Modern Quantum Theory of Color Vision and Statistical Colorimetry, Their Role and Influence on Changing Fundamental Assumptions of the Color Theory and Color Imaging Practice

Dmitry A. Novik
Universal Systems and Technology, Inc., Arlington, Virginia

Abstract

There are presented the cardinal statements and features of a new, quantometric, statistical version of the color vision theory and colorimetry (**CVT&C**) which is alternative to the classic wave Young-Helmholtz-Maxwell's version of the **CVT&C**. The foundations of the proposed new version of the **CVT&C** are the quantum theory of the light radiation and the quantometric methods of the photon-by-photon (ph.-by-ph.) registration (count) of the light radiation quanta in the energydispersive spectrometry regime. The main attention is concentrated on the physical and statistical aspects of the quantometric version of the **CVT&C** and its relation to the classic wave version of the **CVT&C**.

I. Introduction

The scientific understanding and description of the color and color perception has started in 1666 with Isaac Newton's famous experiment of the spreading of the collimated **colorless** sun rays by a prism of glass into a strip of light **colored** by the **spectrum** of **colors** starting from **red** till **violet** along its length. The impressive contributions on this way were accomplished by Young, Helmholtz, and Maxwell who has finalized the creation of the **trichromatic wave C**olor **V**ision **T**heory and **C**olorimetry (**CVT&C**) by his genius experiments with Maxwell's top for a synthesis of any color by weighted mixture of only **three** primary colors.

The prevailing hypothesis of the phenomenological wave **CVT&C**, as it's known (see for example [1],[2]), supposes the presence in the human **CV** apparatus the specially packed mosaic of **three** kinds of the wave, spectral selective in corresponding three primary **R,G,B** colors colorsensitive elements of the retina - the cones. These three kinds of cones are marked as ρ, γ, β cones corresponding to the **R**eddish, **G**reenish, and **B**luish thirds of the spectrum.

In spite of many minor improvements which has been added to the fundament of the **trichromatic wave CVT&C** after Maxwell the credibility of this **CVT&C** and its basic assumptions was undisputable until the last years. And it's in spite to the facts that such wave **CVT&C** is failed to answer on such basic questions as why it is **tri**chromatic; this theory is not capable to explain the shape of the spectral sensitivity responses of mysterious to some extent three different spectral sensitive elements of retina -the cones; it's failed not only to predict but explain also any nonlinear and dynamic effects of color vision perception, particularly the existing of the thresholds of this color perception.

There are some reasons for such survivalence. May be the most critical is a constructive nature of the **tri**chromatic wave **CVT&C** giving the birth to color photo, color TV, and to some extent to color printing; but first of all, of coarse, the absence of the real alternative to the wave phenomenological **CVT&T**.

In the same time it's well known the **dual** nature of the description for the different phenomenon of radiation, light radiation particularly. The light radiation may be described as a flow of photons, quantum of different energy or may be interpreted as a flow of the waves of different wavelengths.

This paper gives, particularly, the principal statements of a new, suggested initially by the author[3,4] quantum (quantometric) version of the nonphenomenological, physical, statistical **CVT&C** substantially guided by the light radiation quantum theory and the quantometric methods of the ph.-by-ph. registration (count) of the light radiation quanta flow in the energydispersive spectrometry mode.

II. The basic assumptions of the quantometric version of the color vision theory and statistical colorimetry (CVT&C).

As it's well known, the potential possibilities of the **CV**, color perception are based upon an initial distribution of the light quanta over the energy $\mathbf{W(E=}\hbar\nu\mathbf{)}$ (or on a corresponding distribution of the light radiation over the wavelength $\Phi\,(\lambda=\mathbf{c}\bullet\hbar/\mathbf{E}) \leftrightarrow \mathbf{W(E)}$). A color perception is a property of the visual apparatus securing the possibility for the **estimation** of this distribution function **W(E)** by the light radiation **registration**.

