Optica Applicata, Vol. XXXII, No. 4, 2002

Standing wave analysis for the vision of color

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Background: A concept explaining retinal visional perception is worked out allowing comprehension of retinal vision in the context of physics and morphology. In particular, color vision and its discriminating facets appear to become transparent. *Methods*: standing wave analysis (SWA) for the energetic values of standing waves within the discs of the photoreceptors produced by different wavelengths generates color-identifying patterns. *Results*: The authors provide evidence that the human eye is able to identify an unlimited number of colors by analyzing directly standing waves produced by reflection on Bruch's membrane. Colorgrams can be generated identifying every color throughout the whole spectrum. Color vision defects are understood by defined norm-deviations of the outer segment of rod and cones. The color vision defects too can be identified by specific colorgram patterns. *Conclusions*: Energetic analysis of the standing wave leaves no need for the three visual pigments theory of Young–Helmholtz. Retinal inversion is the morphological prerequisite for cones and rods to explain the physical findings of this thesis.

1. Basis of the three-color theory after Young–Helmholtz

Without describing the historic development that led to the present teaching of color vision perception one must admit that the main facts of the findings of SWA are different from Young–Helmholtz theory (YHT).

There is no dissent about the anatomical structures of the eye and that rods and cones serve as photoreceptors which absorb light. In YHT it is believed that cones are responsible for color perception and rods for mesopic light perception [1]. On the basic of the YHT three basis colors (red, green, blue) are assumed to be necessary for the perception of the whole spectrum [2], [3].

Different excitements of the assumed three types of cones, each for one of a respective basic color, are thought to allow for color combinations and mixtures. Such information is created by chemical reactions that are transformed in an electric impulse that is transported to the brain.

Research therefore has concentrated to identify three different types of cones, which react to the different wavelengths within the spectrum [4]–[8]. Three or more photo-pigment molecules within the cones were identified, the pigment of which had

spectral absorption maxima at 440, 535 and 570 nm. This research is accepted as a proof of the correctness of YHT [6], [9]–[13].

On the basis of YHT mathematical relationships for color equations and color functions were formulated. Mechanisms of color vision were worked into calorimetric coordination-systems, which up to now serve as a basis for industrial standards and research teaching [14]–[16].

YHT though in spite of seeming to be a proven fact leaves more questions open in detail than it answers.

2. Open questions in YHT

Can we really accept to take the existence of three absorption curves after bleaching of retinal receptors as a sufficient explanation for retinal perception? Even if we suppose that in cones there were only red- or green- or blue-absorbing pigments it is speculation to conclude that released by these pigments a mixture of impulses will ensue to identify the high spectral sensitivity of the eye. The possibility of the generation of almost all colors by mixing three or four basic colors may be feasible under certain light conditions. It does not allow the conclusion that one must research a copying or analysing process of color mixing in the retina.

Within the documentations of spectral absorption curves there is no physical solution to explain tritanopia. There is no explanation how vision is switched between rod and cones under different light conditions. Or how shall we explain the resolution power to be steady and within the range of 0.1 angle/min for all colors? How can it be explained that the ratios of long to medium wave cones differ from 1:1.15 to 1:3.79 in two individuals with normal color vision [17].

The resolution of the cones does not change for a lesser and lesser degree when we look at a bouquet of flowers. This, though, should be the consequence in view of the physiologically occurring movement of the optical axis. The recruitment of the neighbouring cells would permanently interrupt the chemical process within rods and cones. We do not find overlapping colors, as they necessarily should appear when we move our gaze from the center of that arrangement of colorful flowers. Instead, thousand-fold color variations can be perceived clearly, distinct, constant in hue without change in their appearance.

For an understanding of this phenomenon chemical mixtures or chemical reactions in single cells releasing electrical currents that could accomplish such actions are outside of our physical or chemical knowledge. Chemical processes take time and fade away. Metabolic processes generally create metabolic products that have to be eliminated. We find all these open questions unanswerable in this classic context of trichromacy.

Newton's discovery of the existence of all colors in white light and Young's finding that all colors can be mixed from three basic colors only seem to be interpreted so that there is a need for a re-creation of color within the retina before the information is sent to the brain. The conception of 3 types of cones assumes the need to create anew all

colors that come from any object by mixing respective amounts of the 3 basic colors. One assumes thereby that the color stemming from an object has to be broken down in the retina into fractions of the basic color it has been made of.

