Is the fovea vision only photopic?

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Abstract
In the mesopic range, all kinds of the photoreceptors contribute to the vision sense. Rods have zero density on the fovea. Therefore, it is logical to assume that for fovea view the human vision is photopic. On the other hand, it is known that S cones do not contribute to vision at the mesopic levels. Furthermore, the different density for each type of cones in correlation with their different thresholds implies that this assumption is under question. The aim of this paper is to give an answer to the question whether it is meaningful to talk about mesopic vision when the vision is fovea. In this case, mesopic vision is not due to the rods' contribution to the vision, but to the differentiation of the cone types' contribution. For this purpose, we have executed an experiment based on visual acuity for various lamps and for several luminance levels.

Keywords: Mesopic vision, Fovea view, Visual acuity.

1. Physiology

The human eye is sensitive to visible radiation due to two kinds of photoreceptors: cones, and rods. There are three types of cones (L, M, S cones) and only one type of rods [1].

The spatial distribution of photoreceptors on the retina is different for each kind [2]. The cones exhibit their maximum density on fovea within a 4^o angular aperture, while on greater eccentricity, their density reduces dramatically and eventually it is considered constant. On the other hand, rods have zero density on the fovea, which is very important. Their maximum density occurs on 20^o eccentricity. On higher eccentricity, their density decreases smoothly. Rods' density is always, with the exemption of the fovea area, much higher than that of the cones.

The relative absorption versus wavelength is different for each type of cones. This is plotted in Fig.1 [3-6].

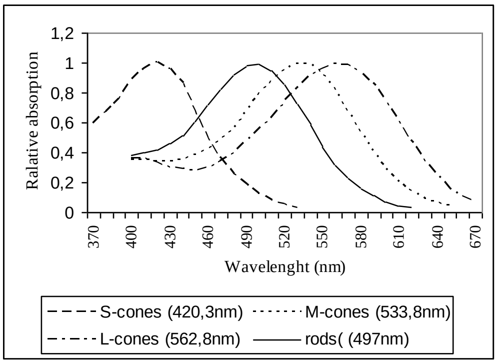

Figure 1. Relative spectral absorptances of human cone pigments measured by microspectrophotometry by Bowmaker and Dartnall (1980).

The activation thresholds of cones are much higher from these of rods. The saturation limits are different too. Rods are saturated completely for luminance values above $10cd/m^2$, while cones are not saturated practically.

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2. Vision photometry

The visual sense is caused by the combined neural signals, which are provoked by the photoreceptors existing on the retina. So light is any radiation capable of causing a visual sensation directly. According to the CIE [7] "Light is radiant power weighted according to the spectral sensitivity of the human eye". Therefore, it is of great importance to define the human eye's spectral sensitivity curve versus wavelength, because this will permit us to measure light.

The influence of the wavelength of the radiation, on the efficacies of the photoreceptors, makes the human eye's spectral sensitivity curve wavelength dependent. The different values of the activation threshold and the saturation limit for each kind of the photoreceptors, along with the adaptation level of the human eye, make the human eye's spectral sensitivity curve luminance dependent. Therefore, the visible region is divided in three sub-regions, according to the luminance levels [8]:

a) Photopic region: $L > 10cd/m^2$, where vision is mainly due to cones activation.

b) Scotopic region: $L < 10^{-3}cd/m^2$, where vision is only due to rods activation, and

c) Mesopic region: $10^{-3}cd/m^2 < L < 10cd/m^2$, which is a transitory region from photopic to scotopic vision. In this region, all kinds of the photoreceptors contribute to the vision sense.

Photopic and scotopic vision share the same feature: the stability of spectral luminous efficiency functions [9, 10]. In photopic vision, as the luminance varies (being always greater than $10cd/m^2$), spectral luminous efficiency function is stable and is represented by the V(λ) function (Fig.2). The same holds for the scotopic vision. As the luminance varies (being always smaller than $10^{-3}cd/m^2$) this function is stable and is represented by the V´(λ) function (Fig.2).

This is not the case in mesopic region, where as the luminance varies (being always between $10^{-3}cd/m^2$ and $10cd/m^2$), spectral luminous efficiency function changes too, between V(λ) and V´(λ) function. This is the main characteristic of mesopic vision and from this stem all the difficulties to investigate it.

