HUMAN NOCTURNAL SPECTRAL SENSITIVITY AND PHOTOELECTRIC V

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Abstract

Various candidate spectral sensitivity functions are compared with photoelectric V, and the dependence of spectral sensitivity on viewing conditions and eye usage is reviewed. These functions are useful for understanding visual and photoelectric magnitude estimates, and in attempting to transform these to standard systems. Several recommendations are made.

1. Introduction

Stars are spectrally broadband, so it is convenient to consider the individual monochromatic components of star light before attempting to integrate their individual contributions to vision. The individual effects of different wavelengths are usually represented as a *spectral sensitivity function* which shows the amount of monochromatic light energy or the number of photons necessary for some constant physiological or behavioral effect at some particular wavelength λ. The function is usually plotted as the reciprocal of one of these measures, often on a logarithmic ordinate. A spectral sensitivity function describes, for example, the sensitivity of an AAVSO observer to different wavelengths when detecting a star at the instrumental limit of the telescope or binoculars. When sensitivity is defined by the inverse of the amount of light energy required for a *luminous*, i.e., an achromatic, or colorless, intensive, *sensation*, it is often referred to as a *visual luminous efficiency function*. Not knowing the spectral functions that apply to variable star observing complicates linking human magnitude estimates that span many decades of observation to photoelectric data.

This problem is, at first sight, a very hard one because spectral sensitivity is determined by several uncertain factors, i.e., skylight, the use of the eye, the extremely small size of stellar images, and the presence or absence of one form of red-green defective color vision. The approach here is to break the problem down into parts. (i) We limit the use of the eye in variable star observations to one of two ways (either "fixation accurate" or "fixation moderately averted," explained below). (ii) For each of these two ways of observing stars we consider the relevant spectral sensitivity functions in the literature, and how these depend on viewing conditions, and thus arrive at the spectral function that applies to the task of detecting a very dim star (i.e., a star at the instrumental limit). (iii) We then consider the additional factors that affect magnitude estimates of brighter stars that are well above the visual threshold for detection. (iv) Finally we compare our candidate spectral functions for the two ways of using the eye to photoelectric V.

As this process might seem arduous, it is helpful to glimpse the main results at this point. Figure 1 and its legend show candidate human spectral sensitivity functions (*I*, *I'*, and *II*) for detection, with relative sensitivity in ordinary astronomical magnitude units as ordinate and wavelength in nanometers as abscissa (see caption). The continuous curve is the photoelectric sensitivity PEP(V). This is markedly less sensitive than all the human functions at short wavelengths, $\lambda<530$ nm, but is otherwise bracketed by them. Table 1 relates the spectral functions of Figure 1 to the two ways of looking at different stellar patterns. The major conclusion of this review is that *cone vision* (see next section) is involved, if not dominant, in all magnitude estimates, whatever the conditions. However, detection at the instrumental limit is mainly, if not entirely, by the retinal *rod* photoreceptors, whatever the color of the star.

2. Accurate fixation and foveal cone vision

This and the next two sections review relevant vision research and terminology. The *photopic relative luminous efficiency function* V_λ CIE 1924 (*1* in Figure 1) is largely determined by the properties of the pure population of *cone photoreceptors* found at the center of the retinal region of most acute vision, called the *fovea*. Photopic means daylight, and discussions of this function typically stress daylight viewing rather than nocturnal. But V_λ CIE 1924 also describes the spectral sensitivity expected for a young night-adapted variable star observer who directly looks at, "*fixates*" or "*foveates*," a star. This statement allows for

- retinal image of a star being very much smaller than the test targets used for deriving the CIE standards,
- the eye being in either in a dark- or a daylight-adapted state,
- the absence of shortwave cones in the foveal center,
- two fairly typical observing tasks (detection of a dim single 2–3 arcmin target, and suprathreshold brightness matching of one small clearly visible target to a neighbor of another wavelength at 20 arcmin separation).

(See Sperling and Hsia 1957; Ikeda *et al.* 1982.) Some studies of small targets do show slightly more sensitivity than CIE 1924 in the blue (conforming better to Judd's correction, see Ikeda *et al.*) but only by about 0.5 magnitude. So if we compare PEP(V) to CIE 1924, as in Figure 1, it is clear that the major difference is that PEP(V) is relatively *far less* sensitive in the blue.

