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Contradictions of Vision

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CONTRADICTIONS OF VISION

It is now an axiom that present-day scientists expect discoveries chiefly at the crossroads of sciences. But just what are these crossroads and what is meant by "expectation of discoveries". Before you is an article that tells how at one of the parts of the infinitely long boundary line between biology and physics the sciences are enriched and penetrated by each other. You will see that this does not always happen smoothly and simply.

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One of the most difficult and complicated problems in biophysics is color vision. How is the human or animal eye able to distinguish light rays from their wavelength?

You know (you have surely been told about it in school) that color vision in the human eye is effected by special cells which are usually cone-shaped.

It has long been known that man can perceive any color through the action of a mixture of only three colors - red, green, and blue. It was concluded from this, also a long time ago, that the human eye has three types of receptors differing in spectral sensitivity. If one of them is excited, there is a sensation of red; if another, green;if the third, blue. But, in general, light usually excites all three receptors in varying degrees.

And now - a theory that interests us greatly. Let us quickly travel over the road that led two Soviet biophysicists to it.

Scientists once had no trouble in agreeing that each cone has one of the receptors and that all cones are divided into three types accordingly: into "red", "green", and "blue" cones. But until recently no one was able to detect any difference between the many millions of cones in the human retina. What I mean is the difference in how they absorb light. Most physiologists insisted that any differences had to be found. But the facts refused to confirm these suspicions. It turned out that there are no cones that specifically receive primarily red or green or blue rays.

And then two physicists, M. M. Bongard and M. S. Smirnov of the Moscow Laboratory of the Sense Organs, concluded that every cone must perceive the rays of all the colors. And the three receptors? They are found inside it. Any cone has all three. The following is evidence in favor of this. Visual acuity is believed to depend on the density of the retinal cones. Until recently scientists agreed that cones on the average are about 3 microns in diameter. Given this fairly large size, the density of the cones is comparatively slight. So slight that a cone is barely able to ensure normal visual acuity. (Visual acuity is characterized by the distance at which two adjacent points do not appear to the eye to coalesce into one. To prevent coalescence, it is necessary for the images of these points to reach different (not adjacent) cones, not one).

But in a room illuminated by a red bulb, visual acuity remains normal, it does not decrease. However, in red light only one type of receptor functions (because the others are insensitive to this light). If they are in each cone, it means that all the cones take part in vision; its acuity in red light, of course, must not change. But if only one-third of the cones function here (i.e., those sensitive to red light), it is very difficult to account for the preservation of visual acuity.

The assumption of three receptors in a single cone can also be explained by some other phenomena. But not everything. A hypothesis is entitled to exist only when there are no facts that directly disprove it. The hypothesis of Bongard and Smirnov, more than others, was "threatened" by the following circumstance.

In no place in the retina is there more than one fiber per cone (and generally one fiber takes care of a whole group of cones). Signals travel along the fiber in the form of impulses of equal duration and intensity. Now, suppose that a nerve used a variant of Morse's alphabet in which there is no dash - there are just dots and spaces in between. It is obvious that this method makes it easy to transmit brightness - the more intense it is, the greater the number of impulses will be sent. But how can a communication about the color of an object be transmitted in this way via a single fiber? For every cone has to send (according to the hypothesis) signals about different colors!

If the two physicists were unwilling to abandon their hypothesis, they had to solve this problem too. They could be helped only by experiments. But on what would they perform them? Man is not a very convenient object. To be sure, he claims to be sensitive, but as you well know, it is difficult to penetrate into his eye and brain.

Only the beginning and end of the process can be seen. But what about the intermediate links? How is the optic nerve reached?

It was necessary to find a laboratory animal with color vision. The scientists decided on the common frog. But the Moscow biophysicists didn't even know at that time whether the frog can distinguish color. Unlike man, it cannot itself report about it. Yet it was possible to force it "to answer". They attached to the animal's retina a microelectrode, a glass tube with electroconducting fluid. Microelectrodes are now made with a diameter of a fraction of a micron, but at that time, ten years ago, they had to work with "real clubs", as one of the heroes of this article put it - only one-third as fine as a human hair. The microelectrodes are used to lead off from the cell surges of electric current that accompany nerve impulses.