Color deficiencies are explained in that YHT by a mixture deficit of the color generating pigments [13], [18]. Why though can a red/green color blind not differentiate certain red and green wavelengths, but can differentiate yellow as the supposed mixture of both?

We find it difficult to explain how visual fields of red and green extend to regions of the retina where only few or no cones can be found. The question remains, when assuming different cones analyze basic colors, how the cells in the macula are able to mix the different signals with the given speed and correctness.

Which function has the pigment epithelium in the visual process? There is a common belief that the contribution of the pigment epithelium in the visual process has its function in the nourishment of the receptors, a phagocytic property of the externals parts of the receptor [19], as well as in the absorption of light to prevent reflections due to its properties of non-transparency. We know from a multitude of pathological conditions that the pigment becomes non-transparent only in response to damage. We can see through the retina diagnosing chorioidal vessels or tumors. We must observe the generation of clotting pigment in cases where nil pigment was visible before in frequently occurring conditions, like trauma, senile macular degeneration or in progressive genetically conditioned diseases, like *retinopathia pigmentosa.*

What objective has the inversion of the retina? Cones and rods are surrounded by pigment epithelium on Bruch's membrane [20] which is believed to serve as carrier of the retina. Bruch's membrane is a structure-less clear membrane with highly polished surfaces similar to the corneal structure of Descemet's on which the corneal endothelium is positioned. These structures are morphologically very similar. The corneal and lenticular coatings are known to fulfill optical functions such as does the coating of a camera lens. Bruch's membrane till now is not considered part of the optical system though.

3. Determining wavelengths

To determine and distinguish different colors the evolutionary development could have used different principles. The methods conceivable are not equally suitable for use in the human eye but are used in technical processes. Five different methods are conceivable:

1. *Selective absorption.* The basic principle of this method is the varying reaction of a substance to different wavelengths of light. This can be used in two different ways to determine the wavelengths. If the sensor for measuring light intensity is itself dependent on wavelength as is the base of YHT, the several sensors (normally three) are used for differing areas of color. In general, three filters are used with the colors resulting from the kind of filter applied. If, though, a color film gets older, the characteristics of individual layers of color change. This as a rule, results in a color

fault. In case of color television, disturbances in the transmission lines immediately result in considerable color distortions.

2. *Dispersion.* With the refraction of light rays on surfaces the angle of refraction depends on the wavelength with which the oncoming light meets the object. As the differences in the refraction angle are generally very small, the light rays would have to travel a long way in order to position the individual colors clearly next to one another. As there is only a limited amount of space in the eye, this method of color determining must be excluded.

3. *Diffraction.* Due to the wave-like character of light, rays of light are diffracted at the edges. This effect becomes especially clear in regular structures like a grid. Sophisticated spectrometers today operate with reflection grids, which are able to produce maximum color dispersal. As the diffraction angles are very small, the construction length of the devices must be correspondingly larger, or mirrors may be used to fold the light ray. As was the case with dispersion, diffraction must be ruled out as a method of measuring wavelengths because the length of the eye would be insufficient.

4. *Interference.* This effect appears on the thin film of a soap bubble or of oil on the water surface. Light is reflected on the front and back of the surface, both waves differing slightly in their course. As a result, some colors are strengthened; others weakened showing the iridescent colors. This form of wavelength determination cannot be used as the absorbed color depends on the thickness of the layers. Such layers would have to be realized at thicknesses from 150 to 350 nm for each individual color. In optical laboratories Fabry–Perot interferometers for the precise determination of wavelengths are constructed according to this principle.

5. *Standing waves.* Standing waves are a special form of interference whereby two waves moving in opposite directions overlap. If both waves originate from the same source, characteristic patterns for extinguishing and strengthening occur which are well suited to determine frequencies. Methods employing standing waves are regularly used to measure electromagnetic wavelengths. Visible light maxima and minima were too close together to be used for technical purposes before the age of digitization. White light holograms use standing waves. In the eye one finds requirements for the analysis of standings waves morphologically verified in an ideal way. Standing waves may be used for color determination. Therefore we analyze this physically given situation in the following.

