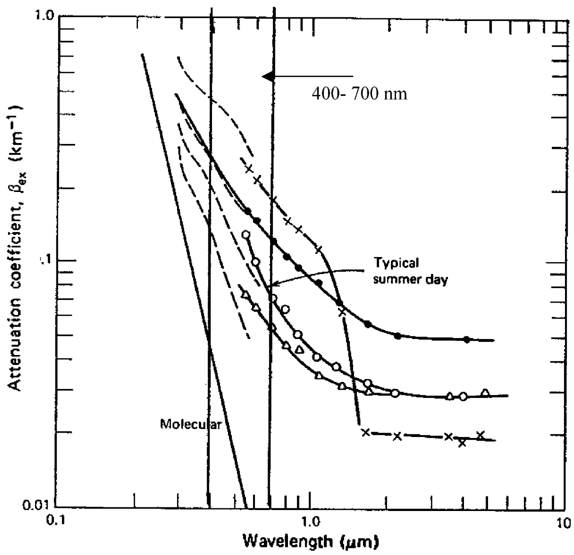



Fig. 3. Attenuation coefficient versus wavelength for a 16.25 km path at sea level (Yates and Taylor, 1960 and McCartney, 1976).

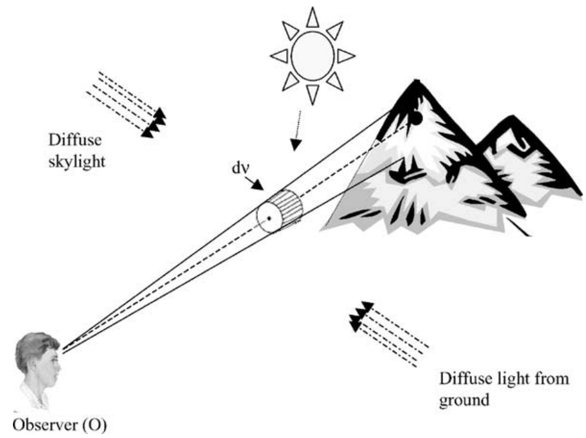



Fig. 4. Source of the air light between an observer and an object, and apparent luminance of an object due to the airlight (after, Middleton, 1952, derived from McCartney, 1976).

Middleton (1952). An empirical formula (similar to Rayleigh's, equation one) is as follows:

$$\beta_{sc} = c\lambda^{-\upsilon}. \quad (2)$$

The exponent varies from 4 for pure Rayleigh scatter to near 0.0 for fog. For the haze aerosol, the exponent is between these two extremes. The actual value for a given atmospheric condition is a weighted sum across wavelength determined by the concentration of particles of various size and their scattering efficiency. Actual determined values range from 0.12 to 2.3 with 1.5 being typical. We should emphasize that all of these values give a dominance at the SW end of the spectrum that varies from slight to large. (An informal way of stating this conclusion is that all haze is blue, from slightly to extremely.)

A frequently cited study by Yates and Taylor of typical haze aerosols is shown in Fig. 3.

Fig. 3 shows the amount of scatter (measured in several determinations) as a function of wavelength in μm. Vertical lines were added to show the visible spectrum. The steep line of negative slope labeled "molecular" shows the scatter from pure Rayleigh air, i.e., no particles. The other lines above the Rayleigh function show the individual determinations. Notice that they are all above the Rayleigh line, indicating that the haze aerosol scatters much more than the air molecules. Also notice that while the curves are less steep than the Rayleigh line of $\upsilon = 4$, they are nonetheless dominated by SW energy. Extreme blue haze would approach the steepness of the Rayleigh line. Haze changing to fog would show a much flatter spectral curve. Extensive observations confirm the empirical formula: scatter in haze aerosols varies from slightly blue to very blue.

### 5.3. Visibility in haze aerosol

Aside from the optical and neural aspects of the human observer, scatter in the aerosol haze is the primary determinant of visual discrimination and range in the outdoors (Husar et al., 2000). As we look out over the landscape, from an elevated location or from an airplane, we notice that the more and more distant elements of the scene become lighter in tone, until sometimes the most distant objects are indiscernible from the horizon. Frequently, the scene seems tinged with a distinctly blue hue. Artists call this phenomenon "aerial prospective" and use it as a depth cue in paintings. Atmospheric physicists call it *air light*. It is explained as light primarily from the sun and sky that is scattered by molecules and (especially) particles that are in the optical path between observer and target. Fig. 4 shows the basic geometry that accounts for how air light affects vision in the atmosphere.

The theory was developed by Kochsmeider (1924) and by Duntley (1948) and elaborated by Middleton (1952), and summarized by McCartney (1976). The basic concepts are quite simple: at every point along a line of sight from the observer (0) to a point on a distant object (T) particles in the aerosol haze in every unit thickness or volume (d$v$) will scatter light towards the observer. Light reflected from T traverses the same path, but much is scattered out by the same process. Thus, the visibility of the object through haze aerosol suffers in two ways: much of the target's light is scattered out of the sight path and the remaining energy must be seen on what amounts to a background that is scattered into the eye, not reflected from the target.

