Role of the retinal detector array in perceiving the superposition effects of light

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ABSTRACT

The perception of light in nature comes through the photopigment molecules of our retina. The objective of this paper is to relate our modern understanding of the quantum mechanical chemical processes in the retinal molecules with our observation of superposition ("interference") fringes due to multiple light beams. The issue of "interference" is important for two subtle reasons. First, we do not perceive light except though the response of the light detecting molecules. Second, EM fields do not operate on each other to create the "interference" (superposition) effects. When the intrinsic molecular properties of a detector allows it to respond simultaneously to all the superposed light beams on them, they sum the effects and report the corresponding "fringes" of superposition. In the human eye the "seeing" (or perception) is initiated by photo-isomerization of retinal, the chromophore of the opsin molecule. There exists several orders of magnitude difference between the characteristic times for the molecular processes of light absorption and the visual signal generation through the photochemical cascade. This allows us to function in the daily chores of walking and visual identification of objects and enjoy the beauty of the natural sceneries even though the retinal layer is bombarded simultaneously by innumerable beams of light with same and different frequencies, which will normally produce a flood of electronic "white noise" over a very wide range of temporal frequencies, namely the heterodyne beat signal. How do the eyes completely suppress this wide range of heterodyne beat signal?

Key words: superposition principle, interference of light, absence of heterodyne signal in vision, modulation transfer function, contrast sensitivity function, photochemistry.

1. INTRODUCTION

The key objective of the paper is an attempt to relate the modern understanding of vision science (cis-trans molecular shape change and the resultant photochemical cascade) [1] with those for optical superposition phenomenon (non-interaction of light) [2] by comparing the responses of retinal opsin molecules and the photo conducting detectors by focusing on their responses to superposed light beams containing two or more temporal frequencies. A photo conductor connected by appropriate electron circuitry, can produce heterodyne beat signal (undulatory electric current) under proper illumination conditions. Under the same conditions, our retina will not send any undulatory electrical beat signal to our visual neural system even though our rods and cones are optically sensitive to broad bands of colors. Otherwise, our neural system would have been overwhelmed by the undulatory electrical signals. This has been an enormous evolutionary advantage for us.

A traditional way to explain the absence of heterodyne signal would be to claim that the natural light underlying our vision-driven-daily-activities are spatially and temporally incoherent and naturally they simply do not produce interference effects. We would like to raise two quick counter arguments. First, until 1957 when Forrester et al [3] demonstrated that two closely spaced and spontaneously emitted atomic spectral lines can produce heterodyne beat signals, we used to claim that light beams of different frequencies do not interfere with each other. This is supported by most interferometric experiments, the most successful one being Michelson's Fourier transform spectrometry [4]. Our second point is designed to remove this apparent contradiction in observing optical "interference" fringes by appreciating that light beams never interfere with (operate on) each other. It is the detectors and their response characteristics that dictate whether the effects of all the superposed waves simultaneously stimulating it will be summed by it and made observable by it. This neglected but obvious fact can be appreciated by critically analyzing

The Nature of Light: Light in Nature, edited by Katherine Creath, Proc. of SPIE
Vol. 6285, 628507, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.683112

daily occurrences around us. One can recognize the face of a loved one at night from a large distance even though billions of other light beams are crossing through the line of sight while allowing the desired light beam containing the beloved information to arrive undistorted! It is ironic that on one hand modern physics recognizes photons as Bosons that can occupy the same space without interacting with each other in the linear domain [5, 6], on the other hand we keep on claiming light beams interfere with each other and accordingly define coherence of light beams in terms of their field characteristics only without reference to the physical properties of detectors [7] that make the light visible. We see light only through the "eyes" of the detectors and the information they communicate to us is always "biased & colored' by their intrinsic limited "minds" (characteristics)! Another way of saying the same thing is that all the detectors are born wearing different "colored QM goggles" and they tell us their view of the world, which is obviously "colored"!