4. Analysis of standing waves

Visible light is an electromagnetic wave of a wavelength of 400 to about 700 nm. The intensity of electric field is periodically dependent on time t and space x so that we can describe it

$$E(x,t) = E_0 \sin\left(\frac{2\pi}{\lambda}(ct - x)\right) \tag{1}$$

where E_0 is the amplitude, λ is the wavelength and c is the velocity of the propagation of the wave, the speed of light. If this wave meets a mirror its propagation direction will be reverted

$$E_{\text{left}}(x, t) = E_0 \sin\left(\frac{2\pi}{\lambda}(ct + x)\right). \tag{2}$$

Only the sign in the inner bracket changes from minus to plus. Directly before the mirror the two waves add

$$E_{\text{total}}(x, t) = E(x, t) + E_{\text{left}}(x, t). \tag{3}$$

According to the addition theorems for trigonometric functions we could express this equation

$$E_{\text{total}}(x, t) = 2E_0 \cos\left(\frac{2\pi}{\lambda}x\right)\sin\left(\frac{2\pi}{\lambda}ct\right). \tag{4}$$

The standing wave has a time-dependent sine-term and a space-dependent cosine term, the latter is responsible for the different energies of the wave at different points. At the positions $x = 0, 0.5\lambda, \lambda, 1.5\lambda, \ldots$, the cosine function has the value +1, or –1. At these points the standing wave has its greatest amplitude, the antinode. At the positions $x = 0.25\lambda, 0.75\lambda, 1.25\lambda, \ldots$, the value of the cosine function is zero. Thus the total functional value at these places is zero for each point of time, *i.e.*, there is no amplitude,

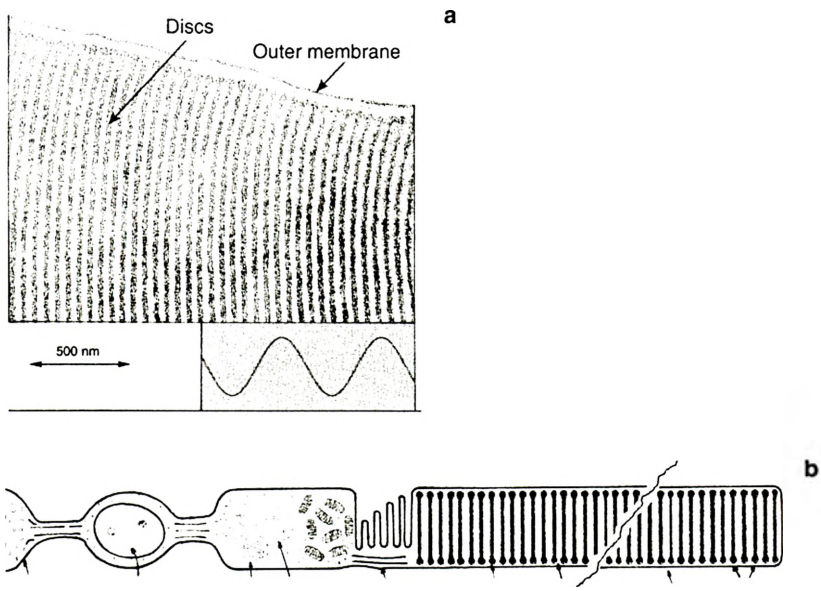

Fig. 1. **a** – Electron microscopic picture of the outer segment of a cone. Sinus curve corresponds to light -wave of 500nm. **b** – Schematic drawing of a cone. Disc-section of cell is shortened. Disc intervals are in 55 nm distance.

and one speaks of a node. The nodes and the antinodes are always 1/2 wavelength apart.

To differentiate colors by SW a reflection of the oncoming light is needed. This reflection, we think, occurs on Bruch's membrane that consists of a homogenous smooth structure.

Directly in front of Bruch's membrane the receptors for light are situated, the rods and cones. The receptors obviously must be orientated in such a way that they are able to measure the wave intensity as it emerges in front of the membrane. The phenomenon of the seemingly incomprehensible inversion of the retina may thus be understood. The receptors themselves consist of layers of photosensitive disks at regular intervals

