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Yarbus's Conceptions on the General Mechanisms of Color Perception

Petr P. Nikolaev and Galina I. Rozhkova
Institute for Information Transmission Problems (Kharkevich Institute) of Russian Academy of Sciences, Moscow, Russia

Abstract
In the last series of papers published during 1975 to 1980, Alfred Yarbus tried to formulate general conceptions concerning the basic principles of retinal image processing in the human visual system. The original ideas of Yarbus were based on the results of his numerous and various experiments carried out with extraordinary inventiveness and great skill. Being concentrated primarily on the problems of color vision, Alfred Yarbus dreamed of elaborating a comprehensive model that would simulate visual information processing at the monocular precognitive level in the visual system of humans with normal trichromatic color perception. In this article, the most important of Yarbus' experimental paradigms, findings, statements, and conclusions are systematized and considered in relation to the classical theories of color perception and, in particular, fundamental theses of the Nyberg school. The perceptual model developed by Alfred Yarbus remained incomplete. Nevertheless, it is already evident that some intrinsic contradictions make it inadequate in terms of comprehensive modeling. However, certain partial advantages deserve more thorough appreciation and further investigation.

Keywords
color vision, colorimetry, color constancy, space of color sensations

Introduction

The purpose of this analytical survey is to consider the last articles by Yarbus (1975a,b, 1976a,b,c, 1977a,b,c, 1979, 1980)—a series of papers united under the title "Human visual system." He wrote them after his famous monograph "Eye movements and vision" had been published in Russian and English and highly appreciated in the Soviet Union and abroad. Yarbus planned to publish a new monograph based on these articles. Impressive psychophysical experiments of Yarbus often evoked heated discussions, in particular, in view of color perception problems, among his colleges in the laboratory vision at the IITP. Since then, many problems have lost their significance, but it is worth to outline the atmosphere

Corresponding author:
Petr P. Nikolaev, Institute for Information Transmission Problems (Kharkevich Institute) of Russian Academy of Sciences, 19, B. Karetny per., GSP-4, Moscow 127994, Russia.
Email: nikol@iitp.ru

of ‘‘brave hypotheses and ingenious declarations’’ of the 1975 to 1985 era because Yarbus’ papers somehow reflected those conceptual disputes. The disputes concerned the automatic field mechanisms of primary processing the image recorded by mosaics of sensors (in particular, photoreceptors), as well as the ultimate visual scene reconstruction stage, including identification of constant properties of the objects. In his studies, Yarbus used his own original approach and paid little attention to investigations of other researchers though their achievements might be related to his experiments and theories. By the time Yarbus undertook his studies on color perception, a number of fundamental discoveries concerning certain levels of input signal processing and particular mechanisms had already been made, and the evidence of extremely complex hierarchical organization of general color vision system had been obtained. For specialists in the fields of color perception and color reproduction, it became clear that the whole process of physical scene analysis and synthesis of visual image needed to be subdivided at least into three stages, or levels,—sensory, perceptive, and cognitive. As signal processing differs radically at different stages, it makes sense to study the mechanisms within the boundaries of a particular stage separately and to discover the rules of interaction between the mechanisms of different stages. Consequently, the arrangement of any experiment on color perception should include accurately formulated experimental target with respect to the signal processing stage and clear understanding of a proper response form and the experimental conditions providing its adequacy.

In this context, it is reasonable to recall that Nyberg (Yarbus’s colleague and the head of the laboratory of vision from 1951 to 1967) was the first who indicated to the source of the data to resolve the problem of *color constancy*. His finding was based on the analysis of ‘‘color solid’’—the mathematical concept elaborated by him and published in German as far back as 1928 (Nyberg, 1928) and with some delay in Russian (Nyberg, 1936). Half a century later, Forsyth (1990) created ‘‘Gamut’’ algorithm using similar but much simplified idea. Nyberg formulated strict definitions of the color concepts, determined the necessary conditions for color experiments, and proposed the method to calculate *color matching functions* of trichromats from the data obtained in colorimetric experiments on dichromats. He also expressed an idea of silent substitution colorimetry. This idea was realized by Bongard and Smirnov (Bongard, 1955; Bongard & Smirnov, 1957). Afterwards, Bongard initiated conducting a series of psychophysical experiments (Nyberg, Bongard, & Nikolayev, 1971a,b) revealing the role of achromatic objects and folded surfaces in the process of finding ‘‘corrections for color illumination.’’ As a result, Bongard substantially expanded the list of the *keys providing color constancy* suggested by Helmholtz (1866), the discoverer of the phenomenon.

At the beginning of computer era, when the ‘‘Artificial Intelligence’’ (AI) and creation of the ‘‘machine vision’’ systems were declared of pivotal importance, the joint intellectual efforts of neurophysiologists and psychologists as well as physicists and psychophysicists were required in order to provide solutions to visual recognition problems. Such multidisciplinary groups collaborated in many research centers both abroad and in the Soviet Union, in particular—at the IITP. Some of their joint intellectual achievements included:

- Retinex model of color constancy (Land & McCann, 1971);
  - mathematical model of lightness estimation for the nonuniformly illuminated mondrians (Horn, 1974) providing 2-D realization mechanism and supported by finding the neuronal parallels in the macaque retinal layers (Marr, 1974);
  - the model ‘‘Application’’ (Nyberg, Bongard, & Nikolayev, 1971a)—the three zonal model of color constancy;

- a novel approach to provide color constancy on the basis of electrophysiological properties of color-opponent neurons developed by younger colleagues of Yarbus (Maximov & Nikolaev, 1974) in the model where the constant color estimates were obtained by calculation (formation) of a color vector hodograph: the differences of the stimuli on both sides of the boundaries between the objects of different colors were summed over the retinal projection of the scene

If to substitute the terms, one can notice the similarity of the procedure mentioned above to the procedure of "estafette" (relay) summations of the color stimulus vector jumps at the boundaries of objects of different colors, developed in the later works of Yarbus (1977c, 1979, 1980). However, it should be noted that, in fact, the "estafette" idea had been put forward earlier, in the paper of Land and McCann (1971) referred to above; the essence of this approach was already clearly expressed there. Moreover, the article described corresponding mathematics, physical model, and some biologic correlates. Going further is beyond the scope of the introduction, since the differences between the theories can be understood only after giving sufficient account of the whole Yarbus's conception on the human visual system work. This conception was not presented as a complete research to a wide scientific community (in contrast to Yarbus's monograph on eye movements), so a brief description is required. Perhaps, our notes could be useful to the readers interested in the history of color perception theories since we participated in some crucial experiments and in discussions evoked by their results.

Yarbus described his "phenomenologically voluminous" *conception* in two forms: as the results of psychophysical experiments and as the theoretical theses. Our main purpose is to present the essence of the original Yarbus's theory (concerning color vision of normal trichromat), to consider the limits of its application and to discuss its place among the ideas of other authors. We will not focus on the details of Yarbus' experimental methods, which are worth to be considered separately, but will rather switch reader's attention to technical aspects, as they contained many "small discoveries" per se.