Older observers are expected to be markedly less sensitive than CIE 1924 in the blue, and to provide a somewhat better approximation to PEP(V), because of often dense progressive accumulations of yellow (= blue-absorbing) screening pigment in the crystalline lenses of their eyes with increasing age. Despite scanty data there is no compelling reason to suppose that sensitivity in the elderly ever approximates PEP(V). In any case it would then be very tempting to fixate slightly away from the star (averted, eccentric, or *parafoveal* fixation) because the rods in the retina surrounding the fovea would offer so much more sensitivity in the blue—which would change the spectral function away from PEP(V). A few males cannot see as far into the red as CIE 1924 suggests, but this special form of common red-green defective color vision affects only about 1.3% of males, who are called *protanopes* (Le Grand 1957). This is discussed in Section 5.5.

The first major conclusion, then, is that the foveal function CIE 1924 can be applied with confidence to the cases where the comparison and variable star are sufficiently bright to stimulate the cones, are both within the pure cone fovea (i.e., are separated by less than 1° of angular separation at the eye, after any magnification), and are simultaneously fixated and compared; or else are more widely separated but are successively compared by eye movements that accurately bring the retinal fovea to each star in turn. Table 1A summarizes this. Foveal cone vision is an important case for night vision because studies show a strong tendency for humans to directly fixate objects, even for nocturnal conditions and targets that are close to the foveal threshold (e.g., Steinman and Cunitz 1968; Kalesnykas and Hallett 1994).

The familiar advice, that variables should be 2–4 magnitudes above the instrumental

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Table 1. Factors affecting human spectral sensitivity to stellar images.

A) FIXATION ACCURATE:

Stellar pattern	*Relative magnitude*[1]	*Sky*	*Fixation*	*Observer's Task*	*Spectrum*[2]
Close	Bright	Dark	Accurate	Simultaneous comparison	*I*
pair[3]	Dim/Bright	Bright[4]	Accurate	Simultaneous comparison	*I*
Spaced	Bright	Dark	Accurate	Successive comparison[5]	*I*
pair	Dim/Bright	Bright	Accurate	Successive comparison	*I*
Single	Cone limit	Dark	Accurate	Detection only	*I*
star		Bright	Accurate	Detection only	*I*

B) FIXATION MODERATELY AVERTED:

Stellar pattern	*Relative magnitude*[1]	*Sky*	*Fixation*	*Observer's Task*	*Spectrum*[2]
Close	Dim	Dark	Averted[6]	Simultaneous comparison	*II*
pair	Bright[7]	Dark	Averted	Simultaneous comparison	[8] *II'-I*
	Dim/Bright	Bright[4]	Averted	Simultaneous comparison	*II'-I'*
Spaced	Dim	Dark	Midway[9]	Simultaneous comparison	*II*
pair	Bright[7]	Dark	Midway	Simultaneous comparison	*II'-I'*
	Dim/Bright	Bright[4]	Midway	Simultaneous comparison	*II'-I'*
Single star	Rod limit	Dark	Averted	Detection only	*II*

NOTES

1 Stellar brightness = relative to the sky background.
2 Spectral sensitivity for detection in a clear moonless sky (Figure1). Text and Note 8 refer to modifications of these spectral functions.
3 Close = interstellar separation of <1° at the eye, allowing simultaneous fixation and comparison of the brightness of the stellar pair.
4 When light-adapted to bright twilight, the visible brightness of the stellar pattern and the use of the eye scarcely matter as cones effectively dominate.
5 Successive = variable and comparison star are each foveated in turn.
6 Averted = aversion of eye by about 3–8°.
7 Foveation is more likely than averted vision when stars are above the cone threshold, in the Mayall-Levy range.
8 *II'* = a mixed rod-cone function with less rod input than spectrum *II* of Figures 1 and 2, closer to the pure cone function CIE 1964 (*I'* in Figures 1 and 2).
9 About 10° stellar separation with fixation on the imaginary center point of the pair.