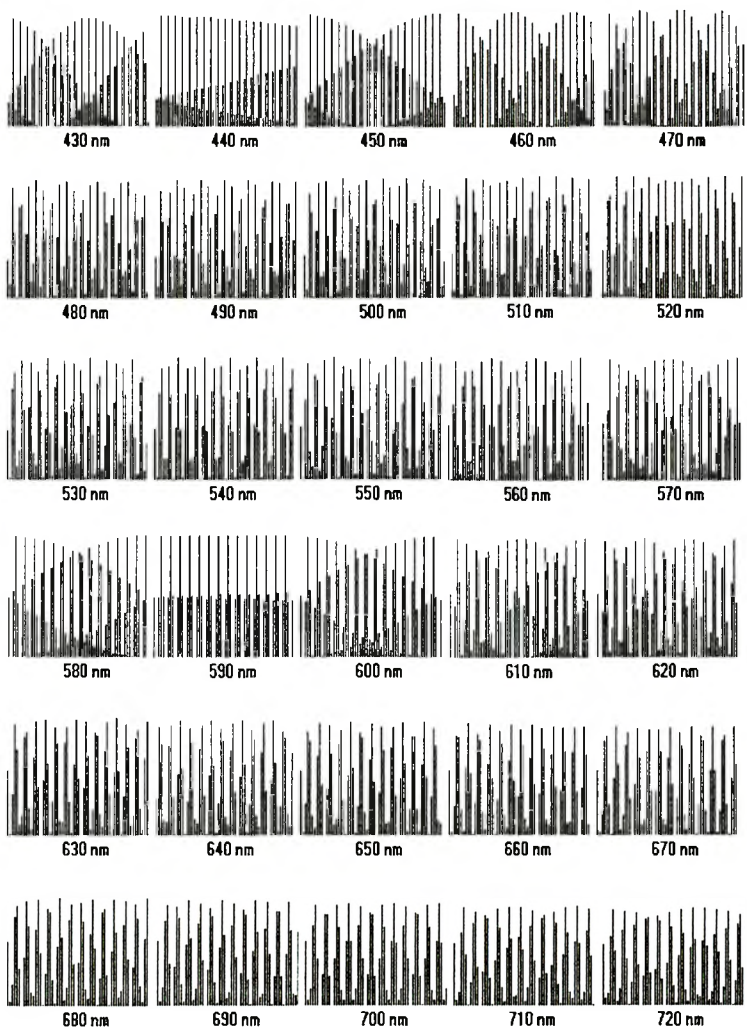

Fig. 2. Colorgrams of the spectrum of visible light. Intensities calculated from standing waves within a normal disc distance of 55 nm.

of about 55 nm (Fig.1**a**, **b**). If the standing wave hits these discs they are stimulated differently according to the energy released by the standing wave. The discs measure the intensity of the standing wave at regular intervals.

In the case of visible light 400 nm is the shortest visible wavelength for the eye, which corresponds in the eye to a shortened standing wave of 298 nm. Due to the refractive index n =1.34, the nodes, therefore, are at intervals of 149 nm ($\lambda/2n$).

For identification of these standing waves the discs should be at a distance of less than 79 nm, because according to Nyquist theorem two measurements in a period are needed to identify the wavelength. The actual recorded distance of about 55 nm is a strong argument for the standing wave theory.

