

Chapter 2

Light Stimulus and Human Eye



Abstract In this Chapter, we summarize the structure of the human eye and introduce the sensitivity functions of various photoreceptors and present the visual regimes and corresponding eye sensitivity functions.

Keywords Human eye · Eye sensitivity function · Colorimetry · Photometry

In order to design high quality and highly efficient light sources, quantitative measures of light stimuli are necessary. In its broadest sense, we can classify the light stimulation in several categories that are actinometry, radiometry, photometry, and colorimetry [1]. Among these, actinometry and radiometry only consider the physical nature of light while photometry and colorimetry take the interaction of light with the human visual system into account.

Actinometry is interested in the particle nature of light and works with light quanta, i.e., photons. According to this classification, the amount of light is expressed in number of photons. Based on this, the light amount per unit time is expressed in number of photons per second, the amount of light per unit time per unit area is given in number of photons per second per meter square, etc. Radiometry, on the other hand, only deals with the wave nature of light rather than its particle behavior. It employs energy to express the amount of light, usually in the units of Joules. Then, the amount of light per unit time becomes actually the power of light and typically expressed in Watts. The irradiance, i.e., the amount of light per unit time per unit area is the power per unit area. Another important quantity in radiometry is the radiance which stands for the amount of light per unit area per unit solid angle.

Both colorimetry and photometry unify the human perception of light with its physical nature. Therefore, both of these categories are strongly related to actinometry and especially to radiometry. Photometry aims to quantify the visual effectiveness of light by considering all the elements of human visual system as a single body. It expresses the amount of light in lumens, which basically stands for the perceived optical power and all the light related quantities are based on this unit. Different than photometry, colorimetry evaluates the light stimuli based on the color perception. It focuses on quantifying the perceived color of an arbitrary light stimulus. From this perspective, it is significantly different than the others and the quantities that

it defines are closely related to photoreceptors in the human eye. Therefore, before going into the details of colorimetry, we find it beneficial to present a brief review of the properties of human eye.

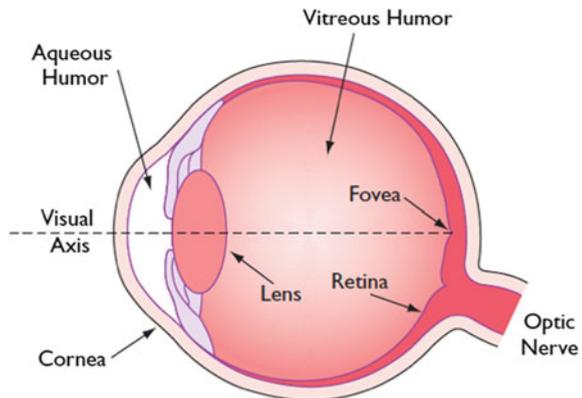
2.1 Human Eye

We perceive the world through our eyes. To understand the process of vision, knowing how we see is essential, especially for the colorimetric quantification of light. As shown in Fig. 2.1, cornea is the transparent layer of the eye where the light first enters. After passing the anterior chamber, light reaches the lens that focuses the light on the retina, which is full of visual neurons transmitting the visual information to brain [2].

The visual neurons have three main layers [3]: photoreceptors, intermediate neurons, and ganglion cells. The latter two layers mainly serve as signal carriers to brain whereas the photoreceptors are the light-sensitive cells in our eyes. They have three types, which are rods, cones, and melanopsin.

Rods and cones, which are named in accordance with their shape, are responsible for the visual perception. Rods that sense the whole visible color regime without any color differentiation are found more ubiquitously on the retina compared to cones. Due to their lack of color differentiation, these cells do not contribute to color perception; however, they are much more sensitive at low light levels. Cones, on the other hand, have three types known as S-cones, M-cones, and L-cones standing for short, medium, and long wavelength sensitive photoreceptors. In other words, S-cones are responsible for the blue color perception while the M- and L-cones perceive green-yellow and red colors (Fig. 2.2). In addition to their differences in color perception, the cones and the rods also differ in their activity levels at different light levels. Under dim lighting conditions, the rods govern the visual process while cones do not have a meaningful contribution. As a result, we cannot see the colors of

Fig. 2.1 Schematics of the human eye. Reproduced with permission from Ref. [1]. © Optical Society of America 2003



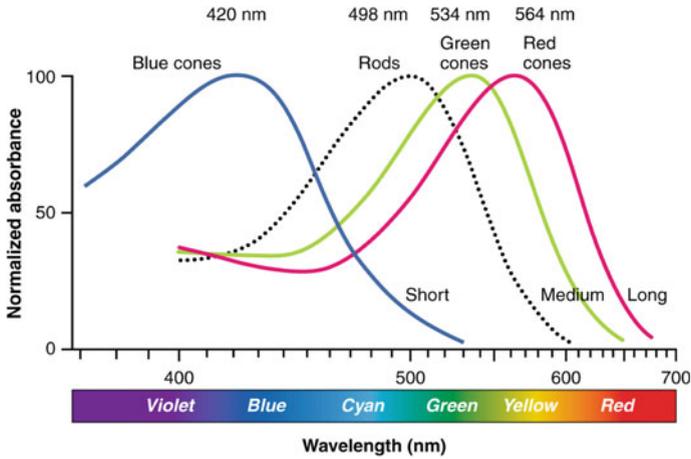


Fig. 2.2 Sensitivity spectra of rod and cone photoreceptors. Adapted from Ref. [4]

