Assignment for Digital Image Processing

in the Master Degree Program CME

at the University of Applied Sciences Offenburg

The History of Colors

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Overview / Abstract

This assignment is an overview of different theories in the field of color research during the last 2000 years. The theory of the antiquity and the theories between the 17th and the 19th century play the most important role in this assignment.
In this periods, the most research of colors were done by scientists, naturalists and artists such as Aristotles, Newton or Goethe.

As there have been so many theories during that time, the assignment is limited to a certain number of scientist which are significant for the research of colors . The most famous and the most popular persons with its theories are mentioned on the following pages.

At the end of this script, there are much more information of several sources available which should complete this assignment.

1. Introduction

Our perception of color is a product of visual perception. The world of electromagnetic stimuli in which we are immersed has a much more rich and varied structure than our visual system can process. We only perceive a limited range of frequencies of electromagnetic radiation, the narrow band of "visible light" which ranges in wavelength from approximately 360nm to 660nm. The visible wavelengths of light that are reflected from the objects in our everyday world are composed of mixtures of sometimes hundreds of separate and distinct frequencies of light. We somehow represent a distribution of frequencies of visible light as a single percept which we call a color. In doing so we have lost a great deal of the information that was originally present in light, in fact many different distributions of visible light can produce the same subjective color percept. [1]

The difference between the objective physical nature of distributions of electromagnetic energy and our subjective perception of this energy caused a great deal of confusion for early researchers in optics. There is still much disagreement about the nature of the transformation from the spectral distributions of photic stimuli into our convincing and stable representations of a world in which color is a quality attached to every visible object. There is still no reliable "uniform color metric" which can accurately predict just noticeable differences across spectral distributions, illumination and contrast. [1]

With that in mind, this paper retraces the history of color science, from the perspective of optical physics, psychophysics, mathematics and neurophysiology in order to gain a clear definition of the proper questions that need to be asked if we are to find a unifying framework for color perception. [1]

2. Antiquity

2.1 Empedocles (ca. 500-430 B.C.)

Empedocles named white, black, red and yellow-ochre, to which he allocated the four elements: fire, earth, water and air. The only sure associations here, however unusual they may appear to us, are those of white with fire and black with water.

The pores of the eye are arranged alternatingly of fire and of water. By passage through the fiery pores we perceive the white objects, whereas through the watery we perceive the black objects. Each sense perception has to fit into its end organ. Colors are carried by emanation to visual perception. [2]

2.2 Demeocritus (ca. 400 B.C.)

The simple colors ... are four. What is smooth is white; since what neither is rough nor casts shadows nor is hard to penetrate, - all such substances are brilliant... . Black is composed of figures the very opposite (to those of white), - figures rough, irregular, and differing from one another... . Red is composed of figures such as enter into heat, save that those of red are larger... . Green is composed of both the solid and the void... . The other colors are derived from thes by mixture. [3]

2.3 Plato (ca. 350 B.C.)

Plato's basic ideas about our visual perception have little in common with our modern explanation. They are not based on light rays entering the eye, but on rays of vision extending from the eye, thus interacting with particles emanating from objects. Accordingly, Plato introduces the first two basic colors: "It is the white which extends our visual rays, and black is its opposite". Regardless of the clarity with which he begins this exposition, the route leading us to his two further basic colors of red and "radiant" requires a highly sophisticated notion. Plato observes that our eyes become filled with tears when we are too close to a fire. Tears, understood as the unity of water and fire, provide the eye's moisture, and eventually create mixtures which lead to the diversity of colors. Objects thus acquire a radiance, and begin to glow. Red as the color of fire is henceforth explained in the following way: because of the flames

"by virtue of the ray of blended fire gleaming through the moisture, a color similar to that of blood is created", and this color "we give the name of red".
With these four basic colors, further mixtures are possible: "The radiance associated with white and red is a golden yellow....The mixture of red with white and black produces the color purple, but a deep violet will arise if the color purple is burned and if black is then generously mixed in... .If white should combine with the radiance and should then encounter a saturated black, a dark blue color will be formed, and through the mixture of this with white, a sky blue", and so on, to "yellow brown" and "leek green". [4]

This theory of Plato does not differ that much from the theories of Empedocles and Democritus which are mentioned aboved in the chapter 2.1 and 2.2. The comparison of water and fire with colors and the theory that all other colors are derived as mixtures from the primary colors is similar.

2.4 Aristotle (ca. 330 B.C.)

Aristotle was probably the first to investigate colors. He arranged for daylight, which is seldom colorless in its effect to fall upon a white marble wall after passing through a yellow and a blue fragment of glass. After observing the two resulting patches of light and their colors, he then held the blue fragment between the wall and the yellow fragment. When Aristotle saw the green component in addition to the original yellow and blue, he came to the conclusion that green will be formed when yellow light and blue light are mixed together.