If we consider the target's visibility against the horizon or the discriminability of two targets side-by-side, the theory of air light leads to a simple conclusion: scattering reduces the contrast of targets. A mathematical analysis from the geometry shown in Fig. 4 leads to a general expression:

$$C_R = C_O \exp(-\beta R), \tag{3}$$

where $C_R$ is the luminance contrast between two targets or two elements within a scene, $C_O$ is the luminance contrast of the same target when seen close up, $\beta$ is the scattering coefficient, $R$ is the viewing distance. ($C_O$ is sometimes called the inherent contrast; $C_R$ is sometimes called the apparent contrast.)

Interpreting this equation, as $\beta$ and/or $R$ become large, the term $\exp(-\beta R)$ becomes small, so that the apparent contrast of a scene, $C_R$, is reduced despite a possible large inherent contrast, $C_O$; as $\beta$ and/or $R$ become small, $\exp(-\beta R)$ approaches zero so that the apparent contrast approaches the inherent contrast. This analysis applies along a horizontal sight path and is our primary concern. A similar analysis can be made for an observer looking up at a target against the sky. And, a more complex analysis can be applied to an airborne observer looking down at a target.

In all cases the inference from the formula for $C_R$ is the same: air light reduces target contrast as an exponential function of scatter and distance. One aspect of the contrast formula is not obvious, but should be noted. As a simplification, the scattering term is given without a subscript, i.e., no wavelength dependency. For most purposes, and broad band light, a value averaged across wavelengths is a reasonable approximation. For our purposes, within the context of the absorption of MP, a specific consideration of $\beta$ as a function of $\lambda$ is crucial and is discussed in detail later. First, however, it is necessary to consider a certain target, $T$. The background could be the height and lateral extent of a mountain range as viewed horizontally from a distant hill. Or, the background could be some area of the earth's surface as viewed from an airplane. For any of these cases, the target, $T$, could be any object that is relatively small in visual angle with respect to the background. This is illustrated in Fig. 5, which shows air light as if it is reflected by a beam splitter in order to emphasize that it acts as a veiling background superposed over the target.

The luminance of the air light, now considered the luminance of the background, $L_b$, can be calculated according to Middleton's (1952) treatment. He points out that the air luminance is simply the luminance at O of an object in the plane of a T with zero reflectance, i.e., the luminance of an ideally black object, which is simply proportional to the amount of light scattered into the observer's eye. He then goes on to derive how the air luminance, our $L_b$, is related to the luminance of the horizon near the object, which is measurable:

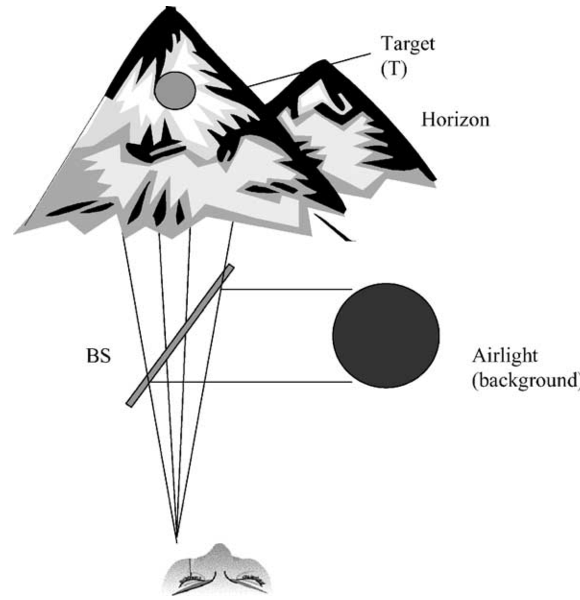



Fig. 5. The observer at O views the target, T, along a haze aerosol path. The light scattered into the eye, the air light, from the same path is considered separately and is symbolically represented as if being reflected by a beam splitter, BS.

$$L_b = L_h(1 - e^{-\beta R}), \tag{4}$$

where $L_b$ is the luminance created by the air light, considered here as a background, $L_h$ is the luminance of the horizon sky near the object, T, $\beta$ is the scattering coefficient, and $R$ is the viewing distance.

Interpreting this equation, as $\beta$ and/or $R$ become large, the expression $(1 - e^{-\beta R})$ approaches 1.0 and so $L_b$ approaches $L_h$ (in other words, the luminance of the air light, $L_b$, is equal to the horizon luminance); as $\beta$ and/or $R$ become small, the expression $(1 - e^{-\beta R})$ approaches 0.0 and so the luminance of the air light, $L_b$, approaches 0.0.

The calculation for the luminance of the target, as separate from the air light, is simpler:

$$L_T = L'_T e^{-\beta R}, \tag{5}$$

where $L_T$ is the luminance of the target at O, i.e., the apparent luminance, $L'_T$ is the luminance of the target close up, i.e., the inherent luminance, $\beta$ is the scattering coefficient, and $R$ is the viewing distance.

Interpreting this equation, as $\beta$ and/or $R$ become large, the apparent luminance approaches 0.0 even for large inherent luminance; as $\beta$ and/or $R$ become small, $e^{-\beta R}$ approaches 1.0 so the apparent luminance approaches the inherent luminance.

### 5.4. *Wavelength dependence of background (air light)*

So far we have not considered the wavelength dependency of $\beta$. It is now necessary to do so in order to see how the MP can improve contrast between the target and a background. For the background considered one wavelength interval at a time:

$$L_{b,\lambda} = L_{h,\lambda}(1 - e^{-\beta_\lambda R}), \tag{6}$$

where $L_{b,\lambda}$ is the luminance of the background at a given $\lambda$, $L_{h,\lambda}$ is the luminance of the horizon at a given $\lambda$, $\beta_\lambda$ is the scattering coefficient at a given $\lambda$, and $R$ is the viewing distance.