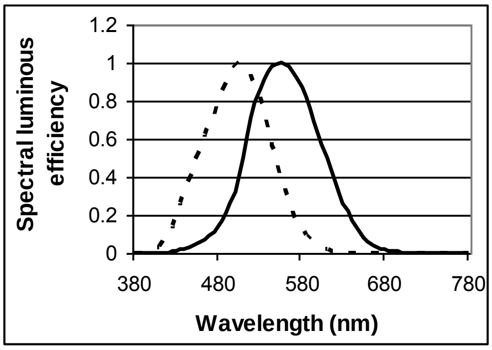

Figure 2. Spectral luminous efficiency functions V(λ) (solid line) and V´(λ) (dashed line)

3. The role of light source's spectral power distribution in the mesopic range

In the photopic or scotopic range, the spectral power distribution of the light source plays no role in the adaptation level of the human eye, given that the adaptation level of the human eye in each range is stable and is represented by the V(λ) and V´(λ) functions.

In the mesopic range, the situation is more complicated [11]. When the overall luminance starts decreasing below the photopic limit, due to Purkinje effect, the sensitivity of the eye becomes higher at radiation of short wavelength. Therefore, light sources rich in short wavelength's radiation in the mesopic range are more effective than light sources poor in short wavelength's radiation [12]. This implies that mesopic luminance depends on two factors. The first is the photopic luminance and the second is the shape of the SPD of the illuminating radiation. The recently developed models of M.Rea [13, 14] and of the MOVE project [15, 17] have recognized this. In these models, mesopic luminance is expressed in terms of photopic luminance and of the value of the ratio scotopic to photopic luminance. This ratio represents a metric of the spectral power distribution of the light source.

Therefore, we can make an alternative definition of the mesopic region. The mesopic region is the visible region in which the adaptation level of the human eye depends not only on the value of photopic luminance but also on the shape of the spectral power distribution of the illuminating source.

4. The role of human eye's physiology in the mesopic range

In the mesopic range, both cones and rods contribute to the vision sense. Therefore, mesopic vision is a characteristic of peripheral vision and central vision, when the angle of view is greater than four degrees. That is because there are no rods in the fovea. From this, could it be concluded that in central vision, when the view angle is smaller than 2 degrees, the adaptation level of the human eye is represented by the V(λ) function independently of the luminance levels?

There are some characteristic differences of the photoreceptors of the human eye, which make the answer to this question not trivial. It is known [18], that S cones differ in several ways from L and M cones. The highest density for S cones ($\approx$2000cones/mm) is found in a ring at about 0.1-0.3 mm eccentricity, which is in accord with psychophysical evidence that the maximum of blue sensitivity is at about 1 deg. In the peripheral retina (10 - 20 deg eccentricity), 7-8% of the cones may be S cones. The distribution of the S cones is irregular, whereas the L and M cones appear to be randomly distributed, with the numbers of each one differing. The ratio of the number of L cones to the number of M cones is 2:1[19].

Furthermore, the role of S cones in the mesopic range is more suspicious than the other two kinds of cones. Early investigations show that S cones do not contribute to luminance in the mesopic range [20, 21]. Recent investigations show that S cones luminance input remains silent unless the L and M cones are excited above a certain level [22]. From the above it can be concluded, that in low luminance levels, S cones function in a different way from that in the photopic region.

Therefore, mesopic vision (in the sense that all kinds of photoreceptors contribute to vision sense) is possible only in the peripheral view and in the wide-angle central view. But this does not mean that fovea view is represented by the V(λ) function, independently of the luminance levels.

5. Visual acuity in the mesopic range

In the photometry lab of the National Technical University of Athens, the visual acuity of six young persons was measured in mesopic conditions. The aim of the experiment was to investigate whether the spectral power distribution of the illuminating source affects the visual acuity of the observer.

5.1 Experimental apparatus

Fig. 3 represents the experimental apparatus. As luminaires were used cubes, whose internal surface was painted with a solution of $BaSO_4$. The light exits the cube through a hole in one edge and goes to the target through a curved tube. The internal surface of the tube is also painted with $BaSO_4$. A shutter controls the output of the light. This shutter can be rotated with the help of a stepping motor. The stepping motor was electronically controlled. This construction permits the formation of a background with very good uniformity. In addition, since the light level is controlled without the usage of any kind of filters, the SPD of the illuminating radiation remains exactly the same at any lighting level.