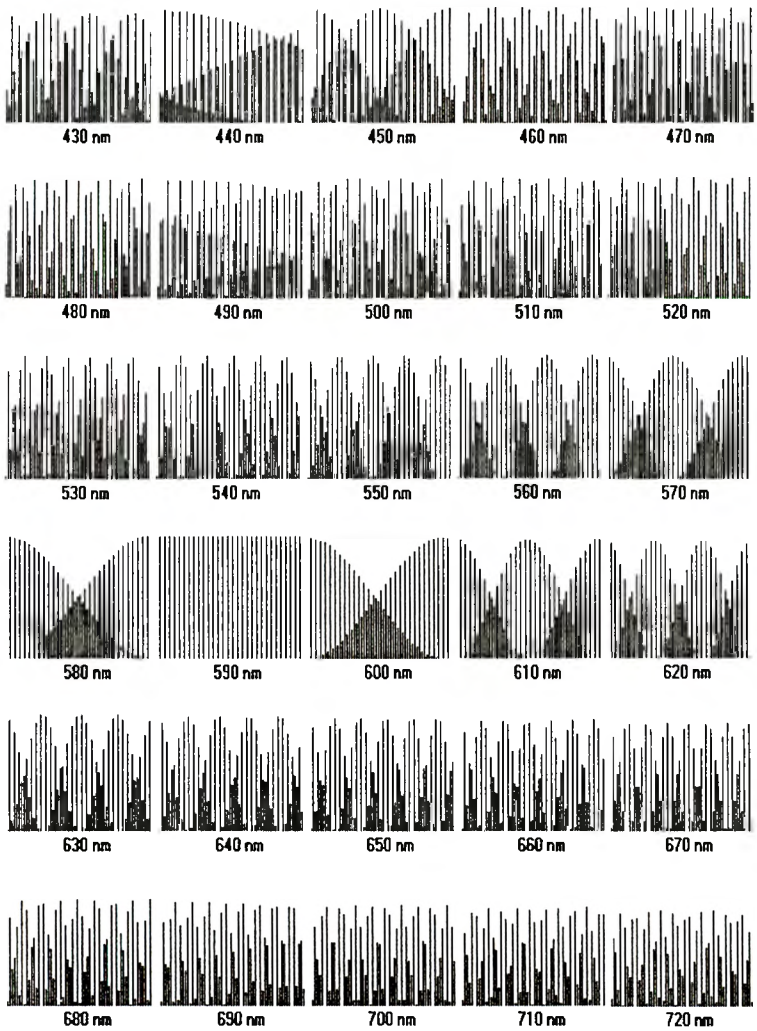

Fig. 3. Probable visual perception in red/green deficiency. Colorgrams of the spectrum of visible light. Intensities calculated from standing waves within a doubled disc distance of 110 nm.

Light intensity I is determined by squaring above function with taking into account the refractive index n

$$I(x) = 4A_0^2\cos^2\left(\frac{2\pi}{\lambda}xn\right). \tag{5}$$

With this equation the light intensity at the discs can be determined for every wavelength.

Figure 2 shows that the intensity of any standing wave throughout the spectrum produces regular patterns. In the Fig. 2 we present the results of our calculation

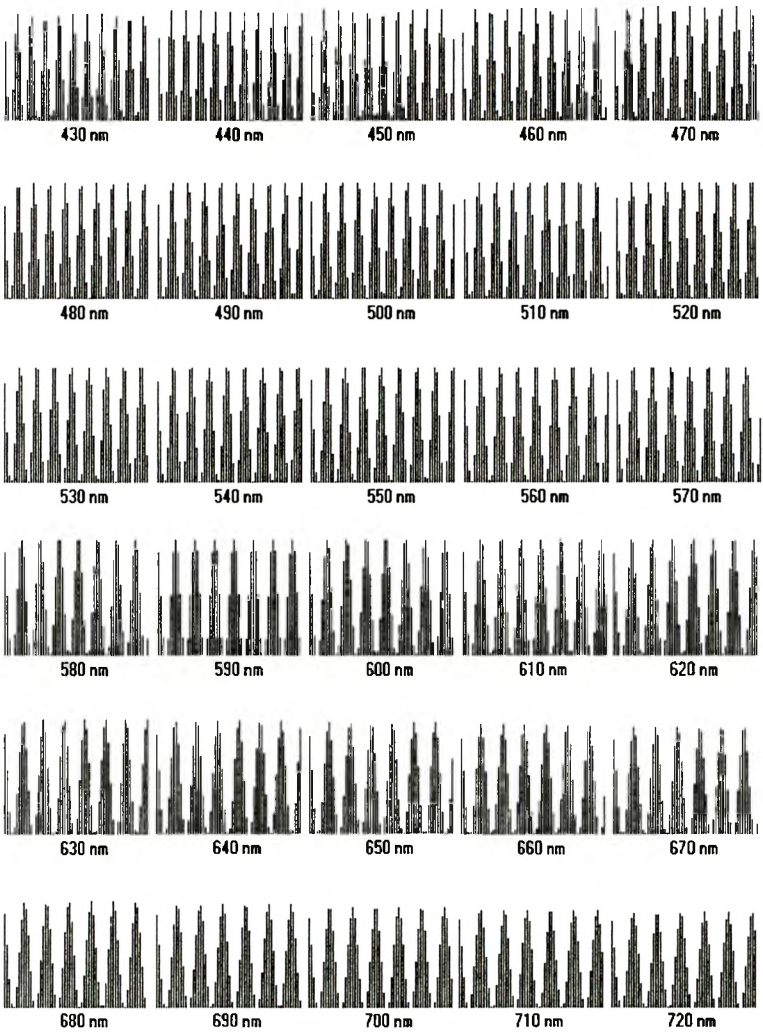

Fig. 4. Probable visual perception in achromatopsia. Colorgrams of the spectrum of visible light. Intensities calculated from standing waves within half disc distance of 27.5 nm.

concerning the intensities for a large number of wavelengths and discs, thereby converting intensities to line lengths. Intensity 4.0 has a 4 units long line.