There are **two** alternative regimes for the registration of the light quanta flow. One of them is the **current, analogue** method when the radiation detector forms on its output the **current** which is proportional to the intensity of the quanta radiation flow. Quite natural that for such current regime an information about energy of the each registered quantum is **lost** because the being formed photocurrent reacts only upon the **mean** quantity of the registered quanta per time unit. Therefore, by this analogue regime of the light quanta registration there is only

one possibility for the distribution function Φ $(\lambda) \leftrightarrow$ **W(E)** estimation. It's to use a number of the **wave** spectral selective filters before radiation detector(s). Such way of the estimation of the distribution function Φ $(\lambda) \leftrightarrow$ **W(E)** by the spectral selective filters is determined as a **wavelengthdispersive** spectrometry.

The second available regime of the light quanta flow registration is the **digital** regime by the **ph.-by-ph. registration** of the light quanta flow. In this regime the detector generates on its output a corresponding output impulse to the registration of each separate radiation quantum. The count of these pulses allows to estimate the intensity of the quanta flow. By this reason a radiation detector working in such ph.-by-ph. regime of registration is often called as a **quantum counter**.

The photoionization method of registration determines the possibility of the "ideal" (in comparison to the analogue one) method of an amplification for the weak signals of the detector, the method of the multiplication (breeding) of the primary charges outcome from the photoionization absorption of the radiation quantum by the detector itself. The mechanisms of such charge multiplication may be the very various ones, it may be a phenomenon of a secondary electronic emission (conduction) and it may be various mechanisms of the plural (chain) electrochemical reactions as well. With the perfection of the photomultipliers[5,6] such ph.-by-ph. digital count regime was realized on the light quanta registration.

The most remarkable effect of the radiation quanta flow digital ph.-by-ph. registration regime lays in a fact that such regime opens an **alternative**, instead of using a number of the wave spectral selective filters, a **new** possibility of the distribution function **W(E)** estimation. As it's well known from the practice of using the ionizing radiation quanta gas counters,[7] these quanta counters can work, depending on the utilized multiplication coefficient (gas amplification) in **two** regimes - in the regime of the **proportional counter (PrC)** and in the regime of the **Geiger-Muller (G.-M.) counter**.

In the **G.-M. counter** regime the process of the charge breeding occurs on the uncontrolled chain reaction mode when the whole value of the counter gas medium is ionized **independent** to the radiation quantum energy having provoked the primary ionization process and therefore an information about the absorbed quantum energy, the value $\mathbf{E}= \hbar\nu$ is **lost**.

In the **PrC** regime the quantity of the formed (bred by the secondary ionization processes) charges is **proportional** to the energy of the radiation quantum having provoked primary ionization act and therefore an amplitude of the **PrC** output impulse **keeps** an information about the energy $\mathbf{E}= \hbar\nu$ of the absorbed quantum.

By the force of the probability nature of the quantum processes of the primary photoionization and the charge breeding processes by the secondary ionization, the proportionality of the counter output pulse amplitude to the absorbed quantum energy has the **statistical** meaning. It means that for an ensemble of **N** absorbed monoenergetic quanta of the energy $\mathbf{E}_0= \hbar\nu_0$ the **PrC** generates an ensemble of the **N** output pulses with such **amplitude distribution function V(U)** for which only the **mean** value $\mathbf{V}_0\mathbf{(U)}$ will be **proportional** to the energy $\mathbf{E}_0= \hbar\nu_0$ of the absorbed monoenergetic quanta. The dispersion of this function **V(U)** introduces the idea of the **limited amplitude resolution power** of the **PrC**.

Such remarkable property of the **PrC** which keeps **statistically** an information about the energies of the registered quanta is the ground of the wide use of the **PrC**, their amplitude resolution power for the **energydispersive spectrometry** of the ionizing radiation, i.e. for the estimation of the function **W(E).** An efficiency of such energydispersive spectrometry, the achievable accuracy of the estimation for the energy distribution function **W(E)** will be increased along the increasing of the amplitude resolution power of the being used **PrC**.