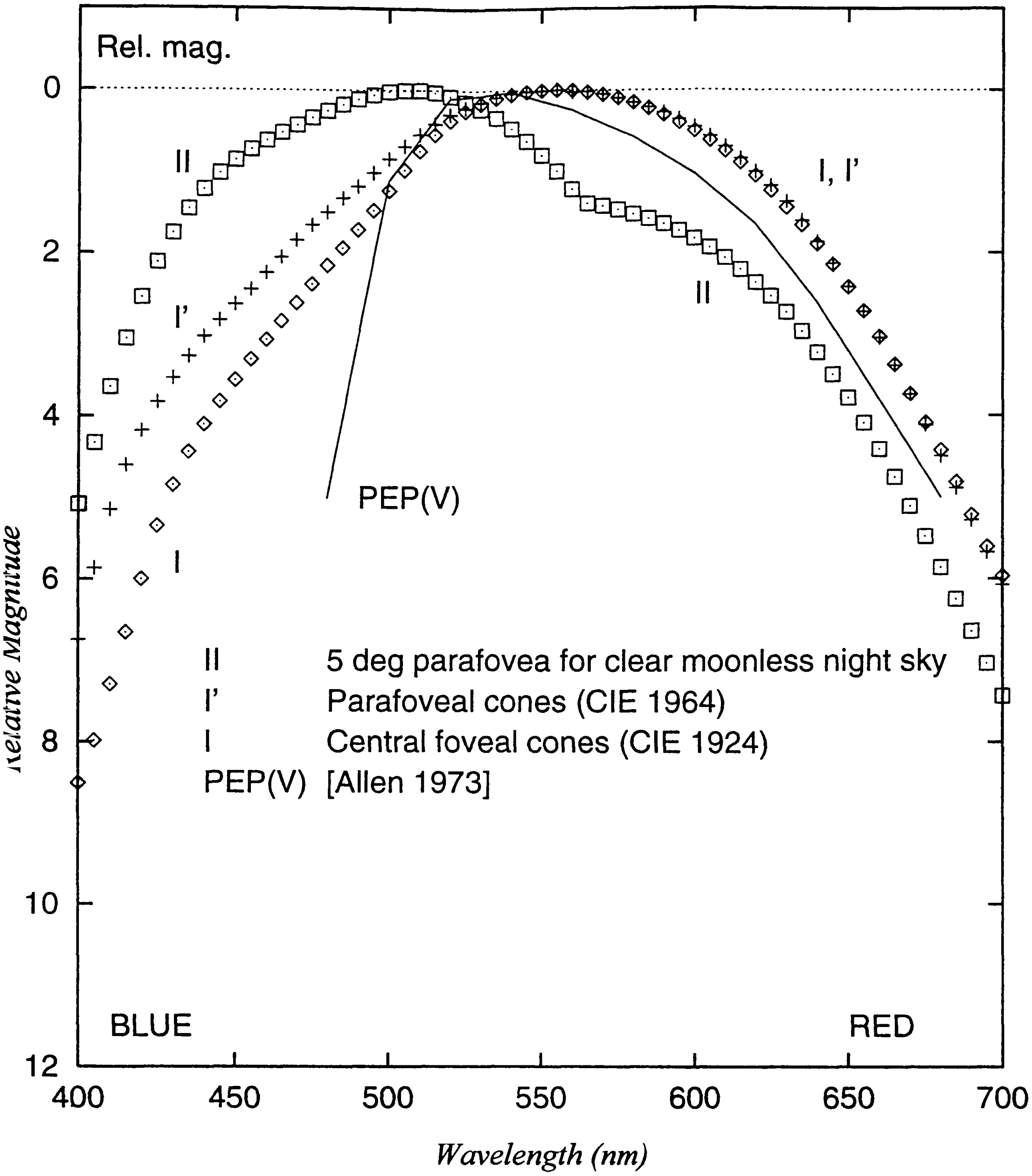

Figure 1. Candidate spectral sensitivity functions for detection at the instrumental limit, plotted as relative magnitude (0.4 base 10 log units) versus wavelength in nanometers. The original CIE (International Commission on Illuminations) functions are specified at each wavelength as power per unit wavelength interval. Curves are normalized to peak at 0 magnitude, but there is little change if normalized, e.g., for equal photon catch from an equal energy spectrum. Curves *I* and *I'* are CIE functions. Curve *II* is the envelope of independent rod and cone functions, as explained in the text and Figure 2 (*r* and *I'*). Small corrections to the visual data for aluminium reflectance are omitted.