The Greeks ideas thrive on the experience provided by our senses. Their world is understood as an organic entity, with its colors arising from the continually observed struggle between the darkness of the night and the light of day. Any system of colors must therefore range from white through to black and, as with all first attempts, the simplest possibility is tried to begin with: namely, the straight line which is illustrated in figure 2.1.

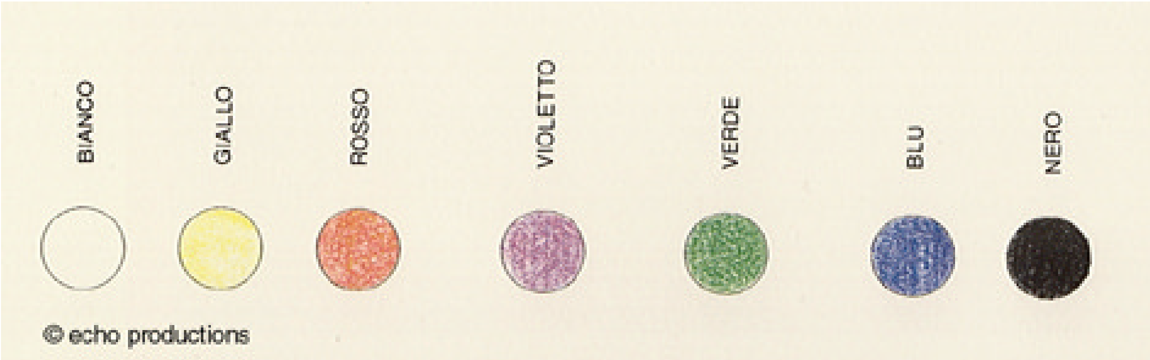


Figure 2.1: Aristotle´s Linear Sequence of Colors

Aristotle's Linear Sequence of Colors can be observed during the course of the day. The white light of noon becomes tinged with yellow, and changes gradually to orange, and then to red. After sunset, this evening red becomes a purple violet, changing to a night sky which appears as dark blue. In between, green light can sometimes be seen. [4]

For Plato, as for Aristotle, it was not light but color that was the principal source of interest in vision. Plato distinguished between light and color, considering that light had its ultimate source in the sun, but color was a property of objects. [5]

Both Plato and Aristotle considered that color was of paramount importance in perception, and that it could be dissociated from light. They knew that pigments could be extracted from certain substances, and they were well aware of the ways in which they could be mixed by artists. However, they stressed the importance of black and white, as it was described in chapter 2.3 and chapter 2.4. Plato treated them as opposites, and Aristotles considered that all colors could be made up from these two. Perhaps it was the observation that no color appeared as light as white or as dark as black that led to this speculation. [4]

2.5 Theophrastus (ca. 300 B.C.)

Aristotle´s theory was extended by his pupil Theophrastus from whom most of our information regarding the earlier theories of visions derives. Indeed, Stratton (1917) went so far as to say that "we are indebted to Theophrastus for more than to all other ancient authorities combined. Not only did Theophrastus describe the theories of the Greek, but he often criticised them roundly. [5]

For example when he has criticiced the theory of Democritus. He (Democritus) should have given some distinctive (figure) green, as he has to the other colors. And if he holds (green) to be the opposite of red, as black is of white, it ought to have an opposite shape. But if in his view it is not the opposite, this itself would surprise us that he does not regard his first principles as opposites, for that is the universally accepted doctrine. Most of all, though, he should have determined with accurancy which colors are simple, and why some colors are compound and other not. [6]

3. Isaac Newton (1642 – 1726)

By this time, Isaac Newton had also undertaken optical experiments, and had long understood that white light was made up of colored rays. He submitted a work to the Royal Society in 1672, in which he presented *"a new theory of light and colors"*. The plague had threatened London in the previous year, so Newton withdrew for several months to his parents' farm in the County of Lincolnshire. Here, he began by repeating Marci´s experiments. In 1648, Marci had directed white light through a prism and observed its deflections. Newton took this a step further, becoming convinced that the deflected light rays ran on in a straight line after passing through the prism. In his *"experimentum crucis"*, Newton directed the rays which had been refracted by a first prism through a second prism. [7]