Now define the horizon luminance as

$$L_{h,\lambda} = V_\lambda E_\lambda, \tag{7}$$

where $V_\lambda$ is the CIE photopic luminosity function, and $E_\lambda$ is the spectral energy of the natural illuminant.

Substituting in Eq. (6), we now have

$$L_{B,\lambda} = V_\lambda E_\lambda(1 - e^{-\beta_\lambda R}). \tag{8}$$

If we now integrate the equation, we have the overall luminance (across $\lambda$) of the background:

$$L_B = \int_{400}^{700} V_\lambda E_\lambda(1 - e^{-\beta_\lambda R})\, d\lambda. \tag{9}$$

Certain choices have to be made about each term in order to generate an illustrative example of our proposed contrast enhancing mechanism. The spectral composition of $E_\lambda$ is determined by such factors as time of day and the relative contribution of direct sunlight (relatively dominated by mid-wave energy) and sky light (relatively dominated by short-wave energy). $D_{6500}$ as defined by Judd (1951) would seem to be the most general since it contains a balanced amount of both direct and indirect sunlight. As discussed earlier, the value for the exponent of the scattering term varies from 0 to 4. We have chosen 2.0 for our example. Obviously, a complete analysis at some point would let the relevant parameters vary over the complete range.

So far the expression for $L_B$ does not incorporate the expected transmission (or absorption) characteristics of the MP. First, consider the spectral luminosity function, $V_\lambda$. It is based upon averaged data from young adults. A safe assumption, given their experimental conditions, is that the curve reflects an average amount of macular pigment, which is about 0.50 optical density at 460 nm. For our analysis, we want to remove this value from $V_\lambda$ and then add it back in order to model an eye from having no MP to having a large amount, say 1.0. After removing the assumed average amount of MP, we call the resulting function $V^o_\lambda$. We can now add in varying amounts of MP after converting from optical density to transmission, $T_\lambda$. Our new expression is

$$L_B = \int_{400}^{700} V^o_\lambda E_\lambda(1 - e^{-\beta_\lambda R})\, T_\lambda\, d\lambda. \tag{10}$$

Using this expression, we can calculate how the relative luminance of the background is affected by varying amounts of MP for a specific (but common) illumination and a realistic haze condition.[1]

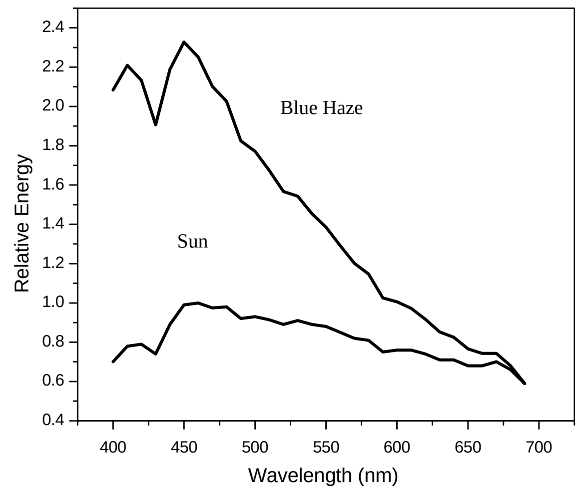



Fig. 6. The relative energy of the D6500 "sun" compared to "blue haze."

Fig. 6 shows the relative spectral energy of D6,500 ($E_\lambda$) labeled "sun." This figure also shows the relative spectral energy of the sunlight after scattering according to the equation

$$\beta = c\lambda^{-v} \tag{11}$$

with $v = 2.0$. Notice the rather severe distortion of the spectrum labeled "blue haze."

For comparison, the two curves are pinned at $\lambda = 690$ nm. It is clear that a reasonable scatter term results in a strongly short-wave dominated spectrum. The question now is: what is the effect on $L_B$ of removing short-wave energy by adding increasing concentrations of MP in an eye assumed to have none initially?

Fig. 7 shows the spectral transmission for peak MP ranging from 0.0 to 1.0 OD, essentially the full range of MP as found in actual measurements (Hammond et al., 1997a, b). The corresponding effects of the spectral transmission curves on the spectral energy for blue haze are shown in Fig. 8.

With increasing amounts of MP, the short-wave energy band is incrementally reduced. Since absorption by the MP is low in the 400–425 nm zone, a considerable amount of energy remains in this region of the spectrum. If we assume an average spectral absorption by the

[1] Any modification of $V_\lambda$ as a model for an individual with some specific amount of MP would yield a valid representation of a light's effectiveness for that hypothetical individual, but it would not technically be luminance as defined by the CIE. Kaiser (1988) proposed for such a case that the term *sensation luminance* be used. Since, however, this term has not been widely adopted we will continue to use the term luminance while recognizing the validity of Kaiser's point.