There is a characteristic pattern for each visible color. The sequence is typical so that each color can be identified by its own specific "finger print". We call these sequences "colorgrams".

5. Color deficiencies

If we conclude that color vision is achieved by pattern recognition, then the conclusion concerning faulty recognition of colors is that either faulty patterns are produced or correct patterns are incorrectly perceived.

The prerequisite of generation of a specific pattern for a given color is the normal spacing of the disc intervals in the outer segments of the receptors. It is imaginable that doubling the distance or shortening it to half could be a genetically induced defect. If we double this distance to 110 nm we find an explanation for red/green color recognition deficiencies. Figure 3 shows that symmetrically to the wavelength of 590 nm the patterns are arranged in symmetrical repetitions. Red light of a wavelength of 620 nm produces the same pattern as green light of a wavelength of 560 nm. There is a high probability that a red/green deficient has a double disc distance of normal or that two neighbouring disks stick together and add their signals.

By trial and error tests we found indiscernible patterns over the whole spectrum in case the disc distance is reduced to half of normal, *i.e.*, 27.5 nm. Figure 4 shows, that colors cannot be appreciated, bacause the patterns are nearly identical. We may conclude seeing the spectrum of a color-blind.

6. Varying intensities

Patterns in Figure 5 are shown to represent low light intensities. In the case of low intensities only the previously most intensive lines are traceable, the weaker lines in between disappear. Thus the color-identifying pattern of the respective wavelength loses important information and can no longer be recognized. Below a certain degree of intensity only single lines without a recognizable pattern are discernible, which our brain interprets as grey. There is no need for different types of receptors for scotopic and mesopic vision.

A similar effect occurs where there is an exposure to very high intensities. It can be assumed that there is a maximal response, which cannot be exceeded even when the intensity increases further. With greater light intensity the shorter lines become increasingly long until they reach their maximum response. A pattern, which initially was clear, disappears with intensive light (colored flood or spot-lights) to a pattern -less structure, which our brain interprets as white. Figure 6 shows the patterns resulting from intensities exceeding maximal response.

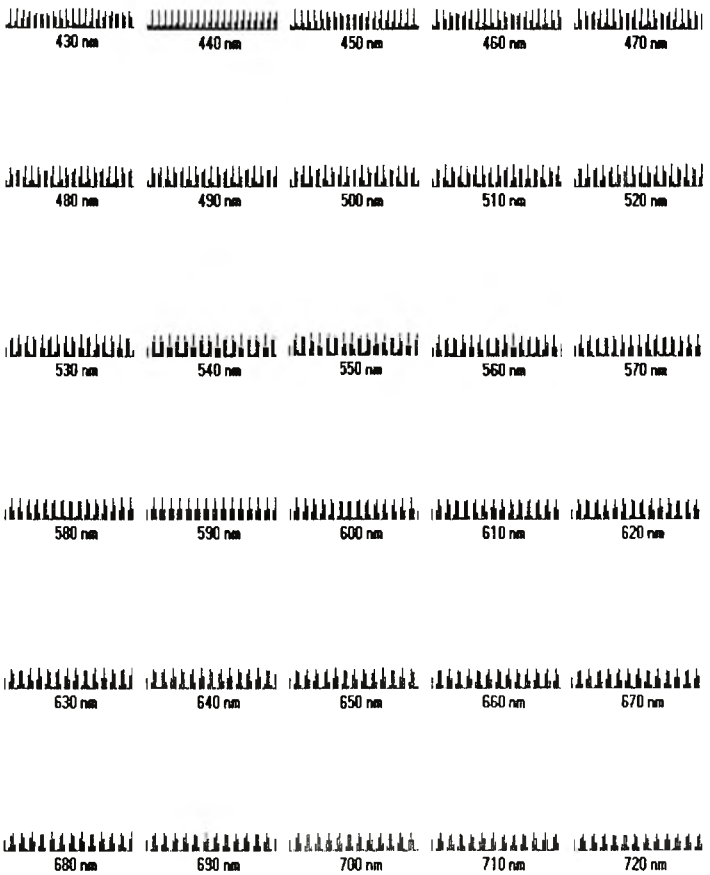

Fig. 5. Low intensity colorgrams of the spectrum of visible light. Intensities calculated from standing waves within normal disc distance of 55 nm.