Such ones are the preliminary initial facts which are necessary for the transition to the basic statements of the proposed quantometric version of the **CVT&C** which may be formulated in the most condensed mode with the help of two assumptions which are logically linked and supported each other:

1. *the light (color) sensitive elements of the visual apparatus, the retina, namely the roads and the cones work in the **ph.-by-ph.** regime of the registration of the light quanta as the light quanta (photons) **counters;***

2. *the color sensitivity of the color sensitive elements of the retina, the cones, i.e. the possibility for the estimation of the energy distribution function of the light quanta flow which forms and transports an image, is determined by the finite quantity of the amplitude resolution of the output signals (pulses) of the cones working in the regime of the **proportional counter** for the visual light quanta (photons) whereas the most lightsensitive, achromatic sensitive elements of the retina, the roads work in the regime of the **G.-M. counters**.*

In contrast to the classic wavelengthdispersive **CVT&C** the modern quantum energydispersive **CVT&C** rejects completely the necessity to have three **different** by spectral selectivity ρ, γ, and β sorts of cones for a color perception-analysis and instead proclaims that such color perception-analysis not only may be but has to be accomplished by an **universal** and **singular** sort of cones analyzing the flow of light radiation quanta as energydispersive proportional quantum (photon) counters.

Such radical innovation in fundamental assumptions for the **CVT&C** is the major step on the way to take a new look with a new vision, a new understanding, a new paradigm on the whole picture of the color science, technology, and applications as well.

The likelihood of the first postulate is directly supported by the results of S.I.Vaviloff's classic experiments[8] and by the electrophysiological investigations for the shape of the signals which are transmitted over the optic nerve fibers.[1]

The likelihood of the second postulate has not right now any direct experimental confirmation. Therefore, the indirect confirmation of the likelihood of the second postulate of the quantum **CVT&C** will come after comparison between the main conclusions and predictions of this quantum **CVT&C** and a number of the basic results of the experimental investigations of the color vision, color perceptions.

III. The general principles of the quantum CVT&C, its predictions.

The **PrC** relates to the absorbed by it ensemble of N_q quanta with **energy distribution** function $W(E=\hbar\nu)$ by an ensemble of N_p pulses with an **amplitude distribution** function $V(U)$. Therefore, being in the range of intensity justified a linear dependence between N_p and $N_q{}^*$, it can be written

$$V(U) = \int W(\tau)\cdot p(U-\tau)\cdot d\tau \qquad (1)$$

where $p(U)$ is the **PrC** pulse amplitude response, its reaction over the monoenergetic "δ" distribution function $W_\delta(E)$ for which $W_\delta(E) = 0$ for $E \neq E_0$ and $W_\delta(E) = 1$ for $E = E_0$.

By its structure the relationship (1) couples an output signal of the linear filter $U_{out}(t)$ ($V(U)$) with an input signal $U_{in}(t)$ ($W(E)$) through this linear filter pulse response $h(t)$ ($p(U)$). The **finite quantity** of the dispersion of the filter pulse response means corresponding restriction on the filter pass-band and frequency spectrum of the output signal $U_{out}(t)$. It's true[9,10] that

$$T_h = k\cdot 1/F \qquad (2)$$

where T_h is duration of the pulse response, F is the filter pass-band, $k \approx 1$. The sampling theorem[10] affirms that with the accuracy to the **information** about $U_{in}(t)$ transported by the signal $U_{out}(t)$ the last one may be given in full by the values of n **independent** samples of this signal $U_{out}(t)$ where

$$n = 2F\cdot T \qquad (3)$$

It means, passing back in our analogue from $U_{in}(t)$, $U_{out}(t)$, $h(t)$ to $W(E)$, $V(U)$, and $p(U)$ accordingly, that a finite quantity of the **PrC** amplitude resolution power leads to the fact that the distribution function $V(U)$ may be given **in full** by the function of the **integer** argument $V(i)$ where $1 \le i \le n$ and $n = 2F\cdot T$. With the terms of the color vision theory n independent samples $V(i)$ of the function $V(U)$ means n **primary "colors"** and any color perception (estimation) of the initial energy distribution function $W(E)$ is a linear superposition of the n primary "colors" with the weights $V(i)$. The value $V(i)$ is the **number** of the ph.-by-ph. registered pulses whose amplitude are smaller than $U_{max}(i)$ and larger than $U_{min}(i)$ where the value $[U_{max}(i)-U_{min}(i)] = \Delta(i)$ is the i-th (from $1 \le i \le n$) interval of quantization of an argument of the function $V(U)$ converting the last one to the function $V(i)$ (here $U_{max}(i) = U_{min}(i+1)$ and $U_{min}(i) = U_{max}(i-1)$). It all means that the transition from $V(U)$ to $V(i)$ for energy (amplitude) dispersive spectrometry needs to be realized by the regime of an amplitude multichannel ($n > 1$) analyzer.