The absence of undulatory heterodyne "white noise" from our retina, which would be observable by an electronic system with a photo conductor, lies solely on the mechanism and the time constant behind the generation of observable signal produced after absorbing energy from the superposed light beams on the detector.

2. PHOTO CONDUCTOR AND HETERODYNE SIGNAL GENERATION

Let us quickly review the optical heterodyne detection process. Consider for simplicity that we have superposed two different optical frequencies on a detector whose valence and conduction energy bands are sufficiently broad to allow electron excitation to the conduction band by both the frequencies ν_1 & ν_2. The two fields of equal amplitudes $\vec{a}\exp[i2\pi\nu_1 t + i\phi_1]$ & $\vec{a}\exp[i2\pi\nu_2 t + i\phi_2]$ will then simultaneously induce dipole undulations $\vec{d}_1\exp[i2\pi\nu_1 t + i\phi_1]$ & $\vec{d}_2\exp[i2\pi\nu_2 t + i\phi_2]$ that are proportional to the incident field dictated by its first order polarizability $\chi_{(1)}$. We assume that the incident light amplitudes are steady and constant over the duration of our observations. Then the resultant dipole undulation strength leading to the rate of number of electron transition D(t) to the conduction band is given by:

$$D(t) = \left|\vec{d}_1 e^{-i2\pi\nu_1 t - i\varphi_1 t} + \vec{d}_2 e^{-i2\pi\nu_2 t - i\varphi_2 t}\right|^2 = 2d^2[1 + \cos\{2\pi(\nu_1 - \nu_2)t + (\phi_1 - \phi_2)t] \quad (1)$$

We have assumed that the polarizations are parallel; the strengths, $\left|\vec{d}_1\right| = \left|\vec{d}_2\right| \equiv d$ and $\vec{d}_1 \cdot \vec{d}_2 = d^2$ when the two states of polarizations are parallel. When they are orthogonal, $\vec{d}_1 \cdot \vec{d}_2 = 0$ because the same detecting molecule cannot execute two uniaxial dipolar undulations in two directions that are orthogonal to each other at the same time. Thus, they fail to sum the induced effects due to two orthogonally polarized, but otherwise coherent light beams. The other implied condition is that collectively, the detecting molecules must have a broad light absorption transition bands such that they can be stimulated to undergo dipolar undulations by all the incident frequencies. Then only their excitation rate and electron transfer rate will be undulating in time with the various difference (beat) frequencies. Fig.1 shows a pair of typical valence and conduction bands with the limiting frequencies of response denoted as $\nu_{\min}$ and $\nu_{\max}$. The detector can produce beat signal only for those frequencies that lie within this range. It is easy to appreciate that radiation with lower frequency than $\nu_{\min}$ will not trigger any detection signal. However, radiation with frequencies higher than $\nu_{\max}$, inspite of higher "photon energy" will not trigger photo excitation; but it may break down a chemical bond if it is of sufficient energy.

The heterodyne signal of Eq.1 is an undulatory DC current at the beat frequency $(\nu_1 - \nu_2)$ that will appear as a steady sinusoidal current if the two arbitrary phases are steady (as in laser sources); if they are randomly fluctuating (as in thermal light sources), the current will appear as fluctuating "white noise" as there will be currents at many different beat frequencies along with phase fluctuations. One should note that the photo excitation induced electron transition time- constant is generally in the femto second regime. Under external voltage applied to such photo detectors [8], the conduction electrons are recycled back through the external circuit and the detector molecules are

ready to be re-activated. Thus the limitation in heterodyne frequency detection, $(\nu_1 - \nu_2)$, is limited by our electronic circuits associated with our detectors [parasitic LCR-time constant].

