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The pathways of human color perception

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Abstract:

Color perception can be able to distinguish between light waves of different frequencies. It is also known as color vision. It is known that humans have trichromatic vision so that they can enjoy the colorful world and receive external information. Although there are thousands of colors in nature, the visible range of humans is limited. Our eyes cannot see the colors produced by ultraviolet and infrared light. Most of the colors in the visible spectrum can be made up of three basic colors (red, green, and blue). When these three basic colors are mixed according to different proportions and intensities, they can produce different colors. Color perception has also been studied to some extent. It is known that color perception starts from pyramidal cells in the retina, then it passes through a complex visual network, and finally, it is transmitted to the visual cortex. Thus, humans can see a colorful world and feel the charm of nature. How do people perceive color? What causes color blindness, and how can medical experts effectively correct this visual deficiency? This research is going to summarize the color vision pathway from the retina to the visual cortex and discuss the causes of color blindness and the existing correction techniques.

Keywords: human color perception; LGN; visual cortex, color blindness.

1. Introduction

Humans are primarily visual creatures, and while there are thousands of colors in the natural world, only a small number of those colors can be recognized by humans. Normal human eyes can only distinguish between visible light with wavelengths between 400 and 780 nm. Humans are able to perceive and process visual information from the outside world because of their sophisticated and flawless visual pathways.

The process of color vision in humans begins with various photoreceptor cells. There are three types of pyramidal cells in the retina. They are, respectively, the L, S, and M cones, which are stimulated by light from outside the human eye and are sensitive to different wavelengths of light [1]. Color perception information is encoded at the retinal level through a complex neural network and finally accepted by the visual cortex of the human brain, allowing humans to perceive the color of the outside world. When there is a problem in one of the modules of the pathway, it will cause the observer to have abnormal color vision. For example, color blindness is a visual defect that is divided into congenital and acquired color blindness, including red-green color blindness and total color blindness. With the research on the mechanism of human color vision and the causes of color blindness, there are some methods to correct color blindness at present, such as color-blind glasses and gene therapy.

This research will focus on the main mechanisms of color vision production, starting with cone receptors at the retinal level, moving on to color vision processes in the lateral geniculate body, and then moving on to the function of various regions on the visual cortex at last. This paper focuses on the processing of color information at the level of the retina and visual cortex, analyzing the recent progress in color vision research and exploring the causes of color vision defects and the existing correction programs.

2. Color perception pathways

2.1 Information processing at the retinal level

Thomas Young's trichromatic theory is important in the early study of information processing on the retina. After a few years, Helmholtz developed Thomas's idea, and this theory holds that three types of pyramidal cells in the retina can sense light waves of all frequencies in the visible spectrum, but different pyramidal cells have different sensitivities to different light waves. When different frequencies of external lights enter the human eye, each of the three receptors is sensitive to specific light waves, resulting in mixed color perception. Hering found that mixing red and three other colors (green, yellow, and blue) can make grey and white. According to this experiment, Hering concluded that there are three pairs of antagonistic visual pigments [2].

Combining trichromatic theory and color antagonism theory, the modern theory of color vision further explains the transmission process of color perception information. It suggests that a trichromatic mechanism occurs in the retina, where three pyramidal cells respond to each of the three colors. Then, the visual information is transmitted to the cerebral cortex. At this stage, it shows the antagonistic mechanism of color.

2.1.1 Color coding on retina

As human color vision cannot be directly measured by physical methods, an experiment that uses color comparison methods is conducted to study the process of human color vision. It is known that patients with abnormal color vision can misread the numbers on the color vision chart under normal light. However, when observing the charts with a corresponding filter, some colorblind patients with different characteristics can accurately read the numbers. The experiment used a computer detector to carry out this experiment, finding that when adjusting the brightness value and the primary color value, some of the patients could read the numbers correctly. This can explain why when the proportion of three primary colors that come into a human eye is changed, the proportion of three primary colors received by the cerebral cortex also changes. This can lead to misreading.

Combined with anatomical experimental results, the pigment epithelium can divide the light into three primary colors (R/G/B) and reflect them to cone cells. In order to convey color information accurately, there are color coding and decoding processes in a human‘s color vision pathway [3].

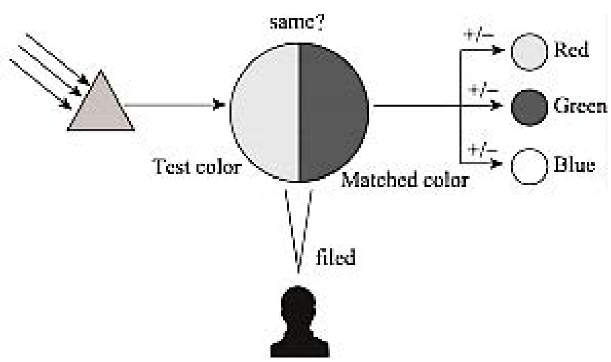

Fig. 1 Most basic color matching experiment [4].

2.1.2 Color matching functions

In order to accurately represent the observer‘s perception of color, a color-matching function can be proposed. The perception of color can be quantitatively characterized by color-matching functions (CMFs). Also, with the rapid development of modern technology, scientists have found that the differences in participants‘ perception of color have become more and more apparent. More and more color-matching experiments that consider different influencing factors have been done. The experimental models of color matching commonly used by researchers are mainly divided into the target color light part, the three primary color mixing part, and the field of view part. Participants need to autonomously adjust the ratio of the three primary colors to get the mixed light that matches the target light, as shown in Fig. 1 [4].