Such one is the linear version of the **quantum, energydispersive**, n primary color components **CVT&C** based on the assumption that the second postulate is true.

As it's followed from [6], there were reached the values of the amplitude resolution power ≈**30%** for the ph.-by-ph. registration regime of the **light** radiation quanta flow by a microchannel multiplier. It leads, using (2) and (3), to the result[3]:

$$n > 3500\text{Å}/1500\text{Å} > 2 \text{ , i.e. } n = 3 \qquad (4)$$

It's necessary to note that the transition from $n > 2$ to $n = 3$ in (4) is supported not only because the pulse amplitude response shape is coarse enough approximated by triangular shape but also by the well known fact that the **PrC** amplitude resolution power is **different** for radiation quanta of **different** energy and therefore will be increased, particularly, on the way from the red boundary to the blue boundary of the visual light spectrum.

As it's followed and stated from (4), the already known today physical process of the ph.-by-ph. registration mode with the help of the microchannel photomultipliers as the **PrC** within the bounds of the quantometric version of the **CVT&C** proves and confirms the **three**component **CV** ($1 \le i \le 3$) in this version.

The point is that the digital ph.-by-ph. regime of the light quanta registration provides the **physical** explanation of the existence of the strongly **restricted** spectral resolution for the **CV** and the number n accordingly, when a current, analogue regime of the light radiation detection has not such restriction at all because the spectral selectivity is provided from the principal point of view by application of **nonrestricted** number of the wave spectral selective filters. It removes some mystery, some God-fearing from **tri**chromatism of our color vision giving instead the natural, physical rationality for this choice.

As it was shown earlier, $n = 3$ and therefore for the forming the function $V(i)$ it's sufficient to have **only two** binary comparators for comparison pulse amplitude U with **two** threshold levels $U_{max}(1) = U_{min}(2) = U_{1,2}$ and $U_{max}(2) = U_{min}(3) = U_{2,3}$ as well as **three** pulse counters for forming the values $V(i) = V(1); V(2); V(3)$. Such principle of the forming the "colorized" function $V(i)$ of the integer argument i ($1 \le i \le 3$) is a way to use an amplitude multichannel analyzer for this goal.

Let's remind the ultimately **statistical** nature of these measurements and transformations in the process of color analysis. Therefore, the color synthesis, color perception has to be a **robust** evaluation of the initial function $W(E)$ measured (analyzed) by corresponding three components $V(1)$, $V(2)$, $V(3)$. It means that a robust evaluation of the function $W(E)$ has to be an evaluation "**in the whole**" for the function $V(i)$ rather than a separate evaluation of its component $V(1)$, $V(2)$, $V(3)$. The experimental results of the color perception confirms such theoretical recommendation. Really, color perception of the light radiation (photon) flow with an energy distribution function $W(E)$, as it's well known (see, for example [1]), estimates its color visual effect by such **three integral** parameters: **brightness** (**luminosity**), **hue** (**color tone**), and **saturation** (**color purity**).

It all means that it' advisable to describe the function $V(i)$ in the mode of its **integral** functional transform provided the possibility of the **synthetic** estimation of the function $V(U)$ ($V(i)$) "in the whole". Let's select as functional integral transformation of the function $V(i)$

the **direct moment transform** (**DMT**) which describes the function **V(i)**) by its moments $\mathbf{m_k}$ of the **k**-th order (**k=0,1,2,3,...**)

$$\mathbf{m_k[V(i)]} = \sum_{1}^{n} \mathbf{i^k \bullet V(i)} \qquad (5)$$

It's necessary and sufficient, in the case **n = 3**, to pick out **only three first** moments $\mathbf{m}_0$, $\mathbf{m}_1$, and $\mathbf{m}_2$ as **independent** values.

