Color Perception is Possible only in the Retina.

Questions and Assumptions.

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Abstract– Investigation of the working mechanism of Color Vision raises the following question: where and how do the perception, sensation, the illusion of light arise and where does the image appear? The electric signals generated by electromagnetic radiation are transmitted from the 6 – 8 million cones of the retina in a condensed manner by the 1 million optic nerves to the brain. The information from the retina is transmitted via ON and OFF optic tracts to the LGN and Visual Cortex in the form of exciting and inhibiting (positive and negative) impulses. As a result of optic chiasm the two LGN and Visual Cortex receive two half of the whole picture from both retinas, but they do no give the whole picture seen by the eyes. For the realization the sensation of light, the electric signal has to cause the sense of a "flash", the sense of light, the sense of colored light in the 'reproducing' neuron. However one neuron is not capable to reproduce the nearly one million shades and brightness, according optical experience. We have to presume that three different neurons give three flashes, blue, green and red, in proportion to the intensity of the radiation, and its joint effect will give the color we see. According to the data in literature and mathematical considerations we can assume that all the necessary information for the whole picture can only be together in the cones.

Index Terms– color, color-vision, cone, eye, image, perception, resolution, sense.

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The range of electromagnetic radiation between 380-760 nm is called visible light. The rods and cones located in the retina, receptors of the eye, perceive radiation with the help of photosensitive pigments, photo-pigments. Rods aren't color sensitive, and perceive only the fact of the radiation. Their number is very high, in one eye may be 120 million rods. Number of the cones is much smaller, approximately 5 - 12 million, or – presumably – only 6 - 8 million. Their sensitivity is also much lower, 100 times less than the sensitivity of rods, but they react much faster than that of the rods. The cones are densely located in the macula, and particularly in the fovea. According to some data, there might be 150.000 - 200.000 cones in the fovea (diam. 0.5 – 1.5 mm.). The number of cones considerably decreases towards the periphery. [1], [2], [3], [4], [5], [6].

There are three different types of photosensitive pigments in the cones. Their sensitivity, sensitivity range to electromagnetic radiation is not the same. The three different types of cones comprehend to three different range of wavelength (380-760 nm) with overlapping, which is very important, because it makes possibly to see a big range of color hues, instead of just three color. The cone types are marked S, M, L, according to their wavelength ranges (Short, Medium, Long).

In the dark the rods and cones are depolarized (-40 mV). Due to the influence of radiation, the pigment molecules chemically alter, undergo photo-isomerization, while in the meantime give an electric signal. As a result the rod cells are hyperpolarized (-70 mV), and transmit a signal to a bipolar cell and then to ganglion cell. Meanwhile, as a consequence of a series of chemical reactions, the photo-pigment take their original form and the cells are depolarized. (-40 mV) [7], [8], [9], [10], [11].

Experimental data [13] show that the increase of graded potential in the cone cell depend on the intensity of radiation. It means, that the number of excited pigment molecules at low intensity of radiation is small, and with the increase of radiation its number also increases. The data also show, that at low intensity the increase of graded potential for a short illumination isn't enough to produce the potential of hyper-polarization.

The intensity of radiation might be constant, or variable, increasing and decreasing. In case of constant intensity for a depolarized cone cell, after the dark state, radiation in the first instant excite a certain quantity of pigment molecules, isomerizing they. But the number of new exited molecules in time will be less for the constant radiation, because the quantity of original pigment molecules in the cones decreases. It takes some time for the excited molecules to be restored into their original shape. Consequently, after some time begins the restoring of excited molecules, and at a given time became an equilibrium between new excited and restored molecules. The level of this equilibrium depend on the intensity of radiation.

If the intensity of radiation constantly increases, the quantity of excited molecules increases with time after dark state, but the number of new excited molecules does not increase linearly due to the above factors and reaches the state of saturation after a certain time.