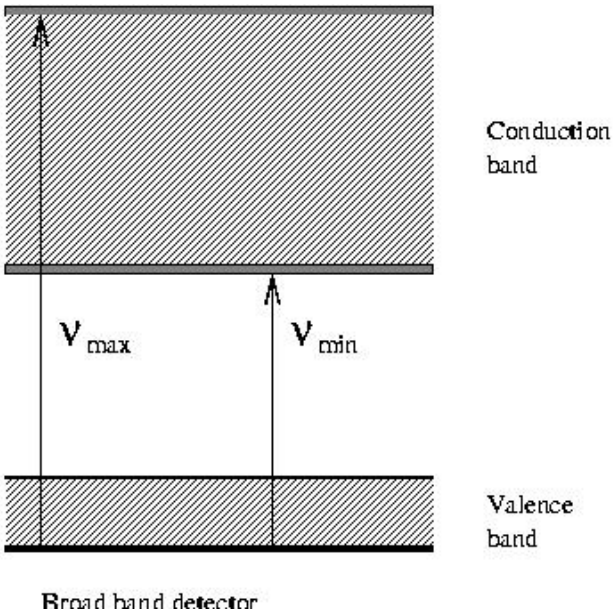


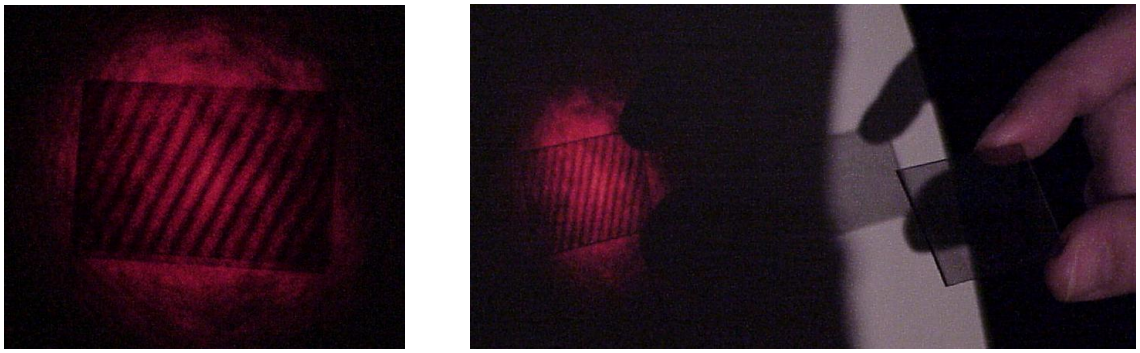
Figure 1. Two incident frequencies on a photoconductor can give rise to heterodyne (beat) current, provided the incident frequencies are within its excitation bands.

There are two limiting conditions necessary for the generation of heterodyne signals that do not come out in any obvious way from the standard formalism of quantum mechanics. They are derived from experimental observations. The first condition is that the wave fronts of the superposed beams of different frequencies must be very similar and collinear (Poynting vectors) for efficient heterodyne energy transfer. The two fields must physically co-propagate to transfer energy efficiently to the molecules in time. The second condition is that the states of polarizations of the incident E-vectors must be parallel to each other. Both these experimental conditions strongly imply that the excitation of the detecting molecules as dipoles is a physical reality, as if the same undulating dipole, even in its isotropic solid state environment, can execute undulations only along one chosen E-vector axis at any one time. The need for the collinearity of the Poynting vector ($\vec{E} \times \vec{B}$) implies that the B-vector also plays some important functional role in the stimulation process for time dependent energy transfer.

3. RETINAL MOLECULES ARE POLARIZATION SENSITIVE

This section presents a simple two beam superposition experiment with orthogonally polarized light to underscore that the complex retinal molecules are as quantum mechanical as semiconductor photoconductors. A monochromatic laser beam is replicated into two orthogonally polarized and then superposed with a very small angle on a diffuse white screen. Fig.2a shows that there are excellent fringes, but only behind a polarizer taped on the screen; outside the polarizer there are no fringes. The scattering molecules of the screen cannot respond simultaneously to two orthogonal E-vector stimulations (dipole like undulations before scattering the light). Hence they cannot sum the superposition effects. So, we do not see any fringes in the beam which is outside that intercepted by the polarizer. Light beams transmitted by the polarizer are now polarized parallel (E-vectors undulation in the same direction). Scattering molecules now can sum the induced stimulations due to both the E-vector amplitudes. Now, where the E-vectors are in phase, we have strong scattering and bright fringes and wherever the amplitudes are in opposite phase, the scattering molecules are not stimulated at all and hence they do not scatter any light; those regions appear as dark fringes. Note that if one looks at the screen through the polarizer (in any orientation), instead of intercepting the superposed beams before they hit the white scattering screen, one can see only the laser illuminated spot without any fringes. This underscores that the opsin molecules of the retina cannot also be stimulated in two orthogonal