Let's form with the help introduced by (5) moments two additional **normalized** moments of the first and the second orders as

$$\mathbf{m}_{1,0} = \mathbf{m}_1/\mathbf{m}_0 \text{ and } \mu_{2,0} = \mathbf{m}_2/\mathbf{m}_0 - (\mathbf{m}_1/\mathbf{m}_0)^2 \qquad (6)$$

The magnitude $\mathbf{m}_{1,0}$ measures a location for the **center of gravity** of the function **V(i)** while the magnitude $\mu_{2,0}$ measures the **dispersion** of this function. From the point of view of the quantometric version of the **CVT&C** the magnitude $\mathbf{m}_0$ measures an **achromatic** parameter of the registered quanta flow, its **brightness (luminosity)**; the magnitudes $\mathbf{m}_{1,0}$ and $\mu_{2,0}$ measure its two **chrominance** parameters – the magnitude $\mathbf{m}_{1,0}$ evaluates its **hue (color tone)**, and the magnitude $\mu_{2,0}$ – its **saturation (color purity)**.

It's the point to emphasize that such correspondence of the **qualitative** evaluations of color perception like brightness, hue, and saturation with corresponding **quantitative** parameters like moments $\mathbf{m}_0$, $\mathbf{m}_{1,0}$, and $\mu_{2,0}$ introduces not only a **quantitative analytical measure** for color perception and recognition, and, therefore, initiates a new real analytical foundation and paradigm for the **statistical colorimetry** but helps to explain some basic **nonlinear** and **dynamic** features of the color vision, color perception as well.

In the boundaries of being introduced definitions and parameters it becomes clear the **statistical** nature of the color perception and the **statistical** character of the quantometric version of the **CVT&C**. Really, as far as there is increased the number of registered quanta **N** at first it's appeared the possibility to estimate, with the known statistical error ($\approx \sqrt{\mathbf{N}}$), accuracy, the brightness of the registered quanta flow; then to estimate the hue, and at last to estimate the saturation of the registered light radiation quanta flow. It coincides and explains in full the results of the psychophysiological experiments in accordance to which our visual apparatus separates ≈ **400** levels of brightness, ≈ **150** levels of hue, and only ≈ **20** levels of saturation.[1] These figures of the visually resolved levels of brightness, hue, and saturation need some general comments. First of all, in reality all these figures are interconnected, it means, for example, that the number of visually recognizable levels of hue depends on the levels of brightness and saturation, and vice versa. Number two, it confirms a **nonlinear** nature of visual perception in general and color perception particularly. Only a nonliearity is capable to explain an existence of the **thresholds** in visual (color) perception of the brightness, hue, and saturation. Number three, this nonlinearity directly connected with the **restricted temporal resolution power** of the rods and cones as the quanta counters, both **G.-M.** and **PrC** types alike. A **nonlinear** effect of the quantum counter registration is accompanied by the effect of according **degradations** of the **achromatic** (brightness) and **color** (hue and saturation) **perception** which starts from some level of the intensity and enlarges along additional increasing of the intensity of the registered quanta flow.

The statistical nature of the color perception and the quantometric version of the **CVT&C** is the key to the possibility for finding the threshold levels $\mathbf{U}_{1,2}$ and $\mathbf{U}_{2,3}$, determining the "colorization" of the function (distribution) **V(U)** to **V(i)**, on the base of the known experimental results determining the threshold level of the hue perception $\Delta\lambda$ as the function of the wavelength λ of the light radiation. The main feature of this dependence is the presence of two local minimums in the green-and-blue ($\lambda \approx$ **5000** Å) and orange-and-yellow ($\lambda \approx$ **6000** Å) parts of spectrum for which the threshold level of the hue separation reaches the value $\Delta\lambda \approx$ **10** Å. As it was shown in [3],[4], the values $\mathbf{U}_{2,3}$ and $\mathbf{U}_{1,2}$ must correspond **exactly** to these points of the wavelength λ (quantum energy $\mathbf{E= \hbar\nu}$) scale.