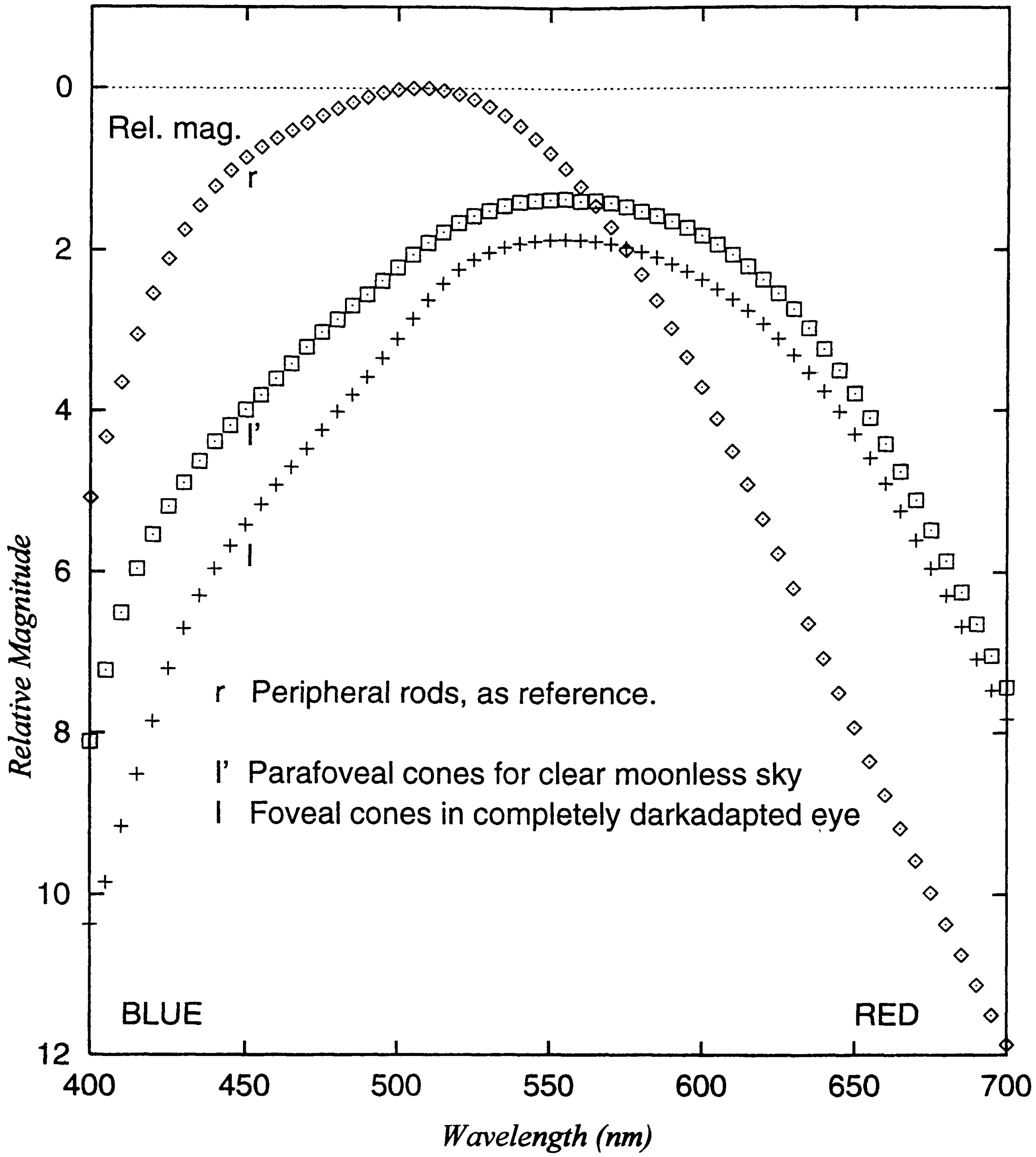

Figure 2. The sensitivities of the cone mechanisms relative to the rods. Axes as in Figure 1, with the rod peak fixed at 0 magnitude. Changing the viewing conditions primarily changes the vertical positions of the functions shown. Adaptation to the night sky depresses the absolute sensitivity of the rods but does not affect the cones, though these change in this plot because sensitivity is expressed relative to the rods. The foveal cone mechanism is shown positioned relative to the rods of the completely dark-adapted eye; for clear-moonless-sky-adapted rods, it would be slightly above the parafoveal function in this plot. Similarly, the parafoveal cone sensitivities for the completely dark-adapted eye, or for very eccentric viewing where cone input is less, would lie slightly lower than shown. Both cone curves will ride entirely above the rod curve when light adaptation sufficiently depresses rod sensitivity.

limit (Mayall 1970; Levy 1989), translates *for direct fixation* to stimulating one's cones adequately but not excessively.

Although this largely concludes the discussion of foveal vision, brevity should not be confused with lack of importance. The following discussions of averted vision are lengthier because there are many more factors. However, the conclusion is very similar, i.e., the cones make an important if not major contribution to magnitude estimates with moderately averted (parafoveal) vision. Numbered sections help cross-reference.