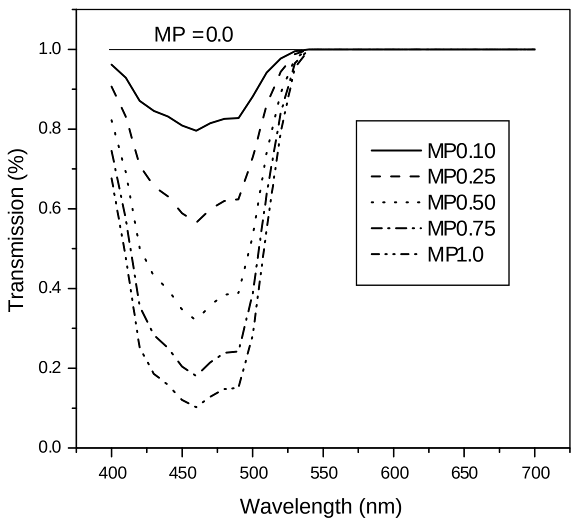



Fig. 7. The percentage transmission versus wavelength corresponding to MP absorption with peak absorption values ranging from 0.0 to 1.0.

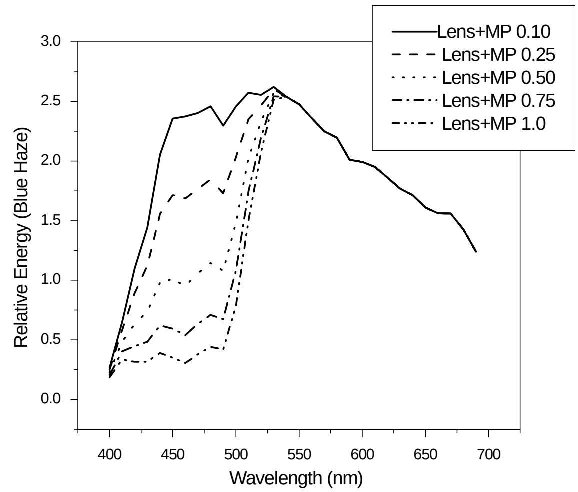



Fig. 9. Influence of lens plus MP transmission on blue haze. Tabular data from Wyszecki and Stiles (1982) was used to calculate average lens transmission.

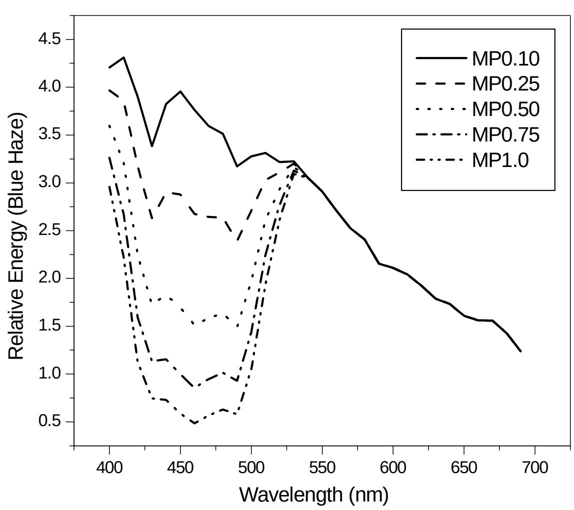



Fig. 8. Influence of varying amounts of MP density on blue haze.

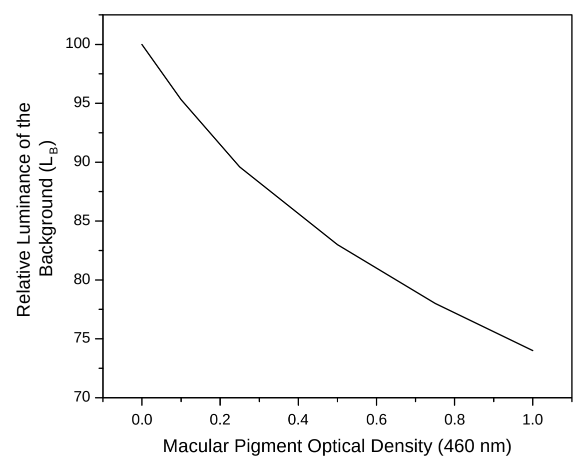



Fig. 10. The relative luminance of a target and background as a function of MP density.

crystalline lens (Van Norren and Vos, 1974), most of this energy is removed, since lens absorption increases dramatically as wavelength is decreased below about 460 nm. Fig. 12 shows the spectral energy remaining from Fig. 9 after filtering by the lens.

Using these assumptions, examples, and Eq. (10), it is now possible to calculate how the luminance of $L_B$ is reduced by increasing amounts of MP. This is shown in Fig. 10, where $L_B$ (in relative units) is plotted against varying amounts of MP density. Clearly, the luminance of a blue-haze background is reduced as MP levels increase.

Notice that with an MP of 0.50, the luminance reduction is about 17%. With a relatively high level of 1.0, the luminance reduction is about 26%. The implications for visibility of Fig. 10 are discussed in Section 5.6.