7. Transport of the pattern

At the present state of the investigation only assumptions can be made about the transport of the pattern information sent to the brain. The information from the discs sent to the nucleus is probably in a sequential mode. The transport of the pattern to the brain is safer if the amplitude information is transformed to a frequency modulation with constant amplitudes.

8. Discussion

The Young–Helmholtz theory was established as it was assumed that a given color must be mixed by fractions of the three basic colors. The analysis of the standing wave

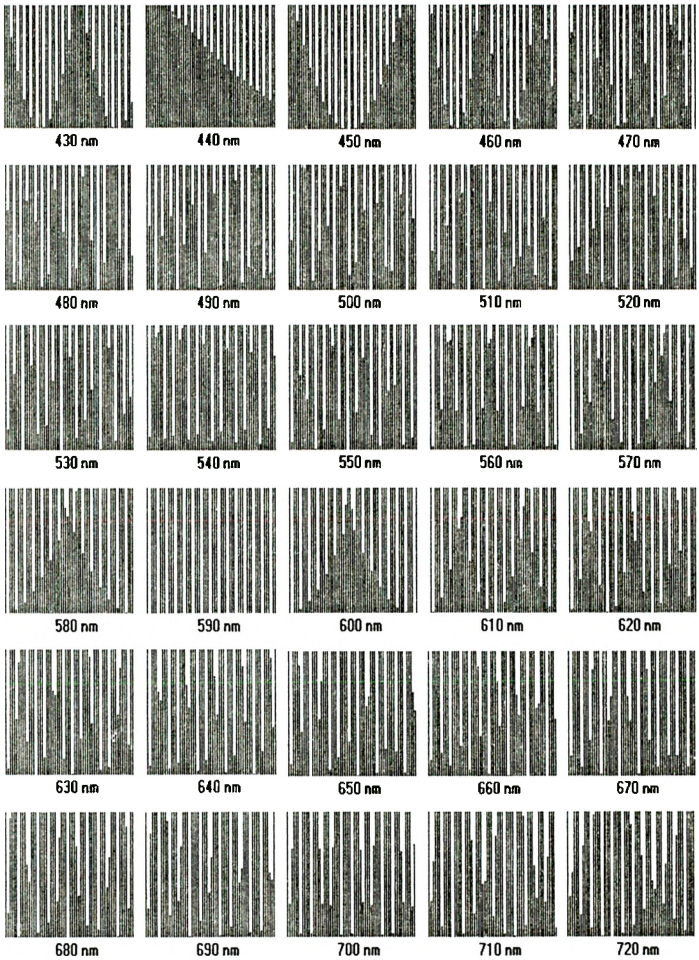

Fig. 6. High intensity colorgrams of the spectrum of visible light. Intensities calculated from standing waves within a normal disc distance of 55 nm.

on the contrary explains that there is no need for color mixing. There is a multitude of more than a million colors present and they can be identified by single receptors. Contrary to YHT the resolution power is not divided by three by different types of cones.

For SWA it is not essential to have different cone pigments. A single photosensitive substance is sufficient to convert the intensity from the discs into action potentials.

The fingerprint type identification of any conceivable color of the visible spectrum by the discs leads to modifications of our understanding of the visual retinal process. Every color may it be created by addition or absorption within the visible spectrum does generate a different standing wave, which is not limited by chemical mixtures or by addition or subtraction of spectral absorption curves.

White must be explained differently to the explanation of YHT. The addition of red (700 nm), green (640 nm) and violet (435 nm) alone, which by definition of YHT is white, leads to colorgrams, where no regular patterns are discernible.

The above-mentioned open questions raised by YHT are answered by SWA: how we can appreciate the bouquet of flowers clearly with no change in resolution, without fading, without afterimages and without loss of brightness. The process of reflection at Bruch's membrane is comparable to a mirror that is moved, reflecting any image with no change or delay.

Standing waves occur directly in front of the reflecting membrane of Bruch's. A sensor that registers these standing waves therefore must be situated in front of the membrane. The inverse structure of the retina is the necessary prerequisite for the perception of standing waves.

The clinical observation of immediate loss of vision in case of a retinal detachment may be explained by SWA. The fully nourished and functional retina cannot receive standing waves when fluid is interposed between Bruch's membrane and receptors. After re-attachment it resumes its function immediately.

The above outlined concept does offer a high likelihood of the mechanism of retinal visual perception. It may be suited to initiate physiological as well as clinical research.

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Received August 8, 2002
in revised form September 18, 2002