When the color of the light rays striking the eye was changed, the biocurrents in the retina also changed. But not always. Sometimes the color changed and the frog failed to notice it, and the nature of the biocurrents remained as before. It was thus possible to find out the colors that appear different to man but cannot be distinguished by the frog. It turned out that the frog has only two receptors, a mixture of only two colors - blue and red - and the sensation of any color can be created. This meant that the frog sees just about the same way as man whose retina likewise has only two types of receptors - Daltonics. Yet the frog had color vision and the scientists began to study it.

They found that a communication about color may be transmitted along a single fiber. Although both receptors are clearly separated in the frog's eye (the cone is one, the rod is another), one nerve fiber proceeding from the eye carries signals from both the rods and the cones. They have a common "line of communications". Information about color is probably transmitted the same way as in man. But how?

The scientists hit upon the idea of a device to study the frog's vision. One part was a semiconductor selenium photocell. From the indicator of the galvanometer connected to it the investigators were able to watch the preservation of the intensity of light when one pencil of rays was substituted for another.

The main colors for the frog are red and blue. In the device the intensities of the red and blue pencils were selected in such a way that with persistent red light the indicator stood at the same place as with persistent blue light. Thus, as long as the red light was slowly weakened while the blue light was proportionately intensified at the same time, the indicator did not move,as though nothing happened. But if the red light was quickly replaced by the blue, the indicator jumped up and took some time before returning to its former position. On the other hand, when the blue light was quickly replaced by the red, the indicator fell but soon returned to its old position.

The biophysicists fussed around a long time with the device which they were quite sure was inaccurate. They finally realized that it was all right, that the trouble was in the inner workings of the photocell. The latter behaved differently when the red and blue lights were turned out (after darkness). Blue rays caused the current to increase more rapidly. It was very apparent that information about color was transmitted through a single "nerve fiber" - wires going from the photocell to the galvanometer. Analogy to what happens in the retina! Isn't it possible that something like it takes place in the eye? Look out...we are present at the birth of another hypothesis. As a result of their experiments with frogs and observations on the functioning of the photocell, Bongard and Smirnov conjectured that vision is photoelectric in nature.

Until that time the photochemical theory of vision held unquestioned sway. Briefly, the theory holds that when light rays strike the eye, they destroy or decolorize the visual pigments. The decay products also excite the retinal cells. (This is exactly the way that silver compounds in a photographic plate change under the influence of light. The eye is a camera, a natural, self-evident analogy).

Visual pigments lose color in light and regain it in darkness. But there is something odd about the phenomenon. The most studied of the pigments is visual purple, rhodopsin. The more of it is in the cells at a given moment, the more sensitive the eyes are to light. Everything all right now? Not quite. Because at night sensitivity is greater than during the day, 10,000 times greater, yet the amount of rhodopsin in the retina at night is greater by several percent. That's something to think about. When you realize that in the eye of cephalopods rhodopsin generally does not lose color in light, you're bound to become suspicious. Maybe the photochemical processes in the retina are combined with photoelectrical processes by which light is converted into an electric current? And the latter play a decisive role here?

The fact is the selenium photocell "notes" only changes in color, the substitution of one color for another, distinguishes one color from another as long as it is in darkness. But a few seconds after it is turned out, the observer is no longer able to judge from the galvanometer arrow the color of the ray. Yet there is a curious thing! The ordinary human eye (and not only the human eye) has "work rules" resembling the behavior of the photocell. You and I note only those objects which move relative to the pupil. In order for us to be able to see trees and stones, nature arranged for the eye to move continuously. That is why we see non-moving objects. The furniture would "disappear" very quickly from an apartment, if it weren't for this phenomenon. And when in experiments using the so-called "Yarbus suckers" small objects were made immovable relative to the eye, they "vanished" after a few seconds, merging with the background. An analogy? Yes.