### 5.5. Wavelength dependence of targets

Having calculated how the luminance of the non-image forming air light (background) varies as a function of MP concentration, it is now necessary to do a similar analysis for light reflected from hypothetical targets. It should then be possible to make some reasonable predictions related to visibility of targets in a blue haze atmosphere. Recall that the luminance at O of a target, $L_T$ (the apparent luminance), is related to the luminance of the target close up, $L'_T$ (the inherent luminance), as shown in Eq. (5). As we did for the air

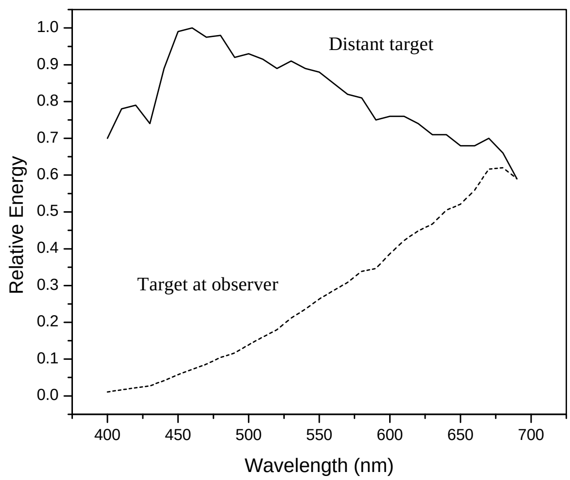



Fig. 11. Solid curve shows the spectral energy of a D6,500 illuminant that is reflected from a spectrally flat target; the dashed curve shows the spectral energy of this same light after it has passed through the intervening atmosphere where $\beta = c\lambda^{-2.0}$.

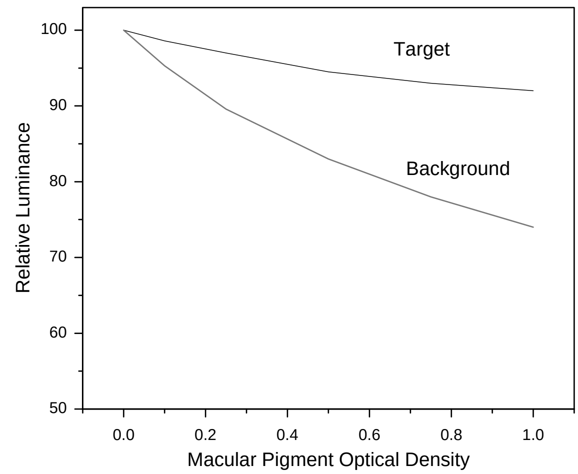



Fig. 12. The relative luminance of a target and background as a function of MP density.

light background, we must now consider the target's wavelength dependence on $\beta$ before the influence of MP spectral absorption can be evaluated. For a target reflecting ambient illumination, consider the luminance one wavelength at a time

$$L_{\mathrm{T},\lambda} = L'_{\mathrm{T},\lambda}\mathrm{e}^{-\beta_\lambda R}. \tag{13}$$

Now define $L'_{\mathrm{T},\lambda}$ as

$$L'_{\mathrm{T},\lambda} = V^{\mathrm{o}}_\lambda E_\lambda a_\lambda, \tag{14}$$

where $V^{\mathrm{o}}_\lambda$ is the luminosity function with MP absorption removed, $E_\lambda$ is the ambient illumination from $D_{6,500,}$ and $a_\lambda$ is the spectral reflectance of the target.

Substituting into Eq. (14), we now have

$$L_{\mathrm{T},\lambda} = V^{\mathrm{o}}_\lambda E_\lambda a_\lambda \mathrm{e}^{-\beta_\lambda R}. \tag{15}$$

We can now incorporate MP into the equation:

$$L_{\mathrm{T},\lambda} = V^{\mathrm{o}}_\lambda E_\lambda a_\lambda T_\lambda \mathrm{e}^{-\beta_\lambda R}, \tag{16}$$

where $T_\lambda$ is the spectral transmission of MP for a given concentration. Now we simply integrate to get the overall luminance (across $\lambda$) of the target:

$$L_{T,\lambda} = \int_{400}^{700} V^{\mathrm{o}}_\lambda E_\lambda a_\lambda T_\lambda \mathrm{e}^{-\beta_\lambda R}\,\mathrm{d}\lambda. \tag{17}$$

Interpreting Eq. (17) with respect to the relative spectral energy distribution, short-wave energy is relatively reduced comparing the light reflected from the target to the light reaching the eye. This is, of course, due to the wavelength dependent term in the exponential, $\beta_\lambda$. This is shown clearly in Fig. 11 where we compare the relative spectral energy of the illuminant ($E_\lambda$; D6,500) after reflection from a perfectly reflecting ("white") target to the relative spectral energy of the target at the observer's eye, i.e., after scatter through the intervening atmosphere.

The spectral energy of the target at the observer is dramatically reduced in the short-wave region by the intervening scatter. We should emphasize that the spectral energy in the short-wave region is for a target with a flat spectral reflectance curve. Most common objects have relatively low reflectance below 480 nm. Thus, the "white" target shown in Fig. 11 represents targets with the maximum possible short-wave energy, i.e., the worse case condition with respect to our hypothesis.

In summary, the non-image forming air light acts as a background or veiling luminance with respect to targets seen through it. Furthermore, the background luminance increases and becomes increasingly short-wave dominant (blue haze) as the viewing distance increases. The luminance of a target, on the other hand, decreases and becomes increasingly short-wave deficient as the viewing distance increases. (The relative spectral effects are seen by comparing Figs. 6 and 11). Since MP absorbs primarily in the 420–500 nm range, it has a quantitatively different effect on the background and target luminances. This can be seen clearly in Fig. 12, where the relative luminance attenuation of the target and background are shown as a function of the peak MP optical density. Notice that the target curve is relatively shallow falling to about 92% for a 1.0 peak MP optical density. For most targets, which reflect relatively poorly in the short-wave region, the attenuation would be even less. Recall that for the background the corresponding attenuation is 26%. This graph clearly demonstrates the main premise of the Visibility Hypothesis: MP improves contrast for a target in an aerosol haze by attenuating the air light luminance (background) more than the target luminance.

