Research of eyesight contrast sensitivity for the work with displays

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Abstract. The article is devoted to determining the adaptation level of the visual system to illumination in condition of changing the surrounding field brightness arising from the dynamic control of artificial lighting in industrial premises, as well as when controlling the brightness of modern displays’ illumination. There is given a general idea of the visual system structure and retina properties and considered two consecutive mechanisms of adaptation to illumination. In the article an experimental calculation of determining the contrast threshold under conditions of complete adaptation is presented, the results of which allow us to conclude that there is no dependence of the color tone perception on brightness in a wide range of its measurements. The research materials can be used to create lighting control systems and select appropriate displays for operators of automated control systems in order to minimize the load on the organs of vision.

1. Introduction

The massive employment of energy-efficient light sources in rooms with display screen equipment leads to significant increase of visual fatigue of workers, which occurs due to the need for constant adaptation of eyesight to variable brightness. Evaluation of the functional capabilities of the visual system becomes an intermedium between physiology, rationing of production lighting and computer image processing methods. The development of display screen equipment is also impossible without taking into account the physiological characteristics of the visual system [1,2]. Evaluation of the characteristics of operator fatigue while working with video terminals is impossible without considering the inertial properties of vision, and the negative effect of screen flickers must be regarded in conjunction with the flicker of general lighting [3]. Studies of the visual system have come a long way - from the discovery of the first empirical laws to the construction of mathematical models to substantiate engineering solutions in the field of lighting control [4].

2. Modeling the processes of eyesight adaptation to brightness

Inasmuch as the perception of the light environment and images depends on the characteristics of the adaptation of the visual system, it is necessary to consider its structure. The visual sensory system is a set of structures and mechanisms that realize the perception of electromagnetic waves (390-760 nm), initiating flows of modally-specific stimulations that ultimately enter the projection zones of the cerebral cortex. The most studied section of the visual system is the retina, which properties determine the basic psychophysical laws [5].
The retina consists of several layers, one of which is formed by photoreceptor cells of two types: rods and cones. Cones are photosensitive cells that are part of the day vision system, which has the ability to distinguish colors. The rods are part of the twilight vision system, which is not able to distinguish colors, but has a high light sensitivity.

There are two sequential mechanisms of adaptation to illumination in the visual system. The first is a mechanism implemented by the triads “photoreceptor – horizontal cells – bipolar cell”, which adapts to the average illumination of the retina. The second mechanism consists of bipolar cells and neurons in the retina and necessary for adapting vision to scenes that have both darkened areas and areas with high illumination [6].

The interaction of photoreceptors, a system of horizontal and bipolar cells ensures the adaptation of the visual system to the average illumination of the observed scene. The value of the signal at the output of the i-th bipolar cell is proportional to the fraction with the numerator equal to the difference between the illumination of the 1st receptor $I_i$ and the average illumination on the retina $\bar{I}$, and with the denominator equal to the average illumination of the retina [7,8]. So, for example, the magnitude of the signal at the output of a bipolar cell transmitting excitation from a cone having a maximum sensitivity in the region of red radiation is measured according to the law of converting the distribution of illumination on the retina into the distribution of excitations, written in mathematical form:

$$S_{ni} = C_r \frac{I_i - \bar{I}}{\bar{I}}, \quad (1)$$

where $C_r$ – a constant coefficient matching the dimensions, its value is determined by the spectral sensitivity of the photoreceptor and the spectral composition of the radiation. Also obtained are the signal values at the outputs of bipolar cells connected to photoreceptors that have sensitivity maxima in the region of green and blue radiation [9].

Formula (1) confirms two features of converting the distribution of illumination on the retina $I_i$ into the distribution of signals at the output of bipolar cells $S_{ni}$. They are:

- an increase in the illumination of the image by a factor of n does not lead to a change in the signals $S_{ni}$, since both the numerator and the denominator in formula (1) increase by the same number of times, which ensures adaptation;
- signals $S_{ni}$ are linear functions of illumination $I_i / \bar{I}$ (figure 1).

![Figure 1](image_url)
The result takes a positive value when the light is turned on and a negative value when it is turned off, which is the basis of the on and off signals of systems that stimulate retinal neurons [10].

In order to determine the illumination on the retina $I$ we consider the ways of determining the contrast threshold under conditions of complete adaptation, setting the image of the disk stimulus consisting of two halves with brightness $L_a + \Delta L_a / 2$ and $L_a - \Delta L_a / 2$, which placed on the field with brightness $L_a$ [11]. $I$ is directly proportional to the brightness of the corresponding portion of the test image $L$:

$$ I = a_0L. \quad (2) $$

We rewrite formula (2) for the average illumination of the retina:

$$ \bar{L} = a_0 (c_1 L_a + L_s), \quad (3) $$

where $a_0$ – a constant coefficient matching dimensions, $c_i$ – a coefficient that determines the addition introduced by the brightness of the field surrounding the stimulus into the average illumination of the retina. By calculating the values of the signals at the outputs of bipolar cells, stimulated by photoreceptors having a maximum sensitivity in the region of red radiation, and taking the difference of these values according to formulas (1–3), we obtain:

$$ \Delta S_r = \frac{C_r}{(c_1 L_a + L_s)} \Delta L_a. \quad (4) $$

In (4) the factor standing at $\Delta L_a$ can be considered as the transmission coefficient necessary to establish a connection between the brightness of the stimulus elements and the signal difference $\Delta S_r$ at the outputs of the corresponding bipolar cells. Similarly can be found the values of $\Delta S_g$ and $\Delta S_b$ for bipolar cells associated with photoreceptors with sensitivity maxima in the regions of green and blue radiation. The difference in the formulas by which one can be calculated $\Delta S_g$ and $\Delta S_b$ and formula (4) is only in the proportionality coefficients $C_g$ and $C_b$[12,13].