If the intensity of radiation is increasing and decreasing there is no equilibrium, but since the excited pigment molecules give electric signals equally, the graded potential is on the rise. In the different cases, when the potential reaches the level of hyperpolarization (-70 mV) the cell gives signal for the bipolar cell. Since the cell can send a signal for the bipolar cell only when it reaches the state of hyperpolarization, in case of low radiation there are shorter or longer time periods when the radiation increase or decrease fails to send information to the bipolar cell. All this means that, the signal sent by the cell couldn't represent the increasing and decreasing intensity of radiation, which would be very important, because these variations of excitement represent the quick movements of the picture what we see. Consequently, the density of the impulses, sent by the cone cell isn't proportional to radiation, and so the impulse can't represent the intensity of radiation.

There exist a difference on comparison to other neurons. In daily light, the cones will not be depolarized, because they are constantly excited by the radiation affecting the pigments and the developing electric signal increases the graded potential. Consequently, the depolarized state only develops in the dark, after adaptation and in daily light, there is always some, variable level of potential in the cone cells.

Simultaneously, in each cone there is also a so called excitation level. It means, that there is a changing proportion of excited and original pigment molecules, and as indicated above, it has an influence on the number of exiting molecules at a given moment. In practise it means that when the excitation level is low, the same intensity can excite more pigments and we sense the light same brighter. At any rate, the number of newly excited molecules at a given moment represents the intensity of radiation, but it isn't in direct correlation with the signals sent to the bipolar cell.

Presumably, this level of excitation explains the phenomenon of after image. /14/ How? If we stare at a bright colored figure on a white surface for a long time, on the surface of retina, which is illuminated by the white surface of the target, all types of cones are excited quite strongly. On the surface illuminated by the colored figure, cones adequate to the given color are excited also strongly, but other cones only slightly or not at all. If, after reaching the state of equilibrium, (30 sec.) we look at a white surface, the cones, which were excited strongly by white light, or the given color, give the same excitement, and result in the same intensity of sensation. But the cones, which ware excited slightly, or not at all, now indicate stronger excitement, then the white surface and thus the sensation is also greater. All this means, that on the surface adequate to the colored pattern, the complementary color picture shall appeare for some seconds.

The information of the 120 million rods and 6 – 8 million cones contained in the retina are transmitted via 1 million optic nerve to the Lateral Geniculate Nucleus, LGN and then to the Visual Cortex. According electron-microscope data synapse of the rods, S cones and M, L cones to the bipolar, ganglion cells and to LGN and Visual Cortex are different.

Every cone is connected to two bipolar cells; one of them is an ON (exciting) and the other is an OFF (inhibiting) bipolar cell. In bright, daily light, the ON bipolar cell becomes depolarized due to the signal and the OFF bipolar is hyperpolarized. These cells give signals to ganglion cell where an Action Potential (AP) is generated. The AP is an electrical impulse, which can be or an ON, exciting, and OFF, inhibiting impulse, but the information transmitted by axon is only binary, yes or no. /15, 16/ In case of different cell types, the AP can be, to some extent different in length (time), height (potential) or density (frequency) but these do not represent the required intensity scale.

Of the rods, 15-30 are connected to one bipolar cell, and then to different types of amacrin cells. The amacrin cells connect the rods to (large) magnocellular ganglion cells (100.000), thus of the 120 million rods a large number of rods have to be connected to one ganglion cell. The magnocellular cells are connected layer 1, 2 of LGN via M way and further to V1 4cα layer of the Visual Cortex. [17].

The M and L cones are very similar, hard to distinguish, but their routes are more or less the same. One cone from the fovea is connected to one ON and one OFF bipolar cell and further on to one ON and OFF ganglion cells. [18].