### 5.6. Implication of the visibility hypothesis

Visibility generally refers to the related issues of how far we can see, i.e., the range, and how well we can see, i.e. the discrimination of targets, through the earth's atmosphere. The specific values of both aspects of visibility depend upon many factors within a given scene, e.g., target size and reflectance, illumination conditions, state of the observer, angle of regard, and (of course) the size and distribution of scattering particles. Generalizations are difficult to make. Nevertheless, with certain reasonable assumptions we can explore some implications for visibility related to our treatment of the haze aerosol on targets and air-light backgrounds. The key is Fig. 12, which shows that MP improves a target's contrast against a blue haze background. The fundamental question is whether or not the size of the effects translates to significant improvements in visual range and target discrimination. A preliminary analysis suggest a positive answer.

#### 5.6.1. Visual range

The first assumption needed to calculate visual range, $R$, is a Weber fraction for the observer. We assume a value of 0.01 in accordance with Blackwell's data (1946) for small stimuli. If we further assume, for an eye with a 0.0 MP, 100 arbitrary units of luminance for the air-light background, then the value for the target's luminance at the observer would be 1.0. For targets with spectral reflectance outside the range of the MP's absorption, i.e., greater than 520 nm, we can ignore $\lambda$ for the target and for the scattering term. We will assume an average value for $\beta$ of 0.1. Recall that Eq. (5) is

$$L_T = L'_T e^{-\beta R},$$

where $L_T$ is the luminance of the target at the observer, $L'_T$ is the luminance of the target close-up, i.e. at $R = 0$, $\beta$ is the scattering term, and $R$ is the visual range. If we let $R = 10$ km, we have

$$1 = L'_T e^{-(0.1)(1.0)}$$

then, $L'_T = 2.7$.

Now let $MP = 0.5$ absorbance as an example. From Fig. 16, we can see that the background is reduced by 17% to a luminance of 83. For the assumed Weber fraction of 0.01, this means that targets with $L_T = 0.83$ are now at threshold. $L'_T$ is, of course, still 2.7.

Substituting these values for $L_T$ and $L'_T$ into Eq. (5), we now have

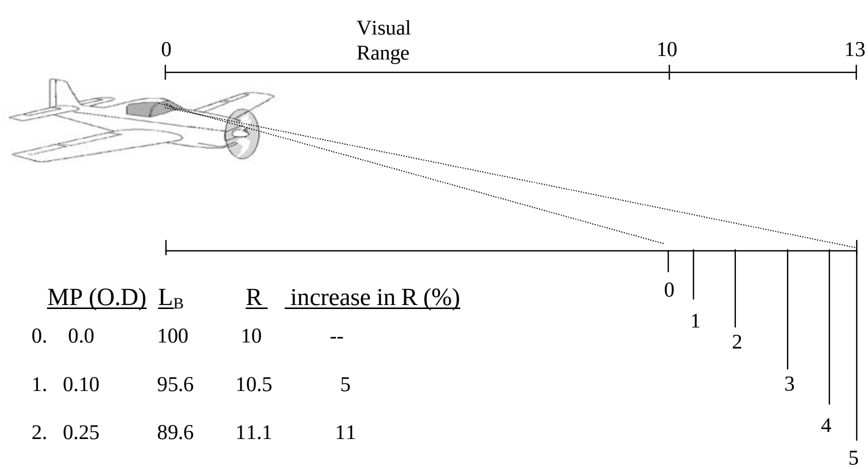
$$0.83 = 2.7e^{-(0.1)R}.$$

We can now solve for a new $R$ that applies to the background reduced to 83 luminance units by an MP of 0.5 absorbance:

$$R = 11.86 \text{ km}.$$

Thus, the visual range has been increased by 18.6% from 10 to 11.86 km due to the improved contrast. Other values are illustrated and tabulated in Fig. 13.

In summary, reasonable assumptions of values for atmospheric conditions, observer sensitivity, and target parameters clearly lead to the conclusion that physiologically realistic values of MP could significantly increase visual range.




| | MP (O.D) | $L_B$ | R | increase in R (%) |
|---|---|---|---|---|
| 0. | 0.0 | 100 | 10 | -- |
| 1. | 0.10 | 95.6 | 10.5 | 5 |
| 2. | 0.25 | 89.6 | 11.1 | 11 |
| 3. | 0.50 | 83 | 11.9 | 18.6 |
| 4. | 0.75 | 78 | 12.5 | 25 |
| 5. | 1.0 | 74 | 13 | 30 |

Fig. 13. Illustration and tabulated values for MP optical density, background luminance, and visual range.