3. Averted vision and the peripheral cones

The spectral function $\bar{y}_{10,\lambda}$ CIE 1964 (*I'* in Figure 1) represents the parafoveal cones (those that lie in the retina surrounding the fovea) and is almost identical at the longer wavelengths to the foveal function *I*. In the blue it shows higher sensitivity because of reductions in the amount of yellow foveal or "macular" screening pigment and increases in the number of shortwave cones. This was because the test target was 10° wide, and subjects were asked to base their settings on the outer parts of the target that were imaged on the parafoveal retina where there is much less yellow pigment. CIE 1964 is a good approximation for moderately averted viewing of sufficiently bright stars by the parafoveal cones over most if not all spectral wavelengths; it also applies reasonably to the cones in retinal regions well beyond the parafovea ("peripheral" cones). For increased blue sensitivity at large viewing eccentricities and large (ca. 1°) targets, see Stabell and Stabell (1981).

4. Averted vision and the rods

The relative luminous efficiency function for *scotopic vision*, V'_λ CIE 1951, is a specialized function describing vision with *the retinal rods alone* (Le Grand 1951; Wyszecki and Stiles 1967), i.e., vision in some specific nocturnal situations where no colors are seen, only a scotopic or achromatic whitish sensation (OSA Committee on Colorimetry 1953). Equating scotopic with "night vision" (which can involve both rods and cones) is erroneous because the term scotopic is much more restrictive, applying to the rods alone. The full function is shown in Figure 2 as *r*. Only the shortwave part is shown in the mixed rod and cone curve *II* in Figure 1.

Rods are relatively red blind, sensitivity falling as much as 6 magnitudes below PEP(V) at long wavelengths. Pure rod vision generally requires fairly strongly averted viewing (> 8°) of large targets (e.g., >1°). Pure rod vision can be largely dismissed for magnitude estimates of long period variables because

- the foveal cones are never excluded by dark-adaptation, and fixating or "foveating" eye movements are natural,
- the peripheral cones also respond to sufficiently bright targets,
- for many, though not all, viewing conditions both foveal and peripheral cones are more longwave-sensitive than the rods,
- the small size of stellar images matches them best to the small spatial mechanisms of the cones (Hallett 1963), facilitating cone vision.

Pure, or almost pure, rod vision does effectively apply, however, to detecting a star at the instrumental limit in a dark sky (e.g., nova hunting), whatever the star color (see Section 5.3). When the sky brightens, the sensitivity of the rods decreases, which increases the relative sensitivity of the cones.

5. Averted vision and variable stars

The elegant experiments of Flamant and Stiles (1948) tell us that spectral sensitivity at the instrumental limit, for adaptation to a completely dark background and moderately averted gaze (5° angular distance from the center of the fovea, i.e., parafoveal retina), is the upper envelope of essentially *independent* rod and cone sensitivity functions. Their data were for a large 1° target but are otherwise generally comparable to Figure 2, where the curves slide independently along the magnitude axis with changes in viewing conditions. Our aim is to derive a mixed rod and cone function for the instrumental limit that will allow us to consider cases where eye movements fall 5° short of the stars being compared, e.g, an observer who looks away by 5° from comparison and variable stars that are very close to each other, or who simultaneously compares variable and comparison stars that are 10° apart at the eye, while fixating an imaginary point midway between them. (See Table 1B.)

Section 5.1.

In Figure 2, the maximum sensitivity of the rods has been set to 0 magnitude, with the foveal cone mechanism 3.1 magnitudes relatively more sensitive than the rods at $\lambda = 635$nm. The reasoning here is: (a) the absolute rod threshold for detecting a small target of 2–20 arcmin has been established for both peripheral and parafoveal vision as being about 100 (to 140) photons at 510 nm (e.g., Hallett 1987; Cabello and Stiles 1950) or 56000 photons at 635nm, using rod vision CIE 1951 and allowing for the change in photon energy with wavelength; (b) the foveal threshold for detecting a 1-arcmin target converts to 3210 photons at 635nm, using cone vision CIE 1924 (Marriott 1963); (c) the relative magnitude corresponding to 56000/3210 is 3.1 magnitudes.

The difference in the peak sensitivities of the foveal cones and peripheral rods is appreciable but not huge—1.9 magnitudes, even for complete dark adaptation. Recall that Mayall and Levy recommend that stars for magnitude estimates be 2–4 magnitudes above the instrumental limit—perhaps cones are relevant even when vision is averted?