In short, much could be discussed, but only new series of experiments could give answers. They had to tell how the frog interprets the signal traveling along the fiber, how it recognizes its "color". Then something happened as though it were in a novel or short story. The investigators started, then postponed their experiment simply because at that time they were interested in something else that seemed very urgent.

Meanwhile some friends who knew about the hypothesis pestered the authors to stop talking about interesting conjectures and to verify them instead. But the reproaches had little effect. However, one of their colleagues, the biophysicist Yefim Liberman, could not restrain himself and he carried out the necessary experiment himself. He took an ordinary frog's eye and tested the nerve fibers of the retina with microelectrodes. He eventually found some of them produced different electrical signals - one kind with red light, another with blue. The fiber reacted to red light with a short volley of impulses and to blue light with a volley followed by a long tail of rare impulses. This confirmed the view that a single line of communications can serve several receptors.

Bongard now suggested constructing a model - a model of the cone-fiber-brain system. The physicist was true to his convictions - he would have as the model an electrical circuit that would report at the output the color of the ray striking its photocell. It was also needed to solve another important problem - how can one decode the signal on color sent by the photocell along the wire by using the simple means available to the living organism?

The model judged color from the speed with which the current in the photocell increased. If it did so slowly, the model decided that the color was red; if rapidly, blue. The intensity of the light had no effect on the accuracy of determination, although it was changed ten times.

I do not know whether it is worthwhile to go into the details of the construction of the model.

When it was already functioning, one of the members of the laboratory, Alexey Byzov, brought in a very important bit of news. I should say that Byzov, in addition to other things, was a specialist in microelectrodes. He makes the thinnest of tubes, reducing their diameter to fractions of a micron (they say that no one in the world, except the Japanese scientist Tomita, can make them so thin). Byzov had come to report that by means of his microelectrodes he found something new in the bipolars - nerve cells behind the cones. Until then it was thought that all the bipolars are alike. But now, it turns out, they are divided into two groups of cells. Some of them send. Biocurrents in the form of a rapid signal; others, in the form of a slower signal.

The newly built model contained two units, one to produce a rapid signal upon entry of an impulse, the other to produce a slow signal. The two units were not designed on the basis of known facts concerning the structure of the eye. The scientist aimed only at analysis of the signal on color. It turned out that the model anticipated the results of physiological experiments. Practical experience not only supplemented the theory but it confirmed it at the same time. The eye apparently used the same means as the model.

If the new discoveries were taken into account in the model created before them, would this not be evidence of its accuracy? Alas! You know the difference between an hypothesis and an invention? In the case of an invention, one "yes" in the form of a finished object is stronger than one hundred "no's" before it is made. But the opposite is the case with a hypothesis. One hundred "yeses" are weaker than one "no". Every "no" must be refuted beyond the shadow of a doubt. And doubts do creep in!

Well, it so happened that, deplorable though it may be, the model regularly made mistakes. If the photocell was illuminated with a gradually intensifying beam of blue light, the electrical circuit called the light red. This was only natural because the current in the photocell increased gradually, and this signified to the model red. But doesn't the human eye make similar mistakes? Of course it does, but they are insignificant ones. Too insignificant to be a decisive reason "for" or "against". It must also be remembered that evolution was able to provide a method to avoid really serious errors by making the visual system static-free, to borrow a term from radio engineering. We know of quite a few corrections made by the eye and brain in the formation of images on the retina. (However, some flaws cannot be eliminated, not to mention the fact that evolution is far from achieving everything that is theoretically possible).

Now lot us digress from the subject. With the heroes of this article. Almost immediately after they constructed their model of "photoelectric vision", the authors of the hypothesis stopped working on it. The reader who is accustomed to the hero of a novel doing great deeds in the name of loyalty to a single scientific idea may be surprised. But for the scientists it was all quite simple. They came to the conclusion that another scientific problem was more important and they were impelled to solve it. So they devoted recent years to the problem of recognition - by machine, animal, and man - of images, a subject of great concern to present-day cybernetics. Seems they were possessed by their idea. But their chief, head of the Laboratory of Sense Organs, Nikolay Dmitriyevich Nyuberg, says: "I don't like this word "possessed". It implies some scientific insanity plus blind faith. A scientist has to be objective and unemotional...especially in relation to his own work."