Obviously, it is reasonable to consider the propositions that constitute Yarbus's *conception* with regard to the history of color perception studies and to those fundamental statements that define certain constraints obligatory for any new theories, including nontraditional views of Yarbus. As has been mentioned earlier, the following three qualitatively different stages of information processing can be naturally distinguished in the human visual system—sensory, perceptual, and cognitive ones, each having specific mechanisms and own laws. The most rigid laws have been discovered for sensory (input) and cognitive (output) stages that will be considered in the first place. For the sensory stage, the input signal is retinal image; for the cognitive stage, the output product is visible image. The perceptual stage is rather uncertain in input or output definition and includes various modules functioning in parallel and receiving not only visual signals originated in the retina but also certain signals from other structures—oculomotor, proprioceptive, and so forth. At this stage, various intermediate products of information analysis are created that are compared and combined to form visible images consciously perceived at the cognitive stage.

Sensor Stage Statements in Psychophysics of Visual Perception

In the middle of 19th century, Grassmann (1854) had founded the color vision science—he discovered experimentally the linear algebraic rules for the colors of mixed radiations of different (arbitrary) spectra. This was achieved due to a special technique of colorimetric experiment developed by Grassmann. In strictly defined conditions of such an experiment, subject's "seer brain" acts exclusively as the null device, only testifying the fact that the two radiations—test and comparison lights—are indistinguishable, the comparison light being composed of the three linearly independent basic radiations. Grassmann's laws define an affine color space of trichromatic human *daylight* vision, allowing accurate predictions of the color measurement results for the linear mix of lights knowing only the data for their component lights.

At the beginning of the 20th century, new discoveries were made:

(1) strict definition for the basic notion (term) "color" was found;
(2) errors of colorimetric measurements were estimated (about 1%);
(3) form of the affine *color cone* was defined in the *physiological color space* where colors were represented by vectors with components corresponding to sensor responses;
(4) distribution of color vectors' central projections onto the chromaticity plane (called "color triangle") was thoroughly studied.

Regarding the first point, it should be outlined that, due to the elegant *spectral* definition proposed by Schrödinger (1920) (not including qualitative categories related to the subjective impressions of the observer), the notion of *color* became immutably fixed as unambiguously interpreted term within the *science of color*, so it could not be subjected to revision forever, regardless any widespread misconceptions! According to Schrödinger, the color is a common property of radiations of different spectra, indistinguishable for human in colorimetric procedure.

The variety of color sensations experienced by human at various adaptation and illumination conditions while viewing objects of various sizes, which are projected to various retinal areas and have various surround, is much richer than the variety of colorimetric color sensations. This circumstance impedes theoretical analysis and interpretation of experimental results. That is why an unambiguous terminology in psychophysical studies is of paramount importance: loss of unambiguity in interpretation of definitions and operations often looks like the "problem with dimensionality" when the author places the result of the experiment into some "color perception space" inadequate to the number of independent variables in the experiment. This leads to the collapse of the theory or to lack of interest in it—due to the loss of trust to its declared conclusions.

In this regard, the characteristic examples are fruitless attempts (undertaken during the past quarter century) to develop a matched contrast "hue/saturation" coordinate grid (USC) in the plane of color triangle and to prove theoretically the consistency of the proposed versions. The following indisputable facts are sufficient for realizing the absurdity of this activity:

(1) an affine color space can't have a unique fixed achromatic axis *by definition* because colorimetry does not determine the subset of "achromatic lights";
(2) colorimetry does not specify the "spectral properties of the light beam" in the form of the analog to the perceptive dyad "chromaticity/saturation" ensuring only a linear law for the behavior of local component "brightness of the beam" and excluding such a possibility of its metrization that can determine the shape of isoluminant surface.

Returning to Yarbus's color perception legacy, as a preliminary remark, mention should be made of some serious difficulties encountered during its analysis. The author never referred to the discipline *colorimetry,* but in the first paper of the series (Yarbus, 1975a) followed its formalism. However, further, he used the term *color* in his own (not colorimetric) sense. Moreover, in the surveyed papers, there are no author's comments on the *dimensionality* of the proposed multidimensional color space with the following stimulus components in *j*th color channel: $k \cdot \ln(a_{ji}/a_{j0})$, where a_{ji} is a usual *j* component of the visual stimulus at the point P_i and a_{j0} means independent action on the *i*th point P_i at the "sighting retina" of the signal in the same channel from the extreme peripheral area. Yarbus called this area a *blind retina* since it could not evoke visual sensations being activated in isolation. The receptors of this blind area are normally stimulated by the scattered light that originates from the projected image, and light with specific spectral characteristics that penetrates into the eye through its scleral cover.

Attempts to define the physiological color space proceeding from the initial colorimetric 3-D space but "completing it in a special way" to explain the phenomena of contrast, irradiation illusion, lateral inhibition, and others (Bezold–Brücke shift, Abney's effect, etc.) had been made throughout the 20th century by many psychophysiologists of different schools and followers of different conceptual paradigms. The only benefit of such attempts was that with every unconvincing version of "synthesis" (and in parallel to increasing opportunities for quantitative model experimentation—in the second half of the last century), among the physical–mathematical Diaspora of the psychological community, the awareness was strengthened in fundamental irreducibility of *cognitive* processes to *sensory* functions. It has become evident that they are explicated in different spaces—by the necessary dimensionality of description (representation) and by the task to be solved as well. The success of the *cognitive* approach for the technical systems confirmed this conclusion also for the automatic AI systems.

Cognitive Stage Statements in Psychophysics of Visual Perception

Let us recall the Nyberg school doctrines constituting as a whole the direct development of the physicist Helmholtz views on the objective physical nature of the recognition problem that can be successfully solved by an observer endowed with color discrimination abilities. In other words, refer to the circumstances, *objective* by nature, serving as the pretests for successful "solving in sensations" the problem of identification in the details of the phenomenon "color constancy." According to Nyberg, the first and the necessary condition for an adequate treatment of the signals from the world of visible 3-D objects in the course of the ongoing in the "seer brain" (Gregory, 1970) *interpretation* process evoked by the input retinal activity patterns is an adequacy of topological partitioning of the visual field on the areas related to the projections of the *primary* sources S_i illuminating the scene (e.g., the sun and the sky for the outdoors scenes) whose radiation enters the eye in its original form, and the areas related to the projections of the solids of various colors formed by the spectra of the primary, secondary, and so forth., sources transformed due to *reflection* from the surfaces. The spectra of the sources and of the reflected radiations are usually very complex (in fact, of infinite dimensions). The spectral function of the light reflected from the object surface and entered the eye can include several independent components determined by the spectra of different sources illuminating the surface and by the angles between the falling rays, normal to the surface, and the visual axis. In any language of reduced description, created for transition from the space of spectral functions to the space of their vector approximations with smaller dimensionality (performed in living or technical sensory systems), the color characteristics of surfaces don't oblige to follow the specifics of the source spectral functions S_i either in power or in color parameters. Their characteristics are *independent*.