Section 5.2.

The rationale for the placement of the parafoveal cone function in Figure 2 is similar to 5.1, except that the advantage of the cones at 635 nm is now set to 3.7 magnitudes because of two additional factors: (i) The parafoveal cones are an additional 0.6 magnitude less sensitive in the red than the foveal (Pirenne 1944). (ii) A clear night sky is expected to depress the absolute sensitivity of the rods by 1.2 magnitudes, i.e., to increase cone sensitivity relative to the rods by this amount in Figure 2. Thus 3.1 - 0.6 + 1.2 = 3.7 magnitudes. The basis for factor (ii) above is an energy integral calculated for the photon density spectrum of the zenith at Kitt Peak (Broadfoot and Kendall 1968, recently endorsed by Leinert *et al.* 1998), and converted to photometric units in the usual way (e.g., Wyszecki and Stiles 1967). The value of -3.57 log cd/m^2 (-3.33 log scotopic candela/m^2) is dominated by the continuous skyglow, being insensitive to the use of the weaker versus the stronger recommended corrections to the OI and Hα lines. As a quick check, the luminance of the clear night sky zenith in World War II London, UK, for a postulated color temperature of 3500K (Pirenne *et al.* 1957), is almost identical. For a 7-mm pupil, the above values convert to retinal illuminances of -2.07 log Td (-1.81 log scotopic Troland), just brighter than the darklight value for the rods, telling us that the skyglow has a small effect on rod vision. Also, skyglow is too dim to have an effect on the cones if blue σ Orionis or red ϕ^1 Aurigae are the targets (see Section 5.3). The parafoveal rod threshold follows a 0.55 power law with a dark light of -2.66 log sc Td (Barlow 1957; Hallett 1991), so the absolute increase in the threshold of the rods due to skyglow is the magnitude corresponding to 0.55x(2.66-1.81) log, i.e., 1.2 magnitudes, the value above.

The resulting envelope of the clear-sky-adapted rod and parafoveal cone sensitivities expresses spectral sensitivity at the instrumental limit, and was given as curve *II* in Figure 1. [As a final check on the values used, I considered what is known about the shapes and and relative positions of the area-intensity functions for rod and cone vision

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at 5° parafoveal viewing (Graham and Bartlett 1939; Hallett 1963; Scholtes and Bouman 1977; Flamant and Stiles 1948), and obtained a fully dark-adapted advantage for the parafoveal cones of about 2.8 magnitudes at $\lambda = 635$ nm, which is consistent with the value of 2.5 magnitudes from Sections 5.1 and 5.2 (i) above, where 3.1 - 0.6 = 2.5 magnitudes.]

These estimates of spectral sensitivity in the red are conservative; cone sensitivity is likely higher in practice. Neglected is the slight broadening of the cone detection spectrum for suprathreshold brightness matching (e.g., Wagner and Boynton 1972; Ikeda *et al.* 1982). Sky light is often brighter than the clear moonless sky assumed here. Also, the longwave cone shoulder is higher at viewing eccentricities smaller than 5° (Metz and Brown 1970).

Note that the rods are never more than 3.2 magnitudes more sensitive than the parafoveal cones at any wavelength (this value at 435 nm), even in a dark sky. Thus we can immediately conclude (without resort to stellar spectra) that using the upper half of the Mayall-Levy range, and estimating magnitudes for stars 3–4 magnitudes above the instrumental limit, means using at least some cone vision, even though the eye is moderately averted and dark-sky adapted.

Section 5.3.

A red star color by itself does not "exclude" the rods, because of their extremely high sensitivity to traces of short-wavelength energy in the star's spectrum (Figure 2, rod curve). As an illustration, integrating the product of stellar energy density (Kharitonov *et al.* 1988) with either the entire rod or entire parafoveal cone function positioned as in Figure 2, gives for the very blue star σ Orionis (B-V -0.24) a 1.5-magnitude lower detection threshold for the rods. For the very red ϕ^1 Aurigae (B-V 1.97), the rod advantage is less, 0.7 magnitude, but still present.