directions simultaneously. Further, if the superposed beams were reflected by a specularly reflecting surface, imaging the eye (or a camera) on this specular surface will not give fringes. Light waves are a collective phenomenon as evidenced by specular reflections and transmissions. But when the superposed wave fronts are intercepted by scattering or detecting molecules, they try to respond to the local resultant E-vectors and thereby generate the fringes.



(a) (b)

Figure 2. Molecules of our retina are as quantum mechanical as those in semiconductor detectors. A Mach-Zehnder interferometer was used to produce and superpose on a white screen at an angle two coherent beams but with orthogonal states of polarizations. Fringes were visible only after the beams were transmitted through a polarizer to make them parallel again. Notice that outside the intercepting polarizer, there are no fringes whether the polarizer is taped on the screen, as in (a), or it is held far from the screen, as in (b). Looking through the polarizer on the screen does not restore the fringes.

4. RETINAL PHOTO EXCITATION & ABSENCE OF HETERODYNE SIGNAL

It is important to recognize that optical response by photo sensitive and slightly different molecules of retina begins with their quantum mechanical transition (excitation) capability from a vibrational band of one electronic energy level to another vibrational band of the next higher electronic energy level as shown in Fig.3 [9]. Without these quantum mechanical frequency selective electronic energy levels and vibrational bands, our retina would not have been able to respond differentially to three different color bands (**L**ow, **M**iddle and **S**hort wavelength bands), endowing us with the power of discriminating enormous diversity and the associated richness of nature and pleasure of enjoying hundreds of different apparent color shades which are nothing but “figments of our imaginations”. Luckily, the consistency of our genetic pool makes us believe that we are “objective” about our color perceptions, albeit slight variation in these interpretations (color blindness) [1] from person to person!

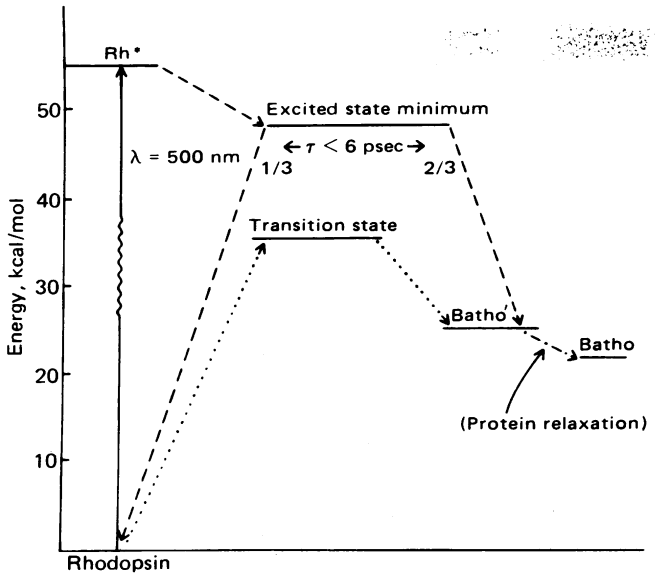


Figure 3. Energy level diagram for primary processes in vision [from ref. 9].