### 5.6.2. Target detection

Related to the potential increase in visual range attributable to MP is the issue of enhanced detection of targets at a given range. If, for example, a 0.5 absorbance of MP increases the visual range from 10 to 11.86 km then it also increases the detection of all those targets at 10 km that were at or near the increment threshold of 0.01. Recall from the previous example that an MP of 0.5 absorbance reduces the background air luminance from 100 to 83. Thus, all previous targets that were at the threshold luminance of 1.0 would now exceed threshold with a target/background ratio of 1/83, or 0.012. Furthermore, some objects that were actually below threshold would now exceed the Weber fraction of 0.01. In general, by reducing the luminance of the background with little or no reduction in the luminance of targets or potential targets the relevant frequency-of-seeing curves are shifted to correspond to better vision. The issue now becomes whether or not these shifts are visually significant.

Fig. 12 shows that an MP level of 0.5 absorbance, for example, results in a 17% reduction in the luminance of a typical blue haze background compared to that for an eye with zero MP. At first glance a reduction of this magnitude seems small, corresponding to a logarithmic value of only 0.08. Its visual significance, however, can only be assessed with respect to the steepness of the frequency-of-seeing curve for a target of fixed luminance as the background luminance is systematically varied. Note that this is the reverse of the usual increment threshold paradigm where the target's luminance is varied while the background is held constant. To explore this issue, we conducted a pilot experiment to model this effect. Hence, in a Maxwellian-view optical system we presented a 1°, circular test field with a retinal illuminance of 5 Trolands (td). This target was flashed for 500 ms on a 6° background that was randomly stepped in 0.1 log luminance increments. The subject's task was simply to report that the target was "seen" or "not seen." It was presented 10 times upon each background level. Thus, a frequency-of-seeing curve could be constructed for "percent seen" vs. relative OD in the background with 0.0 OD corresponding to the 50% seen point. Both the test and background were set at $\lambda = 550$ nm with a 10 nm half width. Once could systematically simulate the spectral composition of realistic targets and blue-haze background over a range of conditions. In this pilot study, however, our goal was simply to define a frequency-of-seeing curve for a background of varying luminance; so we chose a wavelength of target and background outside the absorption band of the MP.

The results of the detection pilot study are shown in Fig. 14. The bold, solid line is a sigmoidal fit through the "percent seen" data points. Notice that the curve is rather sharp, rising from near zero to near 100% over about 0.3 OD. These results show that a relatively small decrease in background luminance results in rather large changes in the detection of near-threshold targets. We can now interpret the effects of different levels of MP. Assume that the bold curve is for an eye with zero MP. The first dashed curve to the right represents a shift of 0.08 OD corresponding to the 17% reduction in background luminance for an eye with an MP of 0.5 peak absorbance. The horizontal and vertical straight, dashed lines intersect the curves at the 50% "seen" points. Thus, a target that was seen 50% of the time for an eye with MP = 0.0 would be seen 75% of the time for an eye with MP = 0.5. Although not indicated on the graph, other points could be interpolated: a target seen 30% of the time, hence below threshold, would rise to 55%, hence above threshold, for the MP = 0.5 condition. To take one more example, a 75% seen target would be shifted to nearly 100% seen. The second curve to the right represents a similar analysis for MP = 1.0 and shows even larger shifts, e.g., the 50% target rises to over 90%.

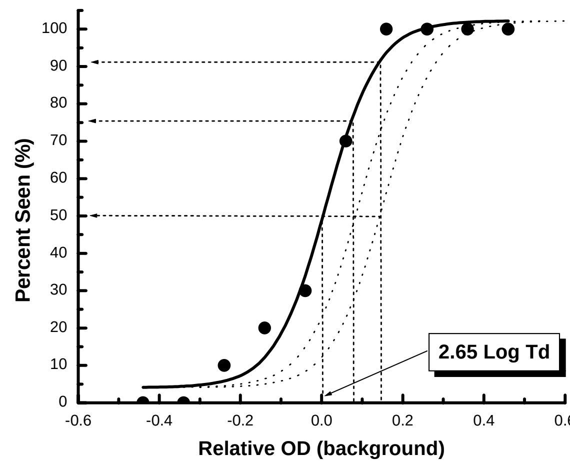



Fig. 14. Detection of a 550 nm target presented on a 550 nm background of varying luminance.

In summary, this analysis demonstrates that physiologically reasonable levels of MP could reduce backgrounds enough to result in visually significant increases in the detectability of targets in natural settings. Although not immense, these effects imply that a whole class of objects below or near threshold at a given visual range would be significantly more visible for observers with substantial levels of MP compared to those with little or none.

### 5.6.3. Target discrimination

In addition to detecting the presence (% seen) of a target against a background, good vision often means that observers be able to discriminate the target's internal detail as a requirement for identification. Here too, the luminance of the background is obviously a critical variable, since any background reduces the

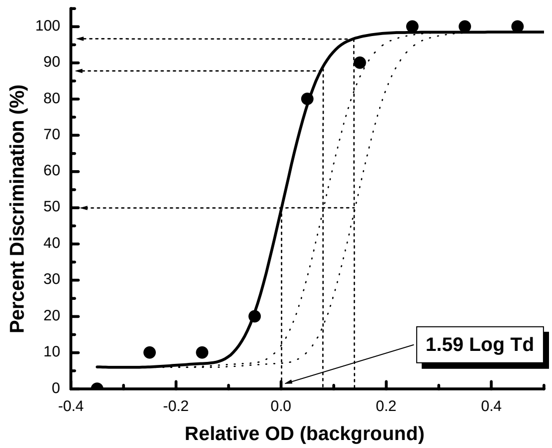



Fig. 15. Constant contrast (5%) discrimination thresholds on backgrounds at varying luminances.

contrast between the elements within a definable target. As for detection and visual range, we can ask to what extent the reduction of background luminance associated with various levels of MP results in improved discrimination of a target's internal elements. Our analysis and assumptions are similar to the treatment for detection except for the target itself. To model discrimination we created a more complex stimulus by introducing a 5% contrast between the left and right half of the circular, 1° target. The observer's task was simply to report whether he could discriminate the two halves or not. The fixed-luminance target was 1.0 s in duration. As before, the background was pseudorandomly varied in 0.1 steps of OD.