Photon calculations give very similar results (within 0.1–0.2 magnitude). So, given averted vision and a dark sky, almost any stellar type is likely at the threshold of the rods, and below the threshold of the cones, when at the instrumental limit. We might almost characterize such detection as pure rod vision, except that there is always some chance of a cone contribution when the cone threshold is nearly as low as the rod, as when the star is very red. We can also conclude from the relatively small size of the rod advantage (0.7–1.5 magnitudes) that the whole Mayall-Levy range (2–4 magnitudes above the instrumental limit) guarantees cone involvement in magnitude estimates, even for blue stars, averted vision, and a dark sky.

Section 5.4.

Perhaps the rods continue to contribute to magnitude estimates above the cone threshold? One answer here is based on the inverse relation between reaction times and perceived target brightness. Experiments with mostly yellow or blue-green small targets (10 arcmin) and complete dark adaptation show that the contribution of the rods to reaction times can be neglected for targets that are more than 2.5 magnitudes brighter than the cone threshold (Doma and Hallett 1988). So with fair confidence, we can now use the values from Section 5.3 to say that cones actually dominate for stars in the upper part of the Mayall-Levy range, even when vision is averted. As a corollary, we must restrict calculations with the mixed rod and cone function *II* to dim stars, appreciably dimmer than 0.7 + 2.5 = 3.2 magnitudes (red star) or 1.5 + 2.5= 4.0 magnitudes (blue star) above the instrumental limit for averted vision and dark skies.

Section 5.5.

The values in Section 5.3 above must be modified for either protanopia or for normal eccentric viewing that is much larger than 5°, because of reduced cone sensitivity in the red in these cases. For protanopes the threshold advantage of rods over cones in the calculation in Section 5.3 changes from 1.5 to 1.4 magnitudes for the blue star and from 0.7 to 1.0 magnitude for the red—not large effects. [For the estimated parafoveal cone sensitivity of the protanope I used the "theoretical" protanope efficiencies and macular pigment corrections tabulated in Wyszecki and Stiles (1967), equating the protanopic peak sensitivity at 540 nm to the 540 nm value given for normal parafoveal cones and skyglow in Figure 2.]

Section 5.6.

A sufficient sky brightening will eliminate the advantage of the rods at the instrumental limit in Section 5.3, increasing the natural tendency to foveate. For calculations the assumptions are that the night sky does not affect the cones and the rod energy threshold follows established rules. The required sky brightening that equalizes the rod and cone energy thresholds is 2.9 magnitudes for the blue star and 1.4 magnitudes for the red. If values for the illuminance at the ground are a rough guide (RCA 1968) then a 1.4-magnitude sky brightening is considerably below either the lower limit of nautical twilight or a quarter moon. This is consistent with experience that modest skylight complicates the estimation of red stars (see Section 7.2). However, very bright backgrounds are required to *completely* saturate the rods (Aguilar and Stiles 1954).

Section 5.7.

To summarize, at the instrumental limit for moderately averted vision and dark skies, the rods detect the presence or absence of a star (as when searching for quiescent novae or deeply eclipsed binaries). We can only ignore the rod contribution to magnitude estimates with averted vision when stars or sky are bright. However, this should not be a problem if foveal fixation is the dominant mode of viewing once a star is near or above the cone threshold, i.e., in the Mayall-Levy range.

6. A recommended check for any appreciable rod contribution to magnitude estimates

Discussants at the 1997 AAVSO Annual Meeting appreciated that light adaptation may alter variable star estimates if the rods normally play a role. However, the experiment must be specially executed if false conclusions are to be avoided, and proper medical or scientific supervision is mandatory! A typical bleaching apparatus would be a 6V 36W heat-shielded headlamp bulb, seen in a Maxwellian view at 2854K, 130,000 Td, and at least 15° diameter, and fixated so as to bleach an extended region of retina (e.g., to ±10°). *If* the pupil of the eye can be safely dilated by means of a short-lived topical drug, and this *very* bright surface safely viewed for 4 minutes, then it is possible to bleach a substantial portion of the rod and cone photopigments, and all vision is temporarily lost in the bleached area. It is known that in this case there is a period between 5 and 13 minutes later (the "cone plateau of dark-adaptation," the timing of which varies slightly with the observer and conditions) when cone vision is physiologically isolated because cone dark-adaptation is complete but the rods are not yet active (e.g., Wald 1945; Rushton 1961; Doma and Hallett 1988; Kalesnykas and Hallett 1994). Magnitude estimates should be made only during the cone plateau, and the whole process repeated until sufficient data are accumulated to decide whether performance is comparable to that in the normal dark-adapted state or not. If cone vision dominates, then correct estimates should be possible between 5 and 13 minutes; if the rod contribution is important, longer dark-adaptation will be required. Using a bleaching adaptation is critical. Rod dark-adaptation from weaker adaptations such as interior room lighting is quite swift (Haig 1941), and no conclusion about a rod dependency, or lack of it, can then be drawn.