Now consider Figure 4. It shows the basic structure for the molecular geometry for absorption of a photon in the disk membranes of the photoreceptor outer segment. Each photopigment molecule consists of a transmembrane opsin bound to a chromophore, 11-cis retinal (Figure 5a). The opsin or protein portion of the molecule is a chain of amino acids running from the amino terminal end (N), exposed on the external aqueous surface of the membrane disks to the carboxyl terminal end (C), exposed on the internal aqueous side of the disk. The chain has 7 coils (alpha helices), which encircle the chormophore (lower cutaway view). The cut-away view (Figure 5a) indicates the approximate positions of the alpha helices and of the three amino acids (open circles) that are believed to have a major influence on the absorption maximum of the photopigment (Figure 5b). The tail of the chromophore is attached by a protonated Schiff base to a charged lysine amino acid residue lying at a nucleotide position 312 in the chain of the opsin of the L and M cones and at position 293 for the chain of the S-cone opsin (and corresponding to position 296 of rhodopsin in rods). Features critical to the function of the opsin seem to be well conserved in all known mammalian species.

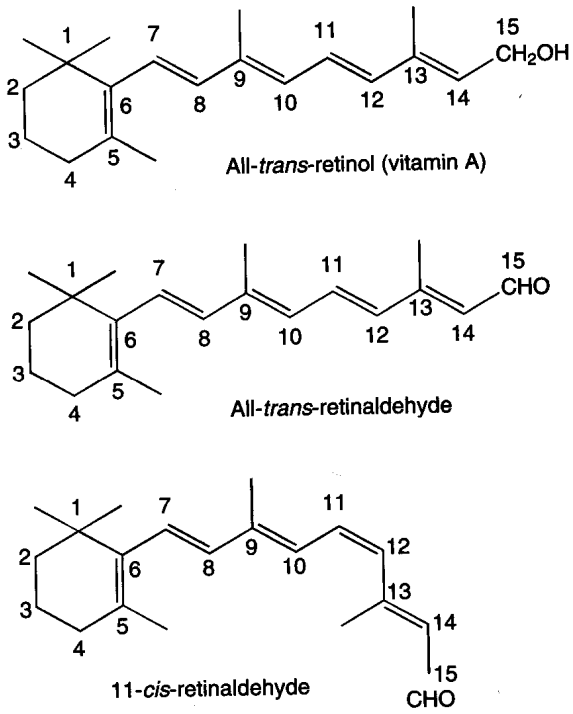


Figure 4. Retinoid structure. During light absorption the opsin chromophore 11-cis-retinal, which is synthesized from all-trans-retinol (vitamin A) in the retinal pigment epithelium, is converted to all-trans-retinal. See text for details (from ref. 10, page 6).

It should be noted that the chromophore lies near the center of the lipid bilayer, with its delocalized electron system oriented in a plane parallel to the disk membrane. Formation of the Schiff base shifts the absorption peak of the chromophore from the UV to the visible and this shift is further exacerbated by the glutamic acid residue in the third transmembrane helix. These ionic interactions further increase the degree of delocalization of the retinal pi electron system. Photon absorption triggers an isomerization of retinal from the cis conformation to the all trans conformation. The absorption of the photon and the subsequent conformational chain has a very high probability (0.7). The time for this conformation change has been shown to be about 20 ps. The resulting relaxation of strain in the retinal polyene chain acts as a major driving force for the subsequent conformational change in the rhodopsin molecule (R). This is thought to be due to steric interactions between the chromophore and the 121 glycine residue as well as rotations with modifications of hydrogen bonds for several residues. The crystal structure of the rhodopsin molecule was determined recently [11]; However, the structure of R* is as yet not known. However many other studies have elucidated the properties of the intermediate states using a number of techniques. The molecular rearrangements underlying phootactivation have been studied spectrophotometrically since each intermediate has a different absorption spectrum. Several transitions occur rapidly. First within about 100 microseconds an intermediate metarhodopsin-I occurs. The second transition to metarhodopsin-II takes about 1-10 milliseconds (depends upon body temperature) & involves a substantial structural rearrangement of the protein [12].