Near to fovea, up to a distance of about 4 mm only 1 or 2 cones are connected to one bipolar cell. Moving further towards the periphery, 3 cones are connected to one bipolar cell, while later on, 3 bipolar cells are synapsed to one ganglion cell. In this case, however, it is not for sure that that to every ganglion cell is connected only the same cone type. It means, that in this case there isn't color information. If we take into account the number of cones (6-8 million) and the number of optic nerve (800.000) than near to the periphery even more than 9 cones have to be synapsed to one ganglion cell, thus no color information is sent to the brain from a large part of retina [19]. These small Midget ganglion cells transmit data through ON and OFF line to 3, 4, 5, 6 layers of LGN. It is the P, parvocellular way. From LGN these information gets to the V1 4cβ layer of the Visual Cortex. [20].

The S cones are somewhat different from the M and L cones. Their quantity is 8 – 10 %. They synapsed personally to the bipolar cells and also have connection to horizontal cells which give negative feedback to the cones. Also here there are ON and OFF bipolar cells and via K way transmit data to Koniocellular layer of LGN. These are very small Midget cells and the Koniocellular layers are the separating layers between 3, 4, 5, 6 layers. The data are transmitted to layer 4a of the Visual Cortex. [21], [22], [23].

The data from LGN get to the Visual Cortex. There are data about the layers where the lines of the S, M, L cones arrive, but it is not clear how close the cones, which are next to each other in the retina are in the cortex.

Between the retina and the LGN is the optic chiasm, which result crossing the way of a part of nerve lines. From the retina the outer half (temporal side) of the axons of the cone cells get to the same side LGN, but the axons of inner half (nasal side) take a turn at the cross section and move towards the LGN of the other side in case of both eyes. In the LGN, the nerve lines of the same side connect to 2, 3, 5 layers, the opposite lines to 1, 4, 6 layers. [24], [25]. The visible field we see with two eyes can be horizontally divided into three parts of nearly the same size. The two outer thirds we can only see with one eye, the left side with left eye, the right side with the right eye. The size of these parts is nearly the half of field, we see with one eye. The middle part we see with both of the eyes, since this is the field of stereo sight.

According anatomical data to the left LGN became data of the temporal half of the left retina and the nasal half of the right retina. As the lens give reversed picture, the temporal half of left retina see the middle part of the visual field and the nasal part of right retina see the right third of visual field. All this means that the left LGN and Visual Cortex get the data of the two third, which we see with the right eye. Problem is, that the two third part became from different point of view and its form didn't give a picture we see with one eye (closed other eye). It means also, that if one eye is closed, Visual Cortex will get only the half of picture.

Experiments on the mechanism of color vision provide information that several neurons in the retina, LGN, Visual Cortex on what type of radiation, arriving the eye give electric signal. Investigation of a given neuron can show that some color or wavelength of radiation cause electric signal in the cell, but other do not. Based on these findings it is presumed, probably by mistake, that the given cell is sensible to the given hue, wavelength, lightness and many other feature. Since the signals, impulses coming from the different types of cones are the same, and there the signals do not have a spectrum or do not possess formal data, the cell simply can not select based on some sort of sensitivity. As a consequence, the data only show that from what type of cones, how many cones from the same type or different the cell in question receives signal. It is possible, that a given neuron (bipolar, ganglion cell) has contacts with cones 1, 2, 3, of the same type, thus it only react to that wave-length interval. But it is also possible that the neuron receives signals from two or three different cones and reacts accordingly. Presumable, these cells are called opponent cells. However, there is another option: if a signal appears from a blue and a yellow monochromatic light, we can not tell whether in addition to the S cone a L or a M cone, or both are also connected to the given cell, because that (570 nm) yellow beam will excite both M and L cones. It seems to be the reason why blue-yellow opponency is considered very important. Conclusions are also drawn from experimental data that some neurons are sensitive to lines, edges, movements, etc., while in reality, the examined neuron only receives, in form of impulses, yes or no signs which simply can not contain such information. [26], [27], [28], [29], [30], [31], [32], [33], [34].