7. Some earlier viewpoints

Given the present perspective, it is now possible to appraise earlier approaches of astronomers to the spectral sensitivity issue.

Section 7.1.

Landis (1977) established the important point that the difference in magnitude, *visual minus PEP(V)*, is positive for red stars and weakly negative for blue stars. This finding does not prove that magnitude estimates depend on red-insensitive rods. A counter argument is that PEP(V) usually provides the magnitudes recommended for comparison stars. Blue blindness of PEP(V) relative to any plausible human function must lead to excessively large magnitudes being recommended by the AAVSO Chart Committee for the blue or white comparison stars [negative or near zero PEP(B-V)] against which red variables [positive PEP(B-V)] are visually estimated. As a result, observers transfer to red stars numbers that are large compared to those that would be directly measured photoelectrically. One practical approach would be to use Howarth's (1979) regression equation to predict the visual magnitude of comparison stars from a linear addition of PEP(V) and PEP(B-V). This prediction can be rewritten as adding a small part of a star's B (shortwave) magnitude to PEP(V), which amounts to compensating for the PEP(V) blue insensitivity. Another approach is suggested in Section 7.2.

Section 7.2.

Mayall (1970) and Levy (1989) asserted that the troublesome brightening of red stars, particularly when viewed against moon light or twilight, is the "Purkinje effect" (which means the transition between rod and cone vision). Given Section 5.6 above, this is reasonable. Also, the rods tend to desaturate perceived colors, so the declining rod contribution must strengthen color perception. However, the troublesome brightening is also expected if vision is purely foveal; although the small size of stellar images leads to a generally weak appreciation of their color (perhaps because of the low spatial density of shortwave cones), it is quite possible that the larger part of the spurious brightening is successive color contrast between the red variable and the blue or white comparison stars, supplemented by simultaneous color contrast between the variable and the sky. For a brief technical review of the (often undesirable) way in which color mechanisms affect perceived foveal brightness by supplementing the response of the V_λ CIE 1924 luminance mechanism see Ikeda *et al.* (1982). Although flicker, "a quick look," or averted vision will reduce color sensation, and permit crude magnitude estimates, the optimal solution for the red variable problem, *whatever its cause*, is to use physically comparable PEP(V)-calibrated red stars as comparison stars for red variables.

Section 7.3.

Stanton (1978) undertook special night vision photometry using a spectral sensitivity similar to the rods, but with an increase in the red to allow for light-adaptation by skylight, citing Teele (1965). One should not argue that Stanton assumed too large a red sensitivity, given Crawford's (1949) criticism of Teele's sources of data, because Teele claimed his approach was vindicated by experience. My concern is the opposite, that Stanton's red sensitivity was too low because Teele's sources used very large 2–22° diameter test targets that are better matched to the properties of the red-insensitive rods than to the cones. Stanton's analysis is still useful, as with hindsight it should approximate viewing when the sky is dark and the eyes are averted considerably, by more than 5°, from the target stars.

8. Conclusions and recommendations

(i) All candidate human spectral sensitivity functions are much more blue sensitive than PEP(V). The one closest to PEP(V) is the photopic relative luminous efficiency function V_λ CIE 1924 (curve *I* in Figure 1), which applies when fixation is accurate.

(ii) When trying to transform visual and photoelectric data to a common standard, the best candidate function is V_λ CIE 1924. This applies to stars separated by less than 1° at the eye after any magnification, that are simultaneously fixated and compared, or are widely separated but are successively compared by eye movements that accurately fixate each star in turn.

(iii) Function *II* in Figure 1 and Stanton's (1978) analysis apply to modestly and strongly averted vision, respectively. These are conservative estimates of cone function, as increasing skylight will relatively increase the cone contributions by depressing the rods.

(iv) Pure or almost pure rod vision is limited in variable star observing to detecting stars at the instrumental limit in a dark sky (e.g., nova hunting).

(v) The studies of Landis (1977), Steffey (1978), Howarth (1979), and Stanton (1981) are consistent with the present analysis, and suggest a possible method for improving the magnitudes given for visual observing. Ideally, however, red variables are best compared to other (calibrated) red stars.

(vi) The present claim, that the role of the rods in magnitude estimates is at best minor, can be checked experimentally.

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