the objects in dark. On the other hand, at high ambient lighting levels the contribution of rods to the vision remains limited while we see the world via the signals received by cones. This enables us to perceive the world in color. The dark-adapted visual regime, in which the vision is governed by the rods, is called the scotopic regime. The regime of high light levels where the cones dominate the visual perception is referred to as the photopic vision regime. The scotopic regime corresponds to dark conditions while room lighting or brighter environments fall into the category of photopic regime. At mediocre lighting levels such as street lighting, both the rods and the cones contribute to the visual perception together, this level of lighting conditions is known as the mesopic regime. Our visual perception adapts to the ambient lighting levels by setting the contribution of rods and cones in vision. As a result, the average sensitivity of our eyes depends strongly on the visual regime (Fig. 2.3) that our eyes are subject to. This brings about the necessity of quantifying photometric parameters in accordance with the ambient lighting levels which we will discuss in the next sections in detail.

The third photoreceptor melanopsin, which was discovered in early 2000s, does not play a significant role in vision. Nevertheless, it has a crucial role in the regulation of the circadian cycle, i.e., the daily biological rhythm [5, 6]. Melanopsin plays this role by controlling the secretion of the melatonin hormone whose concentration is a signal to the body for the time of the day. During the daytime, melatonin secretion is suppressed, and brain interprets this decrease as the daytime signal while the brain interprets the increase of the melatonin concentration as the night time signal. Although it is currently well known that the lighting affects the secretion of melatonin contributing to the control of the biological rhythm, it is still controversial how the suppression of melatonin occurs and how lighting affects it. According to Rea, melatonin suppression is affected collectively by the rods, cones, and melanopsin [7], while Gall [8] and Enezi et al. [9] employ a simpler model and connects the melatonin

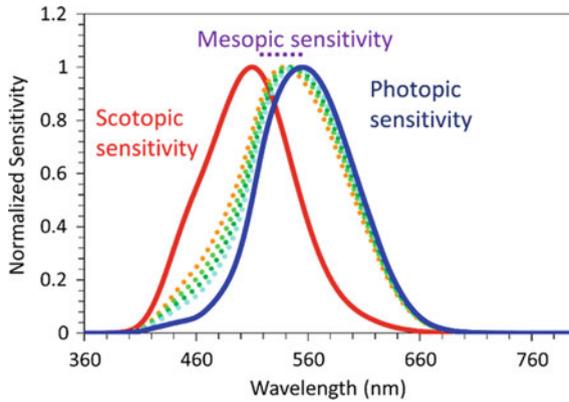


Fig. 2.3 Average eye sensitivity functions as a function of the light levels

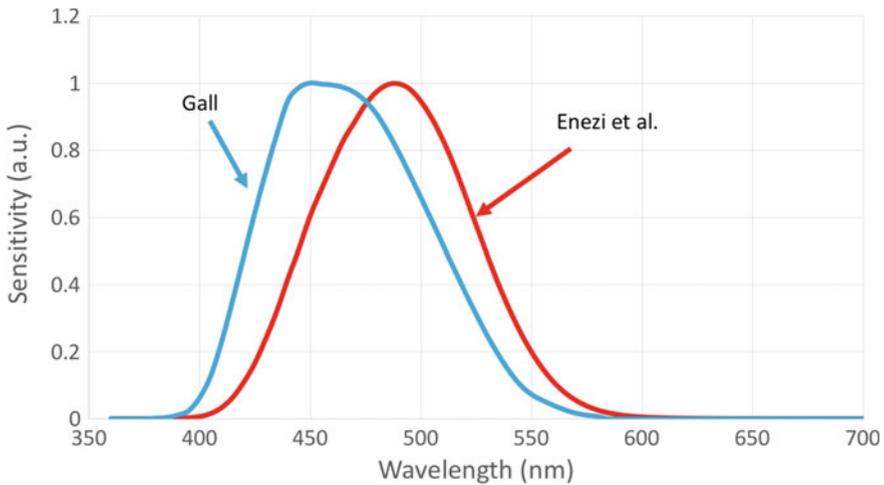


Fig. 2.4 Relative sensitivity spectra of melatonin suppression according to Gall [8] and Enezi et al. [9]

suppression only to the effect of lighting on the melanopsin since some neurons in the brain robustly react to the melanopsin activity but not to that of the cones [10]. The models developed by Gall and Enezi predict different circadian sensitivity spectra (Fig. 2.4). The striking feature of both spectra is that they cover the blue part of the visible regime. Actually, we may also qualitatively guess the contribution of the blue range by looking at the sun’s spectrum at different times of the day. Before the noon and during the afternoon hours, blue content in the sun’s spectrum is much stronger than the red-shifted spectrum in the evening times. As an adaptation to this variation, our body reacts to the blue content of the sun by reducing the melatonin concentration to send the daytime signal and vice versa. Related to this phenomenon,

the duration of exposure to natural and/or artificial light sources affects the circadian rhythm and consequently the human health. For example, insufficient exposure to bluish light in the morning shifts the circadian cycle [11] and artificial lighting with strong blue content leads to the melatonin suppression. This means that great care should be taken while designing artificial lighting and displays.

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