Pursuance of the dichotomy described above excludes confusion of terms during presentation of the experimental results. The visual field segmentation procedure is a partial consequence of the universal requirement to classify the perceptual ensembles on those which fall in the category *radiations* (and only the ensembles having this status can be described by colorimetry language) and those which carry out the information about the reflective properties of the colorful *surface* that transformed spectral characteristics of the light beam. The idea of identifying such properties as "lightness" and "brightness" remains physically absurd even if a scientist, who develops the theory of color constancy, can successfully overcome the difficulties concerning the acceptance of the unified formalism in color dyad "hue/saturation" for description of "rays" and "solids." Let us emphasize that *brightness* is a power parameter of radiation that has physical dimensions whereas *lightness* is a dimensionless quantity. In physics, the term *lightness* (under the name *albedo*) can be correctly used only for *lambertian* achromatic surfaces, for which the "matte" is idealization (and one can estimate the error of this approximation) and the achromaticity is a spectrally determined property. From the point of view of physics and mathematics, the attempt to develop a unified vocabulary and grammar of metalanguage for heterogeneous areas of color perception theory means unthinkable situation—pseudo consolidation of mutually exclusive theories. Nevertheless, some authoritative psychologists couldn't avoid the temptation to make such attempts that led to "legalized aberrations" of initially clear phenomenological picture.

Noteworthy that already in his thesis "on the duality in perception of solids' colors," Helmholtz expressed doubts in sufficiency of three dimensions for adequate description of the colors of the surrounding objects. The mere existence of realistic painting indicates that an artist, who is skillful in a reliable representation of the color in each point of the depicted scene, has an ability to switch off his immanent color constancy mechanism in order to reproduce the colorimetric picture of ray distribution on the canvas. His creative task is to represent an inconstant projection of 3-D space and forward to the observer the task of providing color constancy in perceived image. For example, in order to draw two identical yellow objects located in different parts of the scene—one on the sunny side and the other in the shadow (illuminated by the blue rays of the sky only)—the artist needs to use the dyes of different colors: *yellow* for the first object, but *green* for the second one.

There was no clear distinction between color constant and inconstant tasks in the Yarbus's research. Describing most series of experiments, the author mentioned some conditions of viewing or stimulation and considered as the result the subject's oral report concerning either "own color of the sample" (that means *coloration,* or *body color,* in the language of perception and, physically,—reflection properties determined by the perceptual mechanisms of color constancy) or noticeable changes due to stimulation transforming color estimates (sometimes only brightness) and breaking the link to the "own color" (i.e., leading to the conditions of *inconstant* perception). In this respect, it is worth recalling the Nyberg definitions (Nyberg, Bongard, & Nikolaev, 1971a) that classify the dichotomy of recognition results in the language of the scene features. According to Nyberg, color perception of the scene can be:

(1) objectively adequate, that is, representing invariable reflective properties of the object surfaces;
(2) "almost colorimetric" (i.e., inconstant);
(3) corresponding to regular distortion of the situation (1).

In somewhat simplified form, the classification can be described as follows: in the viewing conditions of color constancy, the requirement for the objects to be indistinguishable by color means to have the same *surface color* (coloration, body color) while, in the color inconstant colorimetric conditions, visual similarity of the stimuli is due to the same *ray* (beam) *color*; and when there is a deficiency of the chromaticity signs characterizing the color of the light source, *false constancy* arises that is manifested as systematic bias in perceptual estimates of the object coloration. It is evident that, locally, the task of color constancy is insolvable in principle: the stimulus received from the point *P* of the scene where the object of an *unknown coloration* transformed the falling light beam of *unknown power and color* cannot be used for solving the inverse task (finding the estimates of coloration) without having a likely hypothesis about dominating illumination color. This hypothesis is based on the signals from the neighborhood of *P* (small or including the whole visual field) and needs to take into account the geometrical 3-D model of the scene, that is required for rendering the picture of light scattering. Thus, the "magical mantra" of Maxwell "any vision is color vision" should be interpreted in the following sense: the obligatory component of the color constancy process is creating the picture of light scattering, and even colorblind subject with monochromatic vision has to do this in his world of "dark and light objects."

In conclusion of this section, we formulate the limitations on the dimensionality of the cognitive output signal (implying color constancy): it has to be not less than 4, but no more than 9. The lower limit is determined by the minimal number of 4-D vector components of "object color" that can not be reduced: hue, saturation, brightness (for the light rays), lightness (for the object surfaces). The upper limit is defined by Petrov's theorem on color constancy in machine vision (Petrov, 1984); this is a majorant estimation for the case of arbitrary inhomogeneous angular distribution of illumination. To avoid misinterpretation of the discrepancy between the theses claiming 3-D and 4-D perception, let us clarify that four-dimensionality of the "cognitive" product only implies the possibility to switch from one 3-D mechanism of interpretation to another 3-D mechanism (the switch is governed by "cognitive centers" of the *integration* level). According to Helmholtz's guess, the color vision system can block color constancy mechanisms when necessary, so there is no need for concurrent realization of the recognition act which requires representation of products in 4-D space.

The next section concerns the cases with a deficiency of the data on the color of illumination when the visible image appears to be a "perceptual merge" of trichromatic vision features that are not already colorimetric but have not yet demonstrated color constancy.

Perceptual Stage Statements in Visual Psychophysics

The visible images produced by visual system are always interpreted as some entities belonging to the outside world—solid objects of various colorations, flows of light, moving liquid and gaseous substances, and so forth. If there is enough incoming information, these entities can be adequately recognized at the cognitive level with participation of constancy mechanism. But if this information is not sufficient for adequate image formation, visual perception appears to end up inside an extensive area of visual impressions revealing false constancy. Mainly this area of visual research is most widely represented in the works of phychologists and physiologists, and Yarbus's experimental and theoretical investigations were concerned with the analysis of its mechanisms. Conventionally, this area can be attributed to the *perceptual* stage in the visual process implying that visual images (percepts) can substantially differ from those "ideal" images of the external objects that could be created in most favorable conditions. To review the works related to this area of research does not seem realizable even with regard to its conceptual framework. In the context of Yarbus's "paradigms and claims," it is reasonable to outline the common experimental facilities and the target ideas that link constantly updated database of results on this topic with Yarbus' *s* "intentions." As follows from the content of the entire cycle of the articles discussed in this research, the author's aim was to reveal the automatic operations (not depending on the will of the subject) inside the visual system and to find its laws in the form of strictly determined mechanisms, not extending beyond the borders of visual sensory modality and not requiring access to memory.

As has been already mentioned in the previous section, in the viewing conditions of *false constancy*, the best outcome of the identification act in its relation to the cognitive task could be expressed as a *systematic* bias of produced estimates describing reflectance characteristics of the objects. According to this, the stimulus scene arrangement should provide a possibility to reveal such biases on the basis of subjects' responses. In the majority of Yarbus's experiments, the results were recorded on the qualitative level: "subjects confirmed the hypothesis of the author" or "the result appeared to be unexpected, but it could be interpreted in such a way..." As a rule, in his experiments, Yarbus used "maximal simplicity" of the visual field organization typical of color illusion studies or investigations of various kinds of contrast (spatial and temporal). In such cases, only a couple of points in the color space describing the experimental field are often sufficient (i.e., the scene can be represented by two sets of *color* coordinates only) for clear manifestation of the expected effect (e.g., lateral inhibition or filling-in).

The common concept of the experimental approach for the perceptual level can be expressed in such a way: Simple visual field organization with minimal complications in comparison to colorimetric conditions allows to reveal *separate* automatic mechanisms of *precognitive* stage used in the hierarchical system of cognitive analysis for the fastest decision in choosing the "leader" among the set of alternative interpretation variants of the perceived stimuli. In situations of real 3-D recognition tasks, with much more complex organization of the scenes as concerned objects' shapes and colorations, various prefabricated solutions produced by some partial automatic mechanisms of the input signal transformation are delivered to the level of cognitive choice of the final decision that acquires clear features of sensations in the form of "actual visual field" with all its "true" and "false" manifestations of constancy mechanisms involved in the process of recognition.