Let's underline that the facts that the values of two amplitude comparators $\mathbf{U}_{1,2}$ and $\mathbf{U}_{2,3}$ correspond exactly to the wavelengths **5000** Å and **6000** Å confirms real **tri**chromatism of the **CVT&C** dividing the whole spectrum of visual light radiation on **three equal** parts.

IV. Relations between wave and quantum versions of the CVT&C

As only we have **two different** versions of the **CVT&C** there is arisen the main question — are they completely opposite with each other or are they, to some extent, supplementary with each other.

Let's enumerate therefore the basic differences and similarities between these both, classic and modern versions of the **CVT&C**.

Whereas the wave version of the **CVT&C** postulates the presence of **three different kinds of the cones** in the retina, the quantometric version of the **CVT** tells about **identity, universality of the cones as the colorsensitive elements** of the retina.

Whereas the classic wave linear version of the **CVT&C** postulates a **wavelengthdispersive** spectrometry principle, the modern quantometric version of the **CVT&C** postulates a ph.-by-ph. **energydispersive** spectrometry principle.

Whereas the **classic** linear version of the **colorimetry** allows in general some **diversity** for the choice of no less than three spectral lines as three **primary** colors to synthesize any color, the modern **statistical colorimetry** specifies naturally not only the number of primary colors for such syntheses as **three** primary colors but their **occupation** on the spectral scale as well.

The modern quantum statistical version of the **CVT&C** not only predicts and explains naturally all the facts of the nonlinear and dynamic behavior of color perception. It even provides a natural explanation of the different **shapes** for **rods** and **cones** as **G.-M.** and **PrC** sorts of quanta counters accordingly, and, therefore, explains the decreased sensitivity in **B**luish thirds of the spectrum for cones, the additional decreasing of the sensitivity in **B**luish thirds of the spectrum for cones located in fovea and especially in its yellow spot of the retina, the difference between spectral luminous efficiency curves for scotopic and photopic vision.

This modern quantum statistical **CVT&C** predicts and provides, particularly, an explanation of the **nonspectral** nature for the arising and existing of the **purple** hue.

The classic **CVT&C** is failed to predict, explain, and confirm all these facts enumerated above. It's enough in order to claim that the classic **CVT&C** is wrong. What unites nevertheless both versions of the **CVT&C** is what it's **right forever** in color science — the fact of the **tri**chromatic **CVT&C**.

Fortunately, the classic wavelength (spectral) dispersive **CVT&C**, being wrong in its main assumption, in the same time is right, to some extent, as a **supplementary** description in the **spectral** (wavelength) terms of the modern quantum ph.-by-ph. energydispersive statistical **CVT&C** and, therefore, the classic wave **CVT&C** may be qualified as a **linear** spectral (wavelength) approximation to the modern quantum **CVT&C**. Therefore many of the experimental results of color perception measured in spectral (wavelength) terms is very helpful to confirm **indirectly** some basic parameters of the modern quantum **CVT&C**.

V. Conclusion

The categorical final answer on the question about the verisimilitude for the quantometric version of the **CVT&C**, its explanation of the construction, structure, and properties of the color vision apparatus of the living organism sought to be postponed until it will be received **direct** psychophysiological experimental verifications of the likelihood for two basic assumptions of the **CVT&C**. By the essence, this paper incorporates the strategy and program for such necessary psychophysiological experiments of the color vision, color perception.

A constructive nature of the presented quantum version of the **CVT&C**, the specific physical and statistical digital information processes and processing accompanying it can and has to be used not only for the scientific explanation of the color vision, color perception but has to be used as according engineering approach in the design of a new specific digital (computer assisted) processing of the color imagery data for such goals as color image data transmission, compression, archiving, and visualization.[11] The constructive results of the quantum **CVT&C** needs to be used for the wide utilization of it for the goals of the theoretical and, especially, practical colorimetry.

Let's emphasized also that a new quantum **CVT&C** is among small numbers of utilization of the principles of quantum, statistical mechanics for an explanation and description of the essential information processes like vision, color vision in living organism, in physiology.

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* The linearity between $\mathbf{N_q}$ and $\mathbf{N_p}$ may be justified only **statistically** in some range of the intensity of the being absorbed quanta flow. (see Section III)