An electric sign, detected, or measured in a neuron does not necessarily mean that the neuron can produce the sense of light. Consequently, experimental data can not at all, or only with difficulty identify where the sense or illusion of 'vision' is created. For this reason let us first consider, what can be required for the sense, the perception of sight.

The cones and rods are external receptors. It means that a receptor contains some a certain component or molecule, which has the property to react to some specific signal. In the case of the eye, the cones and rods as receptors contain the photo-pigments, which are capable to alteration due to the received electromagnetic radiation. For this reason, it can be interpreted as a camera, which sends electric signals to the brain. At the other end we have to find a so-called monitor. The "monitor" neuron ("representing" neuron) has to react to the specific signal from the optic tract and give the sense of a "flash". We have to presume, that the reaction can not be an electric alteration, because in the neuron cell there is always a time graded potential, which constantly alters. We have to presume that that the representing neuron is also a some type of receptors, which contains a specific molecule producing the feeling, the sense of sight.

Since our eye can distinguish nearly 1 million hues, brightness, it seems to be impossible that one neuron is capable to represent this. It is also impossible, that one nerve line can transmit such a high intensity scale (1 million).

We have to suppose, that in compliance with the three different cone types, there have to be three types of representing neurons which give three "flashes", according to the intensity of radiation. Consequently, if there is a flash in three neurons, then the number of acceptable hues is 50 x 50 x 50 =125.000 within the intensity scale 0-50. If the scale is within 0 – 100 the range of acceptable hues is 1 million. All this repeatedly show that the joint, simultaneous presence of three neurons is needed to represent such a great number of hues, brightness. Thus, if the signs of three cones give three flashes in representing neurons (presumable blue, green, and red) according to the intensity of radiation, the brain can accept it as different shades of color. Each of these triple points can be interpreted as a pixel.

The picture we see with our eyes can contain very complicated figures in color, form, brightness with lines, transitions of color, on the whole surface of the retina and a great number of independent pixels are needed for this. That is why we have to check where, in what cores are the required conditions represent, to sense the color image with necessary resolution. In order to do so, let us first consider the following: the electric signs coming from the 6-8 million cones are transmitted via 1 million axons to the LGN, Visual Cortex. According to the literature, that 20 % of axons have other tasks, only 80 %, 800.000 lines transmit the data of S, M, L cones. The Fovea contains 200.000 cones. The data of these cones are transmitted mostly personally via the ON and OFF lines. The cones in the macula (their number is approx. 300.000) are probably connected to ganglion cells in pairs or in three. The remaining axons transmit data from the periphery of retina, so that many cones are synapsed to a ganglion cell. It means that the 200.000 cones of the fovea engage 400.000 axons (ON and OFF) and of the macula 300.000 cones, if they are connected by three engage 200.000 axons. Consequently, only 200.000 axons are left for the remaining cones of the periphery.

On the other hand, we have to see how many pixels give 800.000 neurons. If we presume that the 800.000 axons transmit data of S, M, L cones in equal proportion, - since all the three signals are necessary for one pixel – the maximum number of points is 267.000. But if we take into account that the rate of S cones is 8 %, and an S signal is needed for each pixel, the above number of pixels is reduced to 21.000. And these data relate to the whole retina. If we only see the fovea, one-third of the 200.000 cones is 66.000 and according to number of S cones, we get 16.000 pixels. The above numbers also show, that the number of picture points arriving to the Visual Cortex is not enough to create a picture.

Now we should look at the conditions which have to be realized simultaneously for the sensation of the whole colored picture.

1. In order to represent a great number of color and brightness, a large scale for intensity of signals is needed.
2. In order to assure the whole spectrum of color hues, the three representing neurons have to be near to each other to sense the three flashes as a given color.
3. A great number of pixels are needed for the adequate resolution of the whole seen picture.
4. In order to get the real picture, the pixels have to be in the same topographical position as in the retina.
5. To get the sensation of light, there has to be some component in the representing neuron, similar to the one in the receptors which, at its transformation, can cause the sense of a flash.