To study that "soldered" precognitive mechanisms, the scientists intentionally (or intuitively, by trial and error) simplified the content of psychophysical experiment in order to reveal some unambiguous scheme of the stimulus field transformation (i.e., to obtain unambiguous description of some isolated partial mechanism of sensory signal processing) on the basis of the experiments with such incredibly complex "recording instrument" as the structural material of the subject's psyche. However, they were never be able to prove that they had found the universal laws valid in all situations—probability of obtaining the predicted results was crucially dependent on the parameters and arrangement of test field. In other words, in a general case, one could only select separate segments where some specific automatic mechanisms could work successfully. In this respect, the methods used at the precognitive mechanism studies principally differ from the *technique of colorimetric experiment* that is notable for its important property: it gives no information cause for involving *cognitive* system with its powerful and structurally complex "final product of object interpretation." Due to this property of his ingenuous experimental technique, Grassmann could formulate his three laws, as valid as Newton's laws.

On the Normalization and Symmetry in Color Systems and Models

In the majority of color vision models proposed as the "universal" ones, it is claimed that the main task of "perception" is not an adequate assessment of *coloration* but color signal *stabilization* (with regard to dynamics of dominating illumination). The solution to this problem is achieved by introducing a channel-by-channel adaptation based on von Kries (1905) idea into the procedure of input signal processing. This transformation is not resource consuming in technical implementation and can be incorporated without significant difficulties into theoretical biological schemes. The dynamic adaptation of this kind provides high-contrast sensitivity of the system in a wide range of light intensities that was long ago noted and, for certain realizations, assessed quantitatively both by the developers of hardware for trichromatic cameras and by theorists-biologists. Incidentally useful property of this adaptation is that it transforms color vector field, on average, favorably for the purposes of color constancy. Due to the mechanism of tuning the color channel triad, the spectral sensitivity function of each channel varies proportionally to the power of illumination transformed by the sensor into the vector field of the tristimuli that, in the plane of color triangle, leads to systematic bias of the points in the hue map to the side opposite to the hue of dominating illumination. This property was analyzed long ago, and a number of authorities characterized it as "satisfactory for realizing the phenomena of *color constancy* in psychophysical models of vision" although there were published other opinions (Hurlbert & Wolf, 2004): see the discussion of this issue in (Brill & West, 1986).

As not all the scientists considered this solution as the final one, there appeared other attempts at creating the models of precognitive level, not requiring data from visual memory (on the shape and color of the objects recognized earlier by the intellectual system of associative visual analysis), for the more accurate estimation of object coloration (Brill, 1978; Guth, Massof, & Benzschawel, 1980; Petrov & Kontsevich, 1994; Shafer, 1985). In particular, among the operations of image processing the so-called *normalization* procedures are commonly used in color constant technical models. These procedures consist of specific estimation of the two parameters of object coloration achieved through the transition to the dimensionless (scalar) coloration components and expressed by the ratio of the quantities of equal dimensionality representing the power of the light reflected at the point P_i of the object in the direction toward the sensor and "hypothetical illumination power" at P_i. (This estimation is for the objects of uniform coloration; in human trichromats, the analog of this pair is dyad "hue/saturation.") In the spectrozonal models of color constancy of *applique* type (Nyberg, Bongard, & Nikolayev, 1971b; Nikolaev & Nikolayev, 2007), there were used the ratios $a_{\mathrm{ji}}/a_{\mathrm{j0}}$ (a_{j0} is *j*th component of illumination at P_{i}, and a_{ji} is *j*th component of reflection); in a *gauss* model, where the spectral characteristics of illumination $S(\lambda)$, reflection $\Phi_i(\lambda)$, and sensitivity $S_{\mathrm{j}}(\lambda)$ were expressed by *normal distribution* functions (Nikolayev, 1985; Weinberg, 1976), slightly more complex estimation of hue was employed but with the same purpose—to obtain dimensionless ratio of the reflected power to the power of illumination.

Yarbus's model is worthy to be considered in a class of such models. The above mentioned formula $\ln(a_{ji}/a_{j0}$; Yarbus, 1975b) gives rise to a comparison of his approach with the discussed *normalization* in the technical models of color constancy. Within this analogy, the value of a_{j0} means jth component of illumination hypothesis $S(\lambda)$. Experimentally investigating the effects of stray light stimulating the extreme peripheral zone of the retina, Yarbus came to the conclusion that the peripheral light (including the ambient light from the beams penetrating the eye camera through the pupil and the light transmitted through the sclera of the eyeball) had a ring *uniformity* in each channel *j*, and its impact a_{j0} played the role of an *additional* factor of stimulation. This factor has the following properties: (a) as a member of the formula in the *denominator* under the logarithm, it imitates lateral inhibition, (b) it is a kind of normalization member ("specifies the value of a *unit j* components of the color vector" and generates a vector in the form of a dimensionless triad of *numerical* values), and (c) performs the function of an adequate equivalent for the average illumination of the scene.

Assessing profitability of Yarbus's idea on the role of the peripheral blind retina as an area producing "hypothesis of dominant illumination $S(\lambda)$," it should be noted that, in technical realizations of color constancy, assessment of similar ideas had already been made in a number of studies. Dominant illumination was used as a constancy key in the "Grey World" model (Buchsbaum, 1980; Helson, 1964; Hurlbert, 1986; McCann & Hall, 1980; McCann, Hall, & Land, 1977). "Grey World" model idea is that the scene with the so-called *rich color variety* $\Phi_i(\lambda)$ gives a chance to calculate a reasonable estimate of the dominant illumination color by *averaging* power of all stimuli over the field of view. Now, after its thorough testing, this model is considered as a "zero reference level" for rating the models with other constancy keys since it has the worst scores (Barnard, Martin, Coath, & Funt, 2002; D'Zmura, & Iverson, 1993; Finlayson & Schaefer, 2001; Funt & Drew, 1993; Klinker, Shafer, & Kanade, 1990; Tominaga & Wandell, 1996).

To support our statement that Yarbus's model, like other biological and psychophysical color constancy models available, has low effectiveness compared with the machine vision developments, let's emphasize, that the best modern technical models of color vision have already reached the *cognitive* level of AI. Now, their purpose is clearly formulated as *estimation of reflectance characteristics* of objects in *really complex 3-D scenes* while the models providing only qualitative correspondence of a color transformation effect to a theoretically predicted bias (the criterion usually taken as sufficient for the perceptual color models) have long being considered as unacceptable. Because of unsatisfactory accuracy in recognition of object coloration, many computational algorithms were practically rejected in technical vision, for example, the algorithms based on the laterally controlled color adaptation mechanism (based on changing effective diameter of its receptive field), the "Gray World" model and even "Gamut" (due to the difficulties of its application to the scenes with two light sources, like the scene with "sun and clear blue sky"—quite common for the outdoors situations).

Nevertheless, all the mechanisms revealed by means of psychophysical methods, which promise to be *implementary* for the color constancy phenomenon (i.e., *functionally* rational and, in addition, having neurophysiological plausibility), are worthy of further thorough experimental investigation, (including computational simulation of the theoretical schemes, clarification, and revision of the yet *hypothetical* perceptual color mechanisms—by means of quantitative modeling).