The results for the pilot experiment dealing with target discrimination are shown in Fig. 15. Notice that the 50% point for discrimination falls at a background level of 1.61 log troland, about 1 log lower that for detection. This is expected since discrimination is a more demanding task than simple detection. Otherwise, the results are similar: the transition from near zero to near perfect discrimination is sharp, occurring over <0.3 OD. The shifted, smooth curves and dotted lines are as for Fig. 17. Some examples of improved discrimination are worth noting. A target that is discriminated 50% of the time for MP = 0.0 is distinguished 88% of the time for MP = 0.5; the value reaches almost 100% for MP = 1.0. A sub-threshold target at 40% discrimination rises to about 80% as MP is increased from 0.0 to 0.5.

In general, the discrimination of a target's low-contrast, internal detail increases in proportion to levels of MP. The implications are similar to those for simple detection: relatively small reductions of a blue-haze background resulting from physiologically reasonable levels of MP could result in significant improvements in visual discrimination. Thus, at a given range in a natural setting, a host of indiscriminable objects could be rendered distinct by simply increasing the observer's MP.

## 6. Conclusion and future directions

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. Clearly, people with low concentrations of MP might be seeing at a level less than their potential and less than is needed in their job. To determine what percentage of the general population could be low in MP, we aggregated data from populations that we have studied in the Northeast (e.g., Hammond et al., 1996), Southwest (e.g. Hammond and Caruso-Avery, 2000), Midwest (Cuilla et al., 2001) and Southeast. Their data suggests that approximately 43% of this large ($N = 846$) sample have MP density of <0.2.[2] About 16% have <0.1 OD. An analysis of the diet of these subjects suggests that poor diet is probably responsible for these low values; the Midwest group have a L/Z intake equivalent to eating only one tablespoon of spinach per day. If MP is an important factor for optimal vision in the out doors, as our analysis suggests, then these data indicate that a significant population of people are not seeing as well as is possible.

As noted throughout this review, MP could improve human visual performance through both optical effects (the Acuity and Visibility hypotheses) and by maintaining the health and functional integrity of the retina and lens (Hammond et al., 2001). Thus, increasing MP could both improve vision in the short term and maintain visual performance over the long term. There are currently very little interventions that are aimed at preserving visual performance despite abundant data showing significant declines with age. For example, recently, a large prospective study on the visual acuity of

[2] "Averaged" MP densities is relative to both the measurement conditions (e.g., wavelength, stimulus diameter, and reference value) and characteristics of the population (socio-economic status, etc.). Consequently, determining an "absolute" amount of MP using data from different laboratories is difficult. We have tested the personal characteristics (e.g., dietary intake) and MP density of a sufficiently large number of subjects, however, to conclude that, for a number of different samples, the average (based on our conditions) MP density is low. Most of the modeling data presented in this grant, however, are based on an "average" value that is somewhat higher (0.5). We used this higher value because most of the reference data that we also used (e.g., template data from Wyszecki and Stiles (1982)) is based on an average MP = 0.50. Using a lower value for MP, however, would not change our calculations or conclusions. This is because the reference data would also be lowered by an equivalent scalar and therefore all of the analyses would simply be reduced by a constant. For ease of exposition, and since all the reference data is published, we decided not to adjust the MP value that was the previously assumed average.

Japanese Air Force personnel (Kikukawa et al., 1999) showed that visual acuity and distance vision declined significantly when measured from 20 to 45 years of age. This general observation has often been noted in civilian populations (e.g., 25% decline in visual acuity between the ages of 20–45 yr). By preserving foveal cones (Hammond et al., 1998), and the clarity of the crystalline lens (Hammond et al., 2001), MP could retard such changes.

Issues involved with optimizing visual performance will also become increasingly important due to declining visibility that results form the increasing amounts of smog and haze in the environment. As noted in this review, air light reduces contrast between an object and its surround as a function of distance. This is easily observed. For example, when viewing a series of parallel ridges covered with vegetation, ridges nearby will appear green. With each successive ridge, however, air light reduces contrast, until distant ridges are lost in a milky bluish haze, even on a clear day (e.g., Green River Area, Wyoming, average visual range in June = 108 miles). The Visibility Hypothesis predicts that an individual with high MP would be able to distinguish such ridges up to 27 miles further than individuals with little or no MP, but equal Snellen acuity.

In order to properly evaluate the theoretical arguments in this review, empirical data is needed. If MP does improve visual performance, this information could also be used to improve the ergonomic design of visual displays and equipment used to optimize vision. For example, goggles with xanthophyllic absorption properties could be designed for subjects with low MP density in order to optimize visual acquisition tasks.

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