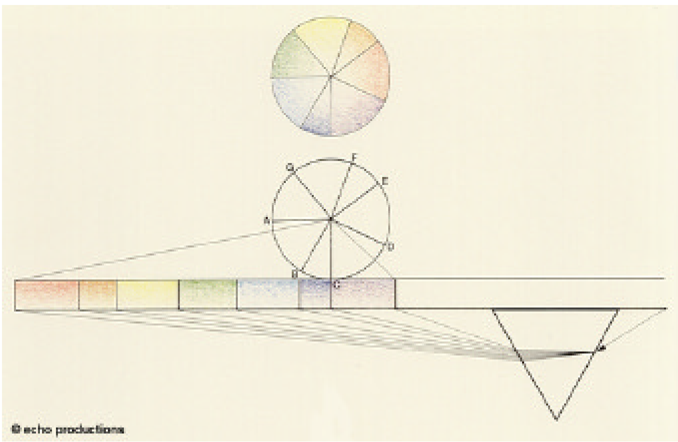


Figure 3.1: Newton´s Prism

He observed that they were deflected once more, but were otherwise not altered (further separated into colors). For Newton, this was proof that colors are not modifications of white light, but are the original components of white light. White light is composed of colored light: in fact (according to Newton), the seven colors which are located within the color-circle. This colored light is not a mixture. It is a single color, and is pure. It can be mixed, of course, to produce secondary colors, but if the components combine in the correct proportions, the light will appear white. [7]

Newton had transformed the normal linear system into a circle, dispensing with the old organisation according to values of brightness and darkness. Using modern lettering and his original script, we can see that "*Newton´s Color Circle"* comprises seven colors in the sequence red (p) — orange (q) — yellow (r) — green (s) — cyan (t) — ultramarine (v) — violet (x). Black and white have been excluded, and the vacant centre of the circle has instead been expressly assigned to white in order to symbolise that the sum of all the specified colors will result in white light. In the following figure 3.2, *Newton´s Color Circle* will be illustrated. [7]

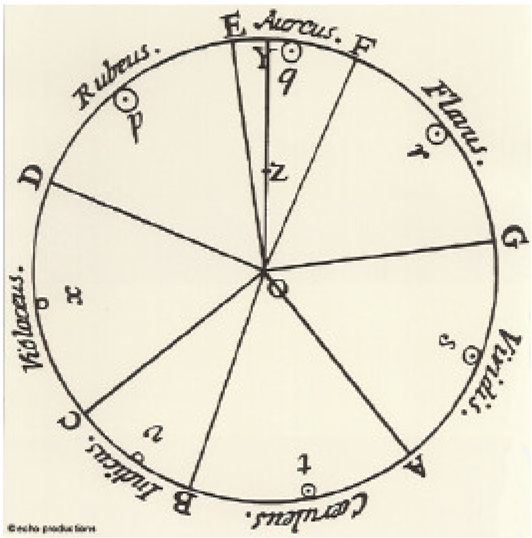


Figure 3.2: Newton´s Color Circle

He also made the observation that an object which appears red in sunlight could be made to appear any color by illuminating it with pure spectral colored light, but that it would appear brightest when illuminated with red light. From this he concluded that the appearance of color is due to differential reflective properties of substances.

While most of Newton's observations had to do with spectral light, he observed that by mixing yellow powder and blue powder together one obtained an apparently green powder. However, by looking at the apparently green powder under a microscope, one could determine that the powder was still comprised of blue and yellow grains. He thus confused additive and subtractive colors, a confusion which persisted until the time of Maxwell and Helmholtz. [8]

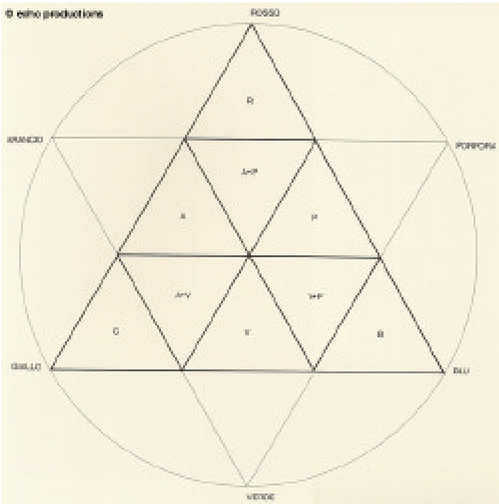
With Newton's color circle, the transition between the one- and two- dimensional color system is complete. It is helpful to realise that although this step was made by a physicist, it actually has little to do with physics. The spectrum which Newton sees on the other side of his prism is a line which he can only transform into a circle because the color tones merge into one another gradually. For this reason alone, and by dispensing with purple, the short-wave end (violet) can be joined onto the long-wave end (red). This omission in physics is overcome by our senses: out of the straight line of physics, it is actually the human brain which creates this circle, first drawn by Newton. We understand colors only when we also take into account those who see them. [7]

4. Johann-Wolfgang von Goethe (1749-