When observing an achromatic image in the visual system, $\Delta S$ signals are generated, proportional to the sum of the signals $\Delta S_r$, $\Delta S_g$ and $\Delta S_b$.

$$ \Delta S = \Delta S_r + \Delta S_g + \Delta S_b. \quad (5) $$

Having completed the necessary transformations, we get:

$$ \Delta S = \frac{C}{(c_1 L_a + L_s)} \Delta L_a, \quad (6) $$

where

$$ \Delta C = \Delta C_r + \Delta C_g + \Delta C_b. \quad (7) $$

In order to detection the threshold stimulus, it is necessary to equate the signal difference $\Delta S$ due to the difference in brightness between its halves $\Delta L_a$, the threshold determined by the rms noise value in the visual system $\sigma$, and the angular size of the stimulus $\alpha$ and the time of its presentation $\tau$:

$$ \Delta S = D(\alpha, \tau)\sigma, \quad (8) $$

where $D(\alpha, \tau)$ — a function that takes into account the influence of $\alpha$ and $\tau$ on the threshold value due to spatial and temporal summation. Noise in the visual system, especially in the achromatic
channel, contains 2 components [14]. The first component is due to quantum fluctuations in the light flux from the stimulus, and fluctuations arising in the photoreceptor when the signal is amplified. The average square of this noise component $\sigma_f^2$ is directly proportional to the average brightness of the stimulus $L_s$:

$$\sigma_f^2 = gL_s,$$

(9)

where $g$ — a constant coefficient.

The second component of noise is caused by fluctuation processes in subsequent neurons, its average square $\sigma_n^2$ does not depend on the brightness of the stimulus. Therefore, the average square of noise in the visual system recalculated to the output of the bipolar will be equal:

$$\sigma^2 = \sigma_n^2 + \frac{C^2}{(c_1L_n + L_s)^2}gL_s,$$

(10)

By substituting in (8) the values of $\Delta S$ from (6) and $\sigma$ from (10), we solve the resulting equation relatively to $\Delta L_s / L_s$ and find that:

$$\frac{\Delta L_s}{L_s} = \delta_i(\alpha, \tau) \left(1 + \frac{c_1L_n}{L_s}\right) \left(1 + \frac{G}{(1 + c_1L_n / L_s)^2 L_s}\right)^{1/2},$$

(11)

where $\delta_i(\alpha, \tau) = D(\alpha, \tau)\sigma_n / C$. The values of $\delta_i(\alpha, \tau)$, $G$ and $c_1$ are determined from experimental data.

Formula (11) is one of the laws of adaptation, which is the dependence of the differential threshold on the average brightness of the stimulus and the brightness of the field surrounding it. The law of Weber-Fechner and fluctuation property are special cases of this law [15].

In the case when the brightness of the field surrounding the stimulus is equal to zero, and the average brightness of the stimulus is large enough to neglect the fraction under the square root due to its smallness compared to unity, (11) makes the transition to the Weber-Fechner law [16]:

$$\frac{\Delta L_s}{L_s} = \delta_i(\alpha, \tau).$$

(12)

besides, $\delta_i(\alpha, \tau)$ has the meaning of a differential threshold, which depends on the angular size $\alpha$ and the time of presentation of the $\tau$ stimulus.

In the case when the brightness of the field surrounding the stimulus is zero, and the average brightness of the stimulus is so small that the unit can be neglected by the square root due to its smallness compared to the second term, formula (11) goes over into the fluctuation law:

$$\frac{\Delta L_s}{L_s} = \delta_i(\alpha, \tau) \left(\frac{G}{L_s}\right)^{1/2}.$$

(13)

In figure 2 are given the experimental points and theoretical dependence calculated by formula (11) for the case. In the calculation it was assumed that $\delta_i(\alpha, \tau) = 0.0115$, $G = 0.46$ Cd/m², $c_1 = 0.057$.

Figure 2 shows the selected experimental points and a family of theoretical curves obtained from calculations by formula (11) for the case when the brightness of the background surrounding the stimulus is not equal to zero. The results of the experiment, the course of which is described in [17] are in excellent agreement with the experimental points in the entire measurement range. This dependence called the Weber-Fechner law and shows that a linear increase in the intensity of sensation reflects a logarithmic increase in the brightness of the stimulus.
The obtained results play the main role in the development of displays in order to demonstrate images of scenes with a large dynamic range of brightness (the ratio between the maximum and minimum exposure values that can be correctly captured on the image). Trying to solve this problem only by creating displays whose dynamic range of brightness would be tens or hundreds of thousands does not solve the problem. The fact is that the next step that limits the range of brightness reproduction is the visual system, which adapts to the average brightness, determined by the average brightness of the screen and the illumination of the room. Modeling of the adaptive properties of vision in relation to general lighting was presented in studies [18-20].

3. Conclusion
The analysis allows us to conclude that the perception of color tone and saturation does not depend on brightness in a wide range of its changes, and the perceived brightness of the stimulus is a weighted sum of color components. When using very large screens in a completely darkened room, conditions are possible when the adaptation of the visual system will be determined by the local brightness of the screen in the areas currently viewed by the viewer. The search for an appropriate solution to this problem is relevant, for example, for operators of automated process control systems, because visual display of information received by the dispatcher is carried out through the main control panel, which has enlarged dimensions of the display elements, when working with which both central subject vision and peripheral vision are active.

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