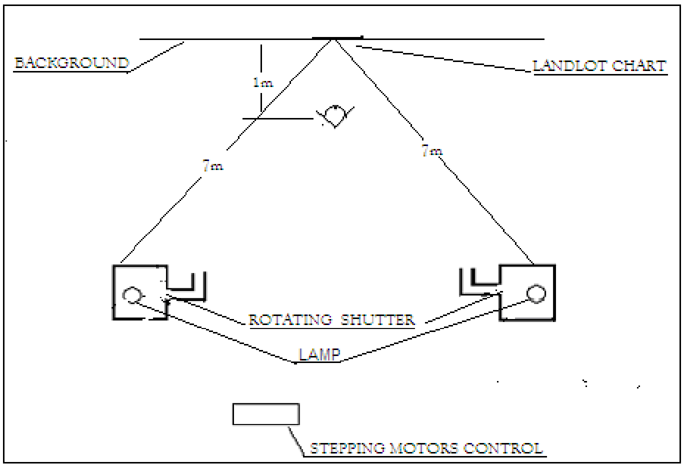

Figure 3. Experimental apparatus

Landlot rings visual acuity charts were used. Charts contain 24 rows of five Landlot rings each. The gap orientation is one of the eight main directions (0, 45, 90, 135, 180, 225, 270, 315 degrees). The

reciprocal of the gap size in minutes of arc of the minimal resolvable Landlot ring, represents the visual acuity. In the used charts, it varies from 1 to 0.035.
The distance between the observer and the chart was one meter. In this distance, each Landlot ring is viewed centrally, with an angle of view about two degrees at most.

Four light sources were used: mercury vapor 400W, metal halide 400W, incandescent 300W and fluorescent. In fig. 4 the spectral power distributions of these light sources are plotted.

The scotopic and the photopic luminance were measured at the exit point of the light, with the use of an IL-1700 luxometer recently calibrated. This was done in order to determine the ratio S/P for each light source. This is because the ratio S/P can serve as a metric of the shape of the spectral power distribution of the light source.

5.2 Procedure

The luminances of the background and of the target were measured with luminance meter MINOLTA LS100, in photopic units. The variation of the luminance of the background was 7% at most and of the target 1% at most, too. Each person was dark adapted for 30 minutes before the visual task got started.

The measurement of visual acuity was made at seven light levels of low mesopic range, for each light source, namely at 1, 0.5, 0.1, 0.05, 0.01, and 0.005 cd/m^2.

5.3 Results

Table 1 represents the average visual acuity for the six persons, for each lighting level and for each lamp. In Fig.4, the visual acuity versus luminance for the various lamps and ratios S/P is plotted. In Fig.5 the visual acuity versus the ratio S/P for the various luminance levels is plotted. In addition, in Table 2 the relative difference of visual acuity, using MH lamp as a reference lamp, is shown. In Fig.6 this relative difference of visual acuity versus luminance for the various lamps and ratios S/P is plotted.

Table 1. Average visual acuity for the six persons for each lighting level and for each lamp

Lamp type	HG400	Incandescent	Fluorescent	MH400
Ratio S/P	0.90	0.97	1.32	1.62
Luminance (cd/m^2)	Visual Acuity			
1	0.64	0.68	0.68	0.51
0.5	0.64	0.68	0.68	0.51
0.1	0.47	0.50	0.50	0.37
0.05	0.37	0.40	0.40	0.29
0.01	0.16	0.18	0.18	0.13
0.005	0.09	0.10	0.10	0.07

Table 2. Relative difference of visual acuity taking MH lamp as reference lamp

Lamp type	HG400	Incandescent	Fluorescent	MH400
Ratio S/P	0.90	0.97	1.32	1.62
Luminance (cd/m^2)	Visual Acuity			
1	126.00	134.53	134.53	100.00
0.5	126.00	134.53	134.53	100.00
0.1	125.99	135.30	135.30	100.00
0.05	127.08	136.46	136.46	100.00
0.01	123.29	135.22	139.83	100.00
0.005	123.88	134.16	139.30	100.00

6. Discussion

The first remark stemming from fig. 4, is that visual acuity, under low level illumination, depends not only on the luminance levels, but also on the spectral power distribution of the lighting source. This is as such, while the view is central with an angle of view of two degrees.

Furthermore, the figures can prove that the worst visual acuity occurs with MH, which has the best ratio S/P (1.62). It can also be seen that incandescent lamp whose ratio S/P is 0.97 has the same results with the fluorescent lamp with ratio S/P=1.32, except for the luminance levels 0.01 and 0.005 cd/m^2. It must be noticed that the difference in visual acuity under the light of a MH and HG lamp has already been mentioned in the literature [23] as being about 20% at $0.4cd/m^2$.

Therefore, it seems that in mesopic range the response of the human eye for fovea view is not represented by the V(λ) curve. Alternatively, if the definition of 2.1 is adopted, there must be mesopic spectral luminous efficiency functions for fovea view. Of course these curves are different from V(λ) not because of the rods' contribution to vision, but because the function of cones is different in the mesopic range than in the photopic one.