Nowadays, the existing color-matching functions can be roughly divided into three categories. Firstly, the average observer color-matching function mainly consisted of CIE1931 and CIE 1964. These two color matching functions all characterize a human‘s average color visual properties. The latter one considers the influence of different angles of vision. However, neither model takes into account the effect of age. The experiment used STRESS factor (normalized residual sum of squares factor) and correlation coefficient r to test the performance of various color matching functions in calculating the responsiveness of cone cells of different age observers. The results show that the difference in age can affect the results [5]. Secondly, the differences between people with normal color vision were found, and a series of models of individual observer color-matching functions were proposed. Like Fairchild‘s Monte Carlo model, the CIE2006 Physiological model, and the Personalized chroma observer model, which Asano put forward, these models all took into account various physiological parameters, such as the optical density of lens, macular pigment, and photopigment optical density. These parameters were found to be related to age and angle of vision. Besides, Asano‘s personalized chromatic observer model also considered factors other than age and field of view. Last, in order to make each observer match colors better, Sarkar designed a Classification observer color matching function, which covered 8 CMFs, by using the K-Mean algorithm.

2.2 Information processing on the LGN

At present, the reaction properties of LGN are not well understood. LGN is the main thalamic nucleus that connects neural pathways between the retina and the primary visual cortex. An important feature of the LGN is its organization. Information input from the retina is passed to the different layers of the LGN. Retinal P cells project to layers 3 to 6, and M cells project to layers 1 and 2.

The sensitivity of ganglion cells to luminance and chromatic modulation was measured to prove that ganglion cells on the M cell pathway were more sensitive to brightness, and ganglion cells on the P cell pathway were more sensitive to color. In summary, multiple experimental data suggest that cells in the M pathway are used to detect changes in brightness, while cells in the P pathway are formed to detect changes in color.

LGN is a very important area in the mechanism of color vision because its different layers provide the basis for the separation of cell-based color properties. P cells constitute the largest population of neurons and form the basis of red-green vision, with strong sensitivity to RG color contrast and antagonistic L/M cones [6, 7].

2.3 Information processing on the visual cortex

Modern science has studied the mechanism of color vision in the retina to a certain extent, but the mechanism of color vision is still not well understood. Until now, scientists have used many scientific methods to study the structure of the color vision center. The understanding of the central mechanism of color vision is also gradually becoming deeper.

Regarding the mechanism of the human visual system at the retinal level, researchers have put forward many theories, such as the three-color theory, antagonistic color theory, four-color theory, and so on. In earlier studies, oppositional color theory and three-color theory were in opposition to each other. Recent research has conclusively shown that these two hypotheses are united. In terms of photoreceptors, photoreceptor cells recognize three independent factors as sources of color information. But, in the visual neural pathway, color information is encoded in an antagonistic form. In the visual cortex of the brain, the regions involved in color information processing are mainly V1, V2, and V4. Information from the retina is transmitted through ganglion cells to the lateral geniculate body, to the primary visual cortex structure, and eventually to the higher visual center for more complex processing [8].

By using phase coding, some experiments locate six visual regions in the human cortex. Scintillation stimulation was used to locate hMT+ region. The VO region, which is in front of the V4 region, is identified by using experimental stimuli. In earlier studies, it was shown that V1, V2, V3, V4 all responded to color information. On this basis, the results of the proximate experiment tend to group the functions of the four regions because these four regions do not have a consistent preference for color information. At the same time, some experimental results show that the V4 region of humans has no obvious response preference to color information. However, the region VO in front of V4 has a clear preference for color stimuli. Some researchers believe that V4 and VO represent a single brain region. Through parts of experiments, researchers found that the response of the VO region to color is different from that of the V4 region. The experimental results show the functions of these two regions are different. This provides evidence that the two regions are relatively independent [9].

Human perception of external colors mainly includes three dimensions: hue, lightness, and chroma. The visual information is transferred to V1, which is situated in the cerebral cortex, by LGN. The area can be divided into six layers of cells. By using histochemical methods to display the cytochrome oxidase in this region, columnar regions rich in cytochrome oxidase can be found on the second layer and the third layer cells. These areas are called Blob areas [10].

3. Color blindness

Color blindness, also known as color vision deficiency, refers to the lack or loss of the ability to distinguish colors. People with color blindness can be classified according to their causes. They can be divided into two categories: congenital color blindness and acquired color blindness. Congenital color blindness includes total color blindness, dichroic color blindness, and so on. Acquired color blindness is due to external factors, like chemical factors and diseases.

According to the mechanism of color vision formation, the colors that a person with normal color vision (also known as a trichromatic person) can see can generally be mixed with the addition of red, green, and blue primary colors. If a person makes an error in matching the various colors of the spectrum with the three primary colors, it is called color weakness. If a certain type of cone cell is missing or the cone cell function is abnormal and cannot distinguish a certain color or cannot distinguish color at all, it is called color blindness [11].

4. Conclusion

This research begins with a discussion of color vision information processing in the retina. Then, it discusses the response and processing of color information in the LGN and visual cortex. From the human color vision, the information transmission process can be known, no matter which level of lesions occurs. As long as the proportion of the three primary colors received by the cerebral cortex visual area is out of proportion, it will cause abnormal color vision. On the contrary, when the trichromatic values of the incident human eyes are changed from the outside, the trichromatic values of the incident human eyes received by the cerebral cortex visual area also change. This undoubtedly provides a theoretical basis and operational methods for the detection, diagnosis, and correction of abnormal color vision. With the continuous progress of science and technology, there are some methods of color blindness correction, including color blind glasses, color blind gene therapy, and red light color enhancers. However, these methods are a certain degree of compensation for color blindness, and they cannot cure color blindness. It is believed that with the deepening of scientific research on the production mechanism of color vision and the exploration of treatment methods.

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