Based on literature and mathematical considerations we can draw the conclusion that data with the required number of pixels and the needed intensity scale do not get to the LGN and the Visual Cortex.

According these facts we can suppose that the only possibly place for the colored picture to appeare is in the layer of cones and rods, namely in the cones themselves.

Let us now look at the possibility of this in the cones.

There are 6.4 million cones in the retina. The density of the cones in the fovea is between 120.000 and 250.000/mm^2, in the macula 50.000/mm^2 and in the periphery 5.000/mm^2. There are different data also on the proportion rate of the three type of cones. For the S cones, 8 % seems to be acceptable. The data are diverse on the proportion rate of M and L cones, for each cone type the rate can be much greater and smaller. /7/

If we consider the rate of the three cones equal, the maximal possible quantity of pixels can be 2.666.000. But if we consider that the rate of S cones is 8 %, the maximum number of pixels can only be 640.000. Based on experimental data on the regular location of the cones in the retina we can presume the following: the larger number of M and L cones are in regular form around the S cones. Due to the influence of the radiation, the different cone types result a sense of colored flash, according to their characteristic color. The neighboring flashes of different color are accepted as a middle hue. Accordingly, the S cone together with the M and L cones on one of its sides accept a given hue, but the other side, with other M and L cones can show some other hue. It really means, that this way the number of pixels can be greater. These many pixels can already produce a picture in the whole field of vision. All this proves that the most probable place of the sense of image is the layer of cones and rods.

There are no data in the literature, about the event resulting in the sense of vision. The possible alteration of graded potential can not be the cause, because the graded potential is constantly changing as a result of the accepted signs. We have to presume, that the reproducing neuron is also receptor, and it contains, for this reason, special component, which is transformed due to the specific signal and this process itself, or rather the characteristic of the developing new compound has the property to produce the feeling of seeing. The photo-sensitive photo-pigments, located in the cones (and rods) - in all likelihood - are the specific component and the new, short-lived compound developing during the transformation produces the sense of flash. Thus the image can alter very quickly and the number of the new compound represents the intensity of the light. [35], [36], [37].

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If, in reality, the sense of light is in the cones than:

1. The excitation of pigment molecules in the cones is proportional to the radiation and it can result in the realization of a "flash" with given intensity
2. The regular and close position of the three types of cones assure that the three flashes arise close to each other and the middle hues appear (transitional shade).
3. The number of the cones assure the needed quantity of pixels for resolution.
4. The representation of the images in the cones assure the identical placing of pixels with the pictures appearing the retina.
5. Most probably, the new, quickly altering compound produced by the exciting of the photo-pigment result the realisation of the flash.

Additional conclusions.

The resolution, clearness, sharpness of the image is the best in the fovea (see the data on cone density), while towards the periphery, the density of cones decreases and so does the resolution. But the sensed picture is continuous geometrically, in hue and brightness. In addition to this, if we close one of the eyes, we still see the adequate visual field and it excludes the possibility that the perception of the image is in the LGN, or the Visual Cortex, since there in one side, the data of the half visual field coming from both eyes are send and these can not be completed for a whole one-side image.

The assumption made for the sensation of colored image do not question the presence of the data transmitted to the LGN and Visual Cortex. Presumably, in addition to other operational tasks of the eyes, they have a role in storing the picture in a simple form (may be in black and white). Presumably, the memory does not store the whole image, but only the important details and even if the observation has been long enough.

We have reached the conclusion that the sensation of seen image evolves in the retina, in the cones was made without direct experiments. But starting from literature data on the anatomy and taking into consideration the great number of distinguishing color hues and brightness, the observed good resolution of seen picture, the independent appearance of image in two eyes this is the only conclusion which can be reached. On the basis of all these we can say that this model of color vision acceptable and probable that this or something similar is the actual mechanism of vision.

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