So, utterly engrossed in the new puzzle, the two biophysicists abandoned for five years their old hypothesis. But the five years did not pass without a trace as far as the hypothesis was concerned. For one thing, some facts in its favor were found. On the other hand...A year ago an event of extraordinary importance took place. A group of American scientists apparently discovered that the cones are different.

Do you know what the color of an unexposed piece of film is? Of course you don't. To find out, you have to throw a beam of light on it, that is to say, expose it.

Examining cones under a microscope, scientists saw them already "exposed". The photosensitive pigment of each cone was destroyed there and then. If cones differ only in color of the pigment, how can it be examined?

Nevertheless, the problem is not absurd. When light is very weak, the pigment is not destroyed immediately. One can still manage to see it. So the scientists successively passed through a individual cone very weak light rays of different colors and learned how the cone absorbs each of them. Then they exposed the cone, i.e., they destroyed the pigment in it and again passed the same rays through to determine how the absorption of each individual color was changed by exposure. They repeated this many times with hundreds of cells.

The cones were clearly divided into three groups. The pigments of some absorbed orange rays, others green, the third blue. Two teams of American scientists headed by Wald and MacNichol made this discovery independently. They were helped by exceedingly sensitive instruments.

But we still don't know just what pigments are within the cones and what they consist of. Even the best known of them, rhodopsin or visual purple, is a puzzle in many respects. Even its chemical composition has been questioned for a very long time. Quite recently M. A. Ostrovskiy of the Institute of Higher Nervous Activity, Academy of Sciences USSR, has taken up the problem.

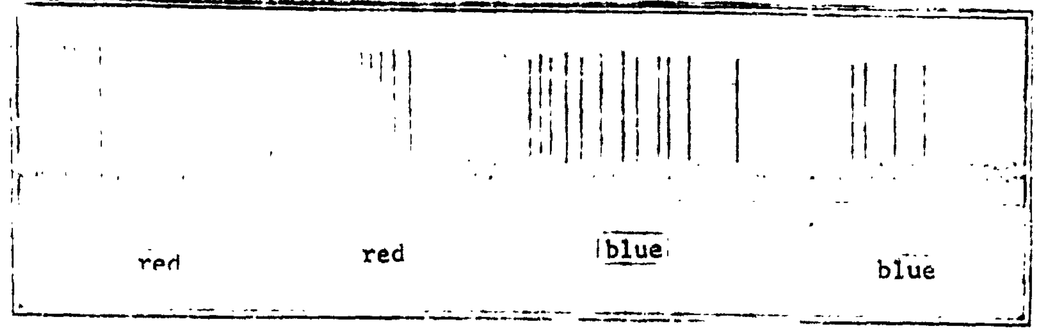
The cones as a whole but not their constituents, have become "red", "blue", and "green". With this discovery the photochemical theory lost one of its most vulnerable aspects.

So, is it possible that the hypothesis is unnecessary? It is still hard to say. At any rate, its authors disagree sharply. Mikhail Smirnov thinks that the discovery of the heterogeneity of the cones has put an end to the history of the hypothesis. He remembers something else. Aleksey Byzov not too long ago showed quite plausibly that light does not seem to give rise to an electric current in the cones of vertebrates. If this is so, it is difficult to speak of photoelectric phenomena in this layer of cells.