In the next section, we'll describe the Yarbus's concepts in more details to give a possibility for the judgments with better argumentation.

Fundamental Postulates of the Yarbus's General Concept of Visual Perception

In the first article of the series with the subtitle "Adequate visual stimulus" (Yarbus, 1975a), the author had brought the reader to the principally important system of the dynamics notions related to the human visual system functioning and conceptually connected with his original idea of the *empty field* phenomenon expressed in the monograph (Yarbus, 1965/1967). He formulated the conditions for the occurrence of visual impressions different from the empty field sensation. In the next articles, the author tried to develop a general theory of color perception; however, the majority of statements were based on simple examples with several flat color stimuli lying in the same plane (most often—as a concentric pattern) and illuminated uniformly.

Embarking presentation of his concept, the author defined the term *total action of light a* as a joint response of all eye receptors and gave the following commonly used formulae for the responses of the three human cone photoreceptors with current functions of spectral sensitivity $R(\lambda)$, $G(\lambda)$, $B(\lambda)$ to the light stimulus with spectral composition $\psi(\lambda)$

$$a_r = \int R(\lambda)\psi(\lambda)\mathrm{d}\lambda;\ a_g = \int G(\lambda)\psi(\lambda)\mathrm{d}\lambda;\ a_b = \int B(\lambda)\psi(\lambda)\mathrm{d}\lambda$$

Each paper of the discussed series has theoretical and experimental parts. For convenience of the analysis, at first, it is rational to present the original basic statements of Yarbus, mostly in the form of citations. The following set of statements seems to be sufficiently representative:

(1) "For the visual system functioning, it is not enough to have temporal changes in the absolute light differences only—it is necessary to have temporal changes in relative differences of light action a; the formal condition for evoking visual impressions is: д/дt(grad ln a) ≠ 0." "The adequate stimulus S, in response to which some temporal and spatial visible color differences appear in the visual field, is the change of spatiotemporal relative differences in the retinal illumination. For a given point (and its vicinity) on the retina, S is defined as S = д/дt((grad a)/a), where t—time, a—action of light" (Yarbus, 1975a, p. 919).
(2) "The starting area (the zero level) in the human visual system is the extreme periphery of the retina, which, in normal conditions, is "blind" and illuminated by a diffuse light, averaged over the whole field of view; the action of light on this part of the retina a0 plays a role of a measuring unit" (Yarbus, 1975b, p. 1100). In the presence of detected boundaries in the visual field, the color of each sample (point) is calculated by means of an "estafette procedure" starting from zero at the extreme retinal periphery and implying summation of all the differences between the adjacent fragments of the visual field along any arbitrary trajectory leading to the given sample (point).
(3) "The illumination of the extreme periphery by diffuse light is considered as an image of the 'largest possible sample' having zero color in all conditions of perception" (Yarbus, 1975b, p. 1101). (Evidently, "zero color" has the same meaning as "empty field" in the framework of another interpretation.)
(4) "The colored sample, surrounded by an area of different color, acquires the color of its surrounding when the border between the two samples is stabilized" (Yarbus, 1975b, p. 1101). If the borders between all the samples in the visual field are stabilized, its visible chromaticity vanishes and all field acquires zero color since calculation starts from zero and all the borders become undetectable.
(5) "For descriptive presentation of the set of visible colors (and their transformations) it is convenient to take a usual three-dimensional space in which color will be represented by the coordinates ln(ari/ar0); ln(agi/ag0); ln(abi/ab0); where the triplets ari, agi, abi and aro; ago; abo mean the responses of the three types of cone receptors at the point of color estimation and at the extreme periphery, respectively. This space will be called "the space of color sensations". Since these coordinates can take positive and negative values, then, obviously, in this space, one can specify the location of any color (the colors of the rays and colors of the object surfaces)." Yarbus, (1976a, p. 152)
(6) "The visual system uses not only color differences but also reversed color differences. The sum of a color difference and corresponding reversed color difference gives zero (the

difference disappears)" (Yarbus, 1976b, p. 735). "If the background is of zero color, then the reversed color difference is equal to ***anticolor***" (Yarbus, 1976b, p. 737).

First of all, let's emphasize that the papers of the series present no definitions of the parameters and constants for calculation of the partial derivatives. Specifically, in the article with subtitle "Color" (Yarbus, 1975b), there are no definitions of the operations "double integration of the signal (over time and space)." There are also no descriptions of the measuring procedures that could provide quantitative verification of the agreement or discrepancy between the theoretical predictions and the experimental data. Thus, the reader has to take on faith the conclusions of the author.

It is notable that, in his model, Yarbus attached a specific sense to the term *brightness* having no analogs in the models of other researches. According to Yarbus, "in full agreement with the experiments," at the point where light action is equal to a_i, visible brightness is determined by $\ln(a_i/a_0)$, a_0 being light action at the extreme retinal periphery; therefore, when a_0 becomes larger than a_i, the ***brightness becomes negative*** and the color at this point appears to be darker than the zero color. To support this thesis, Yarbus carried out the experiment using a single light source with a monochromatic red radiation (680 μm) and changed the proportions of a_i and a_0. The result of this experiment was described in the following way: "when a_{ri} was larger than a_{r0}, the observer perceived saturated red color but when a_{ri} was less than a_{r0}, the observer perceived saturated black–green–blue color (black and additive)." Thus, in the Yarbus's model, brightness can be both positive and negative, and change of the sign automatically means radical change of the color.

Investigating illumination of the extreme retinal periphery, Yarbus has come to the conclusion that, in natural conditions, this part of the retina is lit by the stray light averaged over the whole visual field and consisting of the light entering the eye through the sclera, the light entering the eye through the pupil and scattered in all eye media, and the light reflected from the eye fundus. The crucial point for the Yarbus's model is that light action at the retinal periphery has to be larger than at the retinal images of dark and black objects (Yarbus, 1976c, p. 1101). This circumstance is used by the author to develop his own original model of the color space. In the paper subtitled "Space of color sensations" (Yarbus, 1976a, p.150), he interpreted the sets of black, dark, and "dirty" colors (having no analogs among the spectral colors) as corresponding to the stimuli with "negative values of $\ln(a_i/a_0)$ in three, two, or one of the cone channels."

As a constructive commentary to the Yarbus's *space of color sensations*, it seems reasonable to recall the preceding analogs of color spaces with clearly defined properties—namely, of the *affine colorimetric color space* and the *affine color solid* of Nyberg. To ease the comparison, a schematic presentation of these spaces is given in Figure 1. The three schemas of this figure—colorimetric color space of Schrödinger (a), Nyberg's color solid (b), and Yarbus's space of color sensations (c)—are related to the three different levels of visual information processing.

The first one is a space of physiological colors related to the sensory level. In this scheme, the colors of the light beams are presented as vectors originating from the zero point O and situated inside the coordinate octant *ORGB* determined by the basic vectors (*R, G,* and *B*) corresponding to the responses of three cone receptors. The larger brightness of the light beam, the longer should be the vector. The spectral colors form an unclosed cone surface and determine "the triangles of color mix" at various levels of brightness.