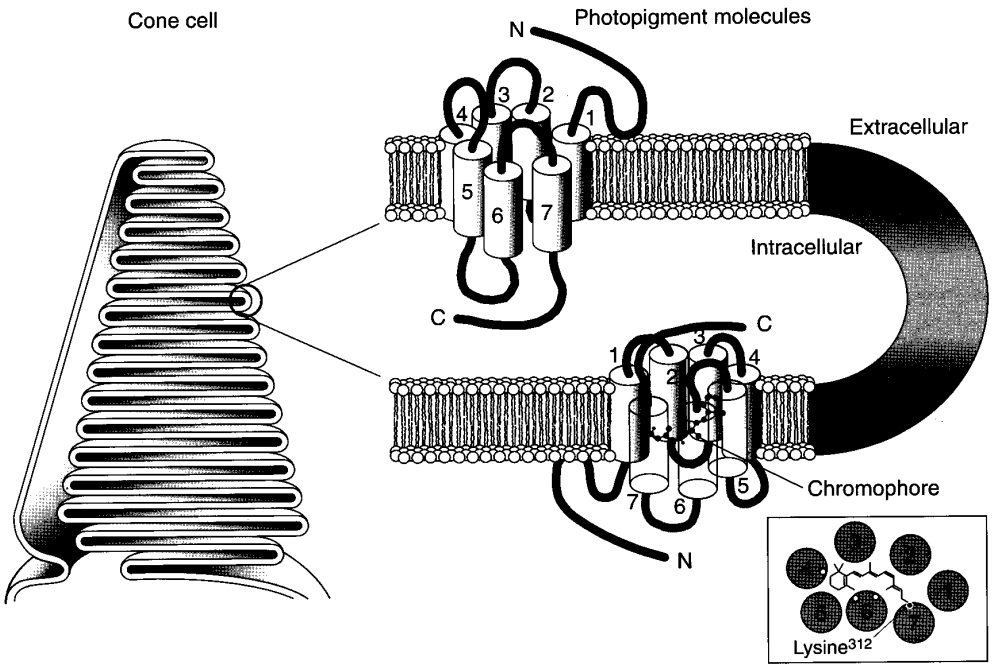


Figure5a. Cut away view of a cone cell. For further details [see references 1, 12-14].

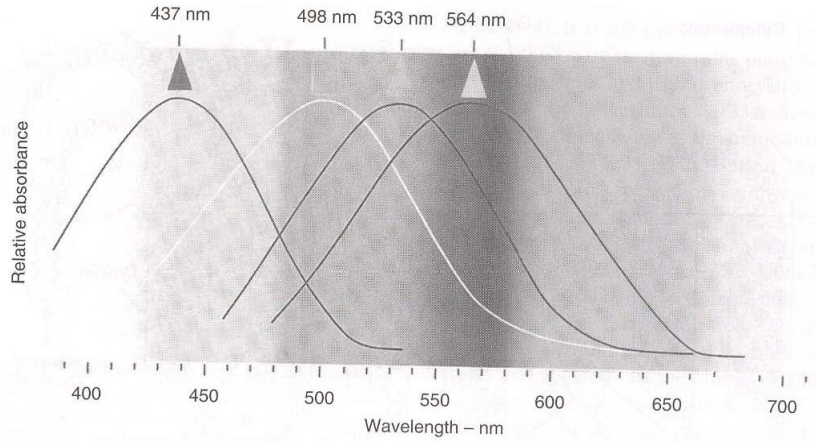


Figure 5b. Absorption spectra of human rhodopsin (437nm) and of the three human and monkey cone opsins (S-498nm, M-533nm, L-564nm) [from ref.14].

This is crucial to the photoresponse as this is the form of the protein that is enzymatically active. The major intermediate metarhodopsin-II, which is the catalytically active form R* for the following transducin activation in the phototransduction cascade. The rhodopsin cycle is shown in Figure 6. The initiation of the photocurrent takes another few milliseconds. The onset of the electrical response (the hyperpolarization) follows a delayed Gaussian time course, wherein the time onset depends upon the light intensity and an effective time delay constant. The reader is referred to the literature [13] for more details of the phototransduction process.