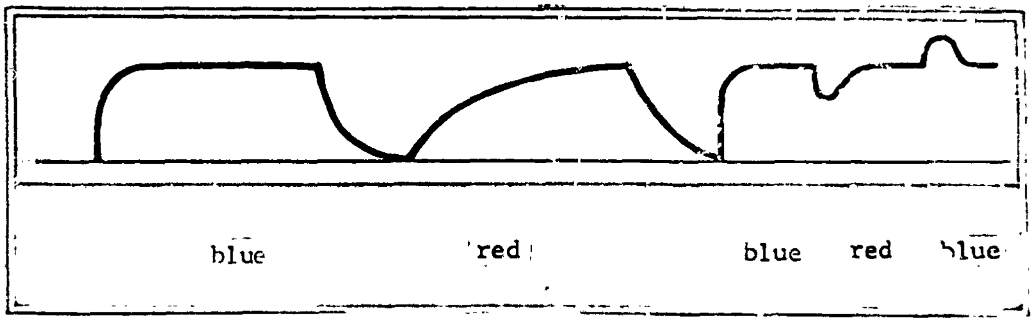
But Bongard is neither able nor willing to admit that it is all over with the hypothesis. There are facts that cannot be explained without it. For example, why does ordinary visual acuity persist in red light. However, a "mine" has been laid under this argument too. Visual acuity is ultimately determined not by the average density of the cones throughout the retina, but by the maximum concentration in at least one place. A number of scientists have lately contented that in the tiny ["krokhotnyy"] part of the retina are concentrated cones that are 1½ times thinner than their "average" sisters. But since there are smaller cones, there must be more of the smallest here per square millimeter than usual. The greater the density, the more acute vision may be. However, even though the mine has been laid, it hasn't exploded yet. Calculations indicate that even so there are not enough cones to explain visual acuity in red light.

The hypothesis has another part - about the signals from different receptors traveling along a single fiber. This notion is not without merit. In the frog, for example, it is believed that this is the way signals travel. And a color signal reaches the brain! Therefore, it may be too early to give up the hypothesis, especially since it is often more difficult for science as a whole to abandon a hypothesis than it is for its authors. How many times has it happened that hypotheses were buried only to be brilliantly confirmed later on, albeit on a new basis.

D. I. Mendeleyev liked to say that it is better to stick to a hypothesis that may eventually prove to be false than to have none at all. The history of the hypothesis discussed here is not yet ended. Perhaps it will acquire the high title of a theory, and perhaps it will be buried for ever. But even if the verdict of history is not appealed and the funeral takes place, science will acquire its legacy. This is because hypotheses die but the facts gained with their help remain.

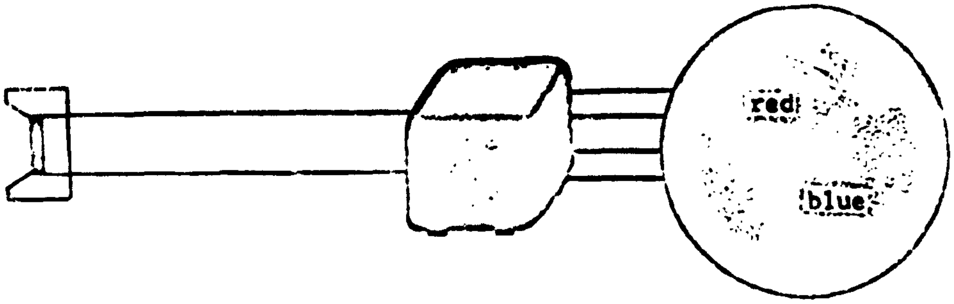


Before you is the recording of biocurrents derived from the optic nerve of a frog. The peaks of the closely arranged impulses correspond to red light. The peaks are farther apart after a blue light flashes.



Pattern of changes in current in a photocell after different colored rays strike it. Blue light causes the current to increase rapidly. Turning off the bulb causes the current to decrease rapidly. Turning on red light results in slow increase in the current to an intensity matching that of the light. The current decreases more slowly after red light is turned off than after blue light.

If, however, red light is abruptly substituted for blue or vice versa, the current does not remain unchanged. In the former, it decreases for a second; in the latter, it increases for the same length of time before returning to the original level.



General scheme of operation of a model of color vision. On the left - a photocell; in the center - operating units; on the right - an oscillographic screen covered for ease in observing color film. The redder the ray of light, the higher the spot appears on the screen; the bluer the ray, the lower the spot. The brighter the light striking the photocell, the brighter the spot.