The schema of Nyberg is related to cognitive level. It systematizes the perceived colors of surfaces (body colors). The concept "color solid" is introduced as a linear 3-D totality of colors generated by a trichromatic system with a fixed set of the sensor spectral sensitivity

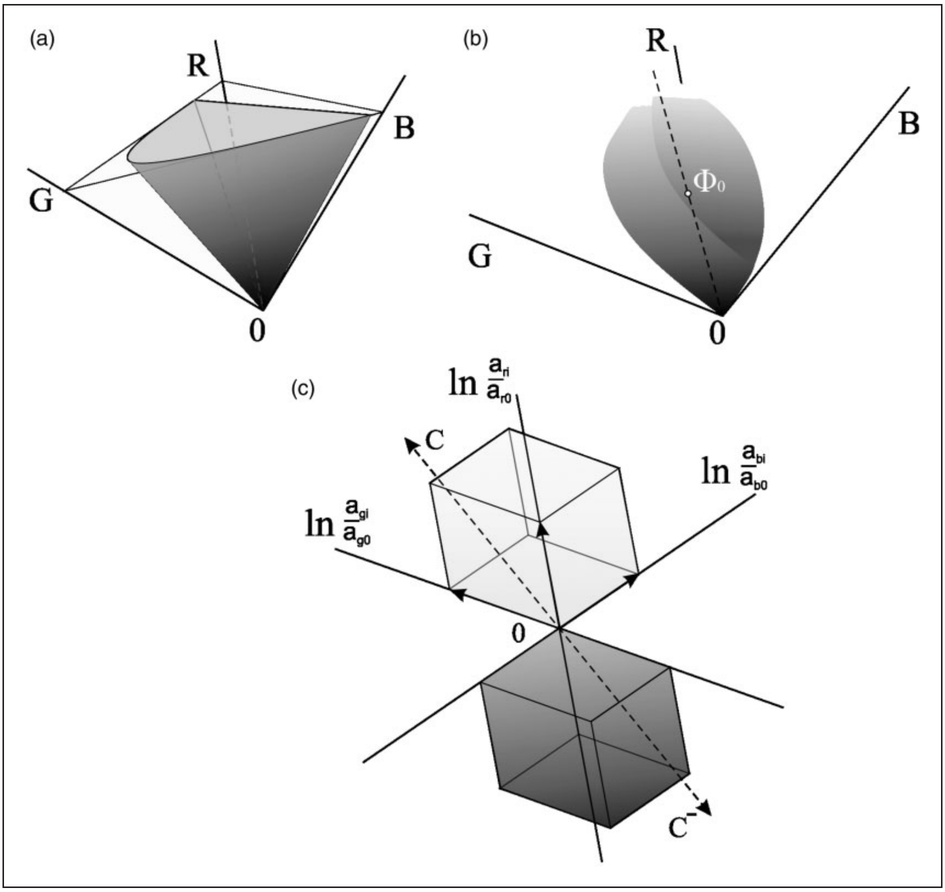

Figure 1. Color cone of spectral rays in the affine space of physiological colors (a), Nyberg's color solid in the affine space of colorations (b), Yarbus's space of color sensations (c): the marked octants with positive (negative) values of all the coordinates include the spectral colors with positive (negative) brightness; the rest of the octants correspond to various "dirty" colors having mixed positive and negative components.

curves, $R(\lambda)$, $G(\lambda)$ and, $B(\lambda)$, in the case of a single source of illumination with the spectral curve $S(\lambda)$. This color solid comprises the triads of responses to all spectrally conceivable colorations $\Phi_i(\lambda)$. It has been shown that a smooth surface of a solid (similar to a lentil) corresponds to the "ideally saturated" colorations. They are named *optimal* and have reflectance coefficients equal either to 0 or to 1 and the spectral curves $\Phi(\lambda)$ with one or two vertical borders in the visible range.

The color solid of Nyberg has a property of central symmetry relative to a point of the color space depicting the response to a 50%—achromatic gray surface Φ_0 with the spectral curve $\Phi_0(\lambda) = \text{const} = 1/2$. The symmetry of the solid is determined by the colors of the stimuli with the so-called *additional colorations* yielding the condition $\Phi_1(\lambda)+\Phi_2(\lambda) = 1$. Thus, $\Phi_0(\lambda)$ is a unique pigment of an object with a body color additional to itself. Black and "dirty" colors are produced by colorations evoking smaller responses than $\Phi_0(\lambda)$ in all sensors or in one to two types of them.

Yarbus's scheme is related to an intermediate—perceptual—level; it is designed for representing the colors of the precognitive percepts—sensations that are not unambiguously recognized as the properties of the external entities. The space of color sensations is defined by Yarbus as the 3-D space where specificity of the perceived color is determined by the following coordinates: $\ln(a_{ri}/a_{r0})$, $\ln(a_{gi}/a_{g0})$, $\ln(a_{bi}/a_{b0})$. The variety of colors determined by these formulae is more voluminous than the sets of colors represented in the two spaces described above. Due to using logarithmic functions and denominators, Yarbus expands the area of possible colors to all the octants of 3-D space allowing the existence of negative coordinate values whereas in the schemas (a) and (b) only positive values are permissible. The reference point in the scheme (c) corresponds to the zero color: $\ln(a_{ri}/a_{r0}) = \ln(a_{gi}/a_{g0}) = \ln(a_{bi}/a_{b0}) = 0$ (when $a_{ri}/a_{r0} = a_{gi}/a_{g0} = a_{bi}/a_{b0} = 1$). The octants with positive (negative) values of all the coordinates include the spectral colors with positive (negative) brightness; the rest of the octants correspond to various ''dirty'' colors. The points C and C^- at the scheme (c) illustrate the sense of the dyad ''color/anticolor'' in Yarbus's concept—it is a pair of vectors whose sum is equal to zero: all the coordinates of anticolor are opposite to the coordinates of color (Yarbus, 1976b, p. 738). In a similar way, Yarbus defines the dyad ''color difference/reversed color difference'' implying opposite differences of color vectors giving zero when summated. It is noteworthy that, in the Yarbus's concept, the colors of light beams and the body colors are not distinguished. As a preliminary commentary to this property of the Yarbus's scheme, it is proper to recall of the principal differences between the color characteristics of the radiations and colorations and the duality of human color sensations: when the observer is looking at yellow dandelion located in the blue shadow, his eyes receive but only green rays from it; however, he simultaneously feels green hue of rays and yellow coloration of the dandelion.

In the theories of other researchers, the properties of color perception subjected to modeling have clear interpretation in view of their quantitative estimation. For instance, in Nyberg's concepts on the phenomenology and mechanisms of color constancy (Nyberg, 1960) and in his model of color solid, the additional colorations (body colors) Φ_1 and Φ_2 are strictly determined in physical terms and color coordinates (giving concrete examples of the opponent pairs: ''black/white,'' ''blue/yellow,'' ''green/purple'') as the colorations evoking three-sensor responses whose vector sum is equal to the responses evoked by the achromatic coloration Φ_0.

The possibilities to investigate Yarbus's color space quantitatively are very restricted—first of all, due to the difficulties of measuring the extreme peripheral light (to find a_0) and, also, due to the lack of the clear rules for operations with negative brightness. To clarify some aspects and to critically evaluate the model, it is appropriate to confine the discussion to the ''key'' experiments of the author himself.