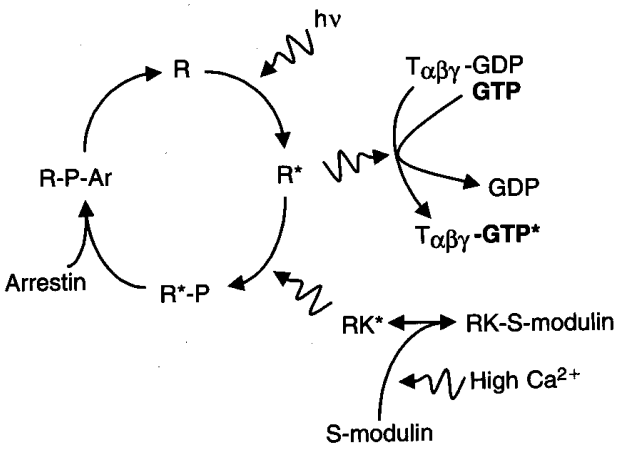


Figure 6. The rhodopsin cycle. Rohdopsin (R) is first activated by light ($h\nu$). The activated rhodopsin (R^*) can thus activate transducin molecules ($T_{\alpha\beta\gamma}$) by inducing a GTP-GDP exchange. The deactivation of the rhodopsin molecule then requires its phosphorylation by the rhodopsin kinase (RK^*). High Ca^{2+} prevents this phosphorylation step by promoting S-modulin interaction with rhodopsin kinase. The phosphorylation step increases arrestin affinity to rhodopsin, thereby preventing further transducin activation and speeding up rhodopsin recovery [from ref.13].

4.1 Absence of heterodyne signal in the eye.

The combined requirements for the initiation of heterodyne response that the superposed beam wave fronts be identical and collinear along with parallel polarizations, essentially eliminates the possibility of such signal generation in natural illumination. However, this is not equivalent to the simplistic statement that our eyes are burdened by such temporal noise simply because the natural light is "incoherent". Under the so-called incoherent illumination during microscopic observations, if the magnification is high enough that it is equivalent to or greater than the size of the spatial coherence that enhances with propagation distance [see ref.15 for van Cittert-Zernike Theorem] one can see spatial speckle patterns, which are random intensity variation in space but steady in time. This is similar to the speckle pattern that we see when a coherent laser beam is reflected by a rough surface (producing randomly varying phases). Some times, some of these spatial speckle patterns may appear as "scintillating" due to fluctuations of the refractive index of the intervening turbulent air; they should not be confused with the heterodyne-process generated "temporal speckle" patterns. A high speed detector can register on an oscilloscope the "temporal speckle patterns" (random temporal undulations of intensity) due to mixing of different optical frequencies of spontaneously emitted "thermal light" light with randomly varying phases. Spontaneously emitted light pulses have sufficiently long pulse length (temporal duration) to be able to generate mutual beat signals in a fast detector. This was first demonstrated by Forrester et al. [16]. However, our neural system is never burdened by such high speed and noisy temporal signals even though we are surrounded most of the time by spontaneously emitted light of continuously varying optical frequencies and all of our visual pictures in nature are created by such light. We suspect that the our evolutionary process recognized the need for temporally stable vision and opted for a very slow molecular structure change followed by ion diffusion process to trigger our neural system rather than sending photo excited electrons at unusually high speed that our solid state detectors experience.