According to the author's opinion, these differences could be attributed to the function of S-cones. This is diminished in the mesopic range. Then the fovea vision in mesopic conditions is due to L and M cones activation [24]. This must be the reason for the bad performance of lighting sources with high ratio S/P in the mesopic range, i.e. of light sources with a spectrum rich in short wavelengths. In addition, the number of L cones is twice the number of M cones. It is known that at the red end of the visible spectrum only L cones are active. Therefore, light sources with a spectrum rich in long wavelengths have a good performance in mesopic range for fovea view.

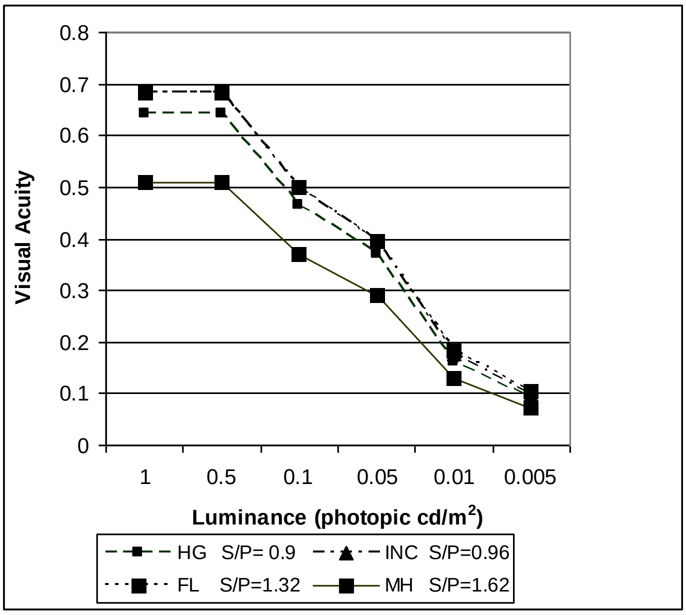

Figure 4. The visual acuity versus luminance for the various lamps and ratios S/P.

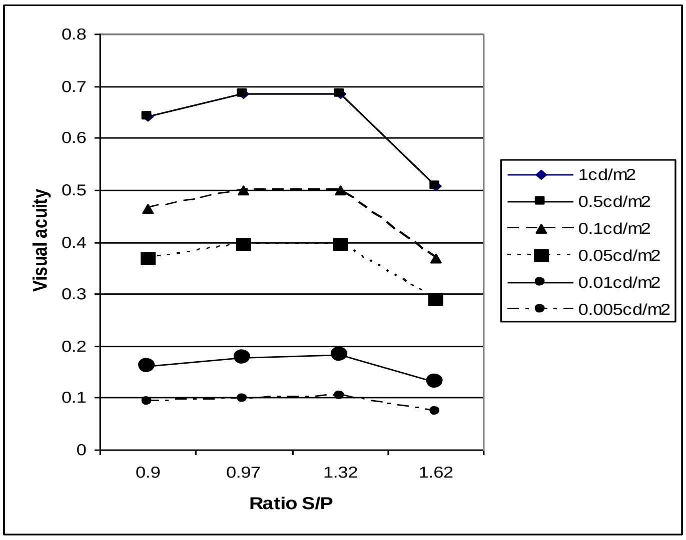

Figure 5. The visual acuity versus the ratio S/P for the various luminance levels.

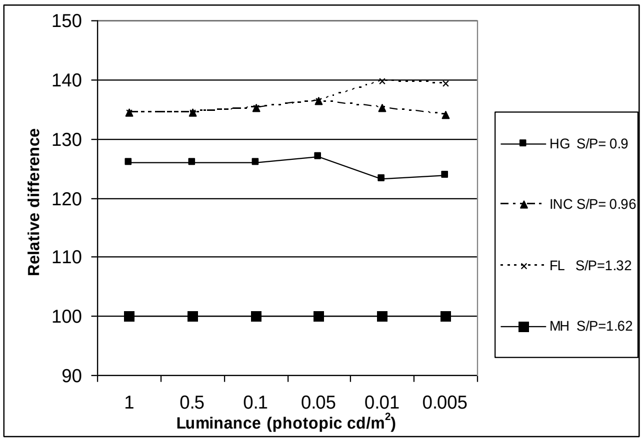

Figure 6. Relative difference of visual acuity versus luminance for the various lamps and ratios S/P.

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