Yarbus (1976b) describes the experimental series designed to give an idea of what happens to the perceived color of the sample presented against a background screen after stabilization of the border between them followed by a fast replacement of the first sample by another one, in particular, having the color identical to the background. Denoting the background screen color as E_1, the color of the first sample as E_2, and the color of the second one as equal to E_1, Yarbus formulated his prediction concerning ''new emerging color of the sample'' on the language of the vector model in the form ''$2E_1$–E_2.'' Yarbus deduced this formula from the relation $(E_1$–$E_2)+E_1$, as the ''sum of the reversed color difference and the color of the screen.'' The subject had to give a report on the correspondence of the perceived color to the color ''$2E_1$–E_2'' through subjective assessments based on the *memory* of the original colors of the samples and the screen.

It is worth noting that, in this and other similar experiments, the sample and the screen were located at different distances from the eyes of the subject. An idea of a real setup is

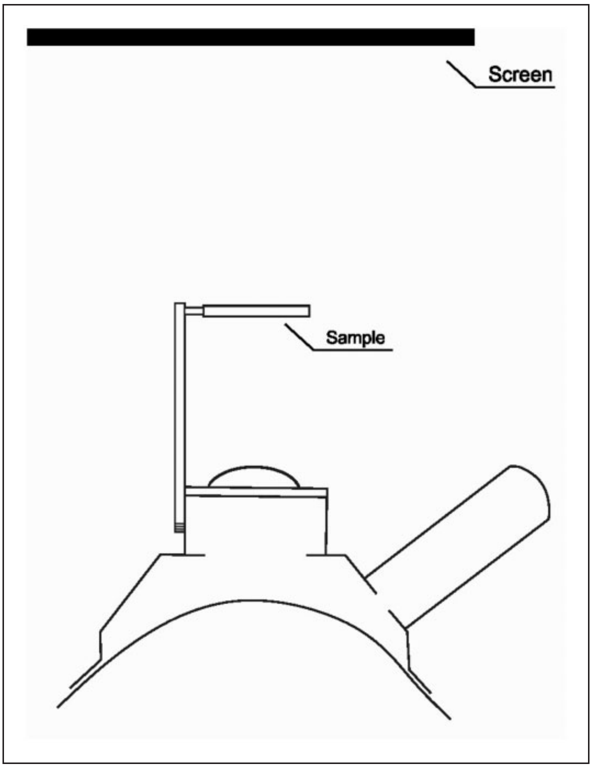

Figure 2. Suction cap with stabilized test sample attached to the subject's eye and a screen with unstabilized background.

shown in Figure 2: the sample is attached to the suction cap while the screen is situated at a distance of 50 to 70 cm. This separation facilitates the filling of the stabilized sample with the color of the screen when the observer's attention is attracted to the unstabilized screen.

In fact, on a qualitative level, explanation of real changes observed in such an experiment is possible in the framework of traditional theories and does not require introducing the new concepts. Let's analyze the description of a typical experiment with a red screen.

> If, initially, a sample had a white color whose brightness was close to the brightness of the screen, at the moment of transition from white to red (removing stabilized white sample from the field of view and substitution of its area by the area of the background red screen) the color was perceived as dark-saturated-red, much more saturated than the red screen color.

Isn't it a result that could be predicted merely taking into account the effects of adaptation? It is evident that, at the retinal image of the red screen, adaptation to red light was more strong than at the retinal image of the white sample having the same brightness (since its brightness was determined by the sum of various radiations). Therefore, red light of the second sample that stimulated less adapted area should evoke larger responses in red cones than red light of the screen, and this difference should lead to the impression of larger saturation. In addition, removing of other spectral components (contained in the first white sample) should evoke an impression of general darkening of the considered area. A total result could be described by the Yarbus's term: "dark-saturated-red, more saturated than the

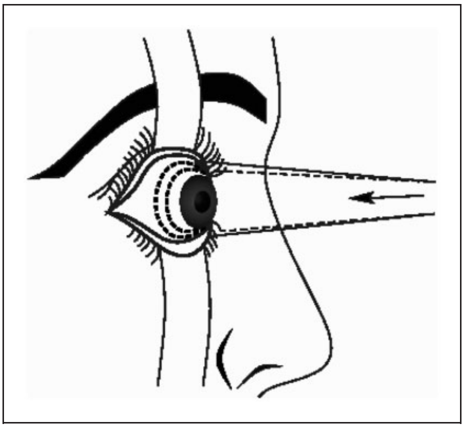

Figure 3. The scheme of a uniform illumination of the retina by means of a narrow light ring focused on the sclera around the cornea (Figure 1 from Yarbus (1975a, p. 917)).

screen color." Since, in such experiments, Yarbus did not perform quantitative estimations (except "larger-lesser"), it is useless to perform a more detailed analysis. Unfortunately, describing the compliance of his experimental results to theoretical predictions, the author really believed that the observed transient qualitative changes supported his *metric* of color and the formal properties of his model.

The conceptual statement on the special role of diffused light falling onto the extreme periphery of the retina was expressed by Yarbus in a clear form and supported by certain experimental results only in the article about the adequate visual stimulus. For this reason, we took from this article both a figure illustrating the experimental approach (Figure 3) and the description of the results obtained.

> Fairly uniform illumination of the entire retina was achieved by means of focusing a narrow light ring on the sclera. The light was directed to the area of the sclera having no photosensitive retina underneath. The experiments have shown that variations in time of intensity and spectral composition of the light stimulating the retina are not perceived by the observer if the entire surface of the retina is exposed evenly. The observer sees only the zero color that remains unchanged even at the moments of the light switching on and off. (Yarbus, 1975a, p. 917)

However, in the book one could read:

> In one of the experiments with the P3 cap, the cornea was completely covered, and the light could enter the eye only through the sclera. The eyes were retracted as widely as possible with strips of adhesive plaster and a bright flickering light was thrown onto the sclera. Usually, with a flicker frequency of 6 to 15 cycles, the subject saw bright mosaics iridescent with all the colors of the rainbow. The mosaics had very saturated colors; they were small in the region of the fovea and larger at the periphery of the retina . . . (Yarbus, 1965/1967, p. 98)

We have no intention to consider different effects obtained in similar conditions as an indication of their erroneousness or contradiction: in our opinion, such apparent discrepancy could be due to some seemingly small but, in fact, crucial differences in experimental conditions. This only means that there are still not enough data for understanding the influence of the extreme retinal periphery (blind retina) on visual perception.

Conclusion

The theory reviewed here, which would be better to call *model = hypothesis*, while offering its answers to some of the main issues among the unsolved problems of neuro- and psycho-physiology of color perception, evokes at least as many new unanswered questions. Moreover, some conclusions seem logically incompatible, according to the alternatives of the interpretation, formally not excluded by the model and, most often, not even claimed by the author as the aspect of its *ambiguity*.

The Yarbus's theory is based on the analysis of the simplest cases of visual stimulation with presentation of uniformly colored and evenly illuminated test samples in the frontal plane; moreover, in the majority of his experiments, the organization of the test field is concentric. This facilitated for the author the task of describing the performance of his postulated estafette mechanisms for calculation of colors starting from the extreme periphery of the retina, however, there remained problems even for such simplest stimulation. How these estafette mechanisms will work in the cases of intersecting or not fully identified borders, the author does not consider. It is evident that the model cannot pretend to be applicable in the case of retinal projections of the real 3-D scenes illuminated with multiple light sources and including not clearly defined contours since the interpretation of such projections critically depends on detection and classification of borders and a plausible segmentation of the image. Perhaps the model may be useful to explain some partial automatic mechanisms of the intermediate levels.