4.2 Interference Fringes on the retina:

Spatial frequency analysis of the pertinent visual signal seems to be performed by our visual system quite efficiently. The MTF (modulation transfer function) is a measure of the extent to which each spatial frequency gets through by a given optical system. In optics, we routinely measure the MTF directly by imaging gratings (dark-bright periodic contrast) of known spatial frequencies and then determine the contrast in the image. This straightforward method cannot be done for the in-vivo eye. To psychophysically detect contrasts sensitivity of retina to gratings of different spatial frequencies one has to generate interference fringes of variable spatial frequencies directly on the retinal plane. The basic idea is simple – a pair of coherent beams, polarized parallel to each other, is allowed to directly illuminate the retinal plane [17]. Each opsin molecule, as a quantum device, responds to the two incident E-vectors on it. Wherever on the retina the fields are in phase, the opsin molecules undulate strongly and initiate the prolong

process of generating the positive visual stimulus and the spatial regions corresponding to this state is registered by the brain as bright fringes. Wherever the fields are of opposite phases, the molecules are not stimulated as dipoles and consequently they cannot initiate the visual stimulus. The brain interprets these locations as the dark regions, or dark fringes, even though the two optical fields passed right through the opsin molecules, get scattered by lower layers of molecules and create background noise. The spatial frequency of the resulting grating will be a function of the tilt between the two laser beams entering the eye. A contrast sensitivity function (CSF; the contrast required by the observer to detect each of a number of different spatial frequencies) for such gratings will give a measure of the MTF of the eye (minus the aberrations of the eye's optics). The typical CSF is shown in Figure 7. The CSF has a band-pass like characteristic, with a low- and high- frequency "curt-off" (fall). The low-frequency fall is due to the neural factors and the high frequency fall is due to the optics.

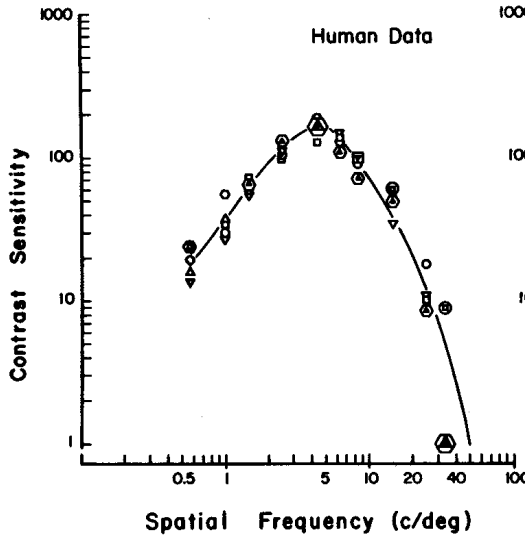


Figure 7. The contrast sensitivity function (CSF) of a human eye [see references 14, 17, 18].

5. DISCUSSION

In this brief paper we have not considered various neural/psychophysical findings such as temporal summation or spatial summation by the visual system. Nor are major neural processing events covered. Instead we have tried to show that the absence of heterodyne white noise on the retina is due to the mechanisms and time delays in the generation of the visual signal when multiple superposed signals are presented on the retina. This obviously has evolutionary, survival consequences – other wise we would have been overwhelmed by the 'white noise" due to superposition of light on the retinal. This allows us to pick out the pertinent visual signal without getting confused by fluctuating temporal noise. This once again underscores the fact that what we perceive is really the information filtered and communicated by the detectors (namely the photoreceptors) and its interpretation by the brain. This is further elucidated by using the famous Campbell experiment of placing two sources close in the entrance pupil of the eye, which produces the perception of superposition fringes in the plane of the retina. Why then do we not see the heterodyning? This is due to the basic molecular mechanisms of vision and the underlying physiology. First, the amount of signal that meets the double criteria for temporal heterodyne excitation molecules, i.e. parallel polarization and perfect collinearity of the wave fronts, is very small. Second, even if the entering small quantity of light is collinear with polarization parallel to each other, the neural signal generation process is too slow to recycle the detecting molecules at the beat signal. What we see therefore depends upon the nature of the detector. We have actually learned to exploit this unusually slow recycling process of our visual photo sensors to enjoy the projection of a rapid succession (~40Hz) of still pictures as fully animated "movie" or "television programs"!

ACKNOWLEDGEMENTS

CR would like to acknowledge partial support from the Nippon Sheet Glass Corporation. Thanks to N. Tirfessa for assisting in the preparation of some diagrams.

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