The most vulnerable statements lying in the basis of the model concerns the symmetry of *positive* and *negative brightness*, and *color* and *anticolor*. In fact, the author has not presented any realistic procedures for verification of the results described in such terms. (As has been already mentioned, in the theory of Nyberg, symmetrical pairs of colors are defined correctly and have clear physical meaning.) The opinion of Yarbus that his space of color sensations is 3-D looks also like poorly grounded. Indeed, the simple example of identical signals in the channel j: $0.5a_j/a_0 = a_j/(2a_0)$ for the two cases that are so different in their origin means that the case of the twofold reduction of the central stimulus is indistinguishable from the case of the twofold increase of the peripheral stimulus. Taking into account all eight indistinguishable combinations possible, one has to decide what is true: either the space was considered as trichromatic unreasonably or the *metamerism of the signals* is so multidimensional. The latter case needs verification in specific psychophysical experiments with not yet clear measuring procedures. Noting that *metamerism of the signals* is not the same as *metamerism of body colors* (Allen, 1966; Maximov, 1984; Ohta & Wyszecki, 1975), and reminding that Yarbus's theory does not define the criteria for distinguishing rays from colorations and brightness from lightness, we'll stop consideration of its declared properties.

Our purpose was to present a brief account of the Yarbus's concept regarding color perception; we had no intention to discuss a possibility of its development. Taking into consideration all the theoretical statements and experimental data described in this survey, we could formulate the following conclusive remark: Yarbus had no time to bring his model to definitely correct status. We have a manuscript representing the beginning of his uncompleted monograph on the subject, where some new steps toward further formalization of the model were taken; however, these steps were not principal. Nevertheless, sacrificing costs of gaps in the theory, we could accentuate on the three certainly interesting findings of Yarbus concerning an early color processing of monocular signal by trichromats. (Under the *early color processing* we mean the lower levels in the hierarchy of the structures ascending to the final cognitive image, in which is embodied the actual model of the perceived world, with its mutually connected *constancy mechanisms* that determine perceived color, shape, apparent position, gaze direction, and other parameters of the observed scenes (Logvinenko, 1981)). These findings are the following ones:

(1) The experiments with varying power or color of the illumination exclusively stimulating the peripheral blind area of the retina in conditions of invariable stimulation of the central retina through the pupil and crystalline lens (including situations without stabilization of boundaries in the visual field of the observer) showed that the blind extreme periphery of the retina can exert an inhibitory effect reaching the central retinal areas.
(2) In the presence of several stabilized borders in the subject's field of view (created on the retinal projection of the scene in any region), "the inhibitory effect from the periphery" is provided by the "estafette" mechanisms (acting in the direction from the periphery to the center) *smoothing* the gradients Δa_j of the "central signal" a_j on each stabilized border. (In the monograph, the action of this mechanism was described for the concentric stimulus configurations as the phenomenon of "filling-in": the region with stabilized contour acquired the color of its surrounding.)
(3) The spectral stimulus transformed by the cone apparatus into the retinal tristimulus pattern can be "perceived" (transformed into a visual sensation S that is different from the reference sensation called "zero color") only in the cases yielding the conditions of differential nature (both in space and time): $S = \partial/\partial t((\text{grad } a)/a)$.

It should be outlined that the phenomena that provided the reasons to talk about these interesting findings was only observed by Yarbus under certain conditions, which were usually selected both in the course of the experiment preparation and in the course of the experiment conduction since it was often not possible to obtain the "desired effect" immediately. Thus, in general, these findings cannot be considered as universal laws, even at the perceptual level. In addition, each finding deserves more specific commentaries.

The point 1 comprises the basis of the Yarbus idea of color perception suggesting that perceived color of the stimulus is determined by the values $\ln(a_{ri}/a_{r0})$; $\ln(a_{gi}/a_{g0})$; $\ln(a_{bi}/a_{b0})$ where ($a_{ri,}$ $a_{gi,}$ a_{bi})—the central stimulus components, and (a_{r0}, a_{g0}, a_{b0})—the components of the peripheral light. According to this idea, dark and "dirty" colors are perceived in the cases when denominators are larger than numerators. However, the author himself mentioned (Yarbus, 1976a) that he succeeded in obtaining the peripheral signal that exceeded the central one but only in the case of red illumination. Therefore, until now, the idea seems to be not sufficiently supported experimentally.

In relation to the point 2, it should be noted that, in reality, all the experimental scenes contained few borders and, therefore, the conclusions concerning many borders were only extrapolations but not the experimental facts.

The point 3 needs the following commentaries. First of all, it has been shown (Bolanowsky & Doty, 1987; Rozhkova, Nickolayev, & Shchadrin, 1982a,b) that the conclusions from the presented formula become invalid in the cases of binocular perception. In our experiments with binocular perception of a stable homogeneous field, the emerging visual image of the space filled with light and surrounding the head of the viewer could keep its brightness and chromaticity within a few minutes (until the end of the experiment), showing only a slow decline of these parameters (if at all). There were noticed no processes of fading images during few seconds at the typical everyday photopic luminance levels indicating that the laws of Yarbus had no relationship to the daylight binocular perception. This could mean that these laws described the operation of the monocular mechanisms, and that binocular channels of information processing obeyed other laws . . . However, there are also problems with monocular mechanisms (see Rozhkova & Nikolaev, 2015).

Within the framework of Yarbus's *monocular* concept, the processes of border contrasting and color adaptation are not correctly explicated into his vector color model. To interpret the results of the experiments as evidence in favor of his hypotheses, the author inserts the ''additional'' members into his model, whose inclusion definitively breaks the link (in the mathematical sense, outside the ''resources of the verbalization plasticity'') between ''generalized'' formula and the ensemble of the phenomena to be described (accumulated by the discipline and discovered by Yarbus (1977a, 1977b, 1980)).

It is also necessary to mention the circumstances, related not to an internal consistency of the ''operators'' suggested for the developed formalism, but to the pithiness of the mathematical description of the signal transformation in neurophysiology and ''image transformations'' in psychophysiology, providing *prognostics* of the effects during experimental studies of the mechanisms having *complex* organization (in comparison, e.g., with the mechanism of transformation of the spectral stimulus into the tristimulus in the retina). In the ''living calculator,'' ''differentiation'' of the neural signals (in numerous variations involving *derivatives*) is not often accomplished according to the recommendations of Newton's scheme, and ''classical Fechner's taking the logarithm of the stimuli'' is unlikely to be expressed in literal accordance with the properties of the log or ln functions. Finally, in the plane of expediency—for the paradigm of the ''filter of differential nature'' as the basis of Yarbus's point 3—the problem remains regarding computational and informational benefits of filtering the constant component of the external signal at the *perceptual* stage of processing since the final level of creating the ''cognitive image of the world'' implies ''restoring'' this clipped component.

Summarizing the results of our analysis, we emphasize that phenomenological aspects of the Yarbus's studies (and these are the results of complex experiments using original techniques) in no way detract from the incompleteness of the attempt to create a perceptual model of the trichromatic vision mechanisms. The continuation of the works started by Yarbus—for example, in the most original track of clarifying the role and the mechanisms of the ''blind retina'' influences—would be a worthy tribute to the memory of this tireless researcher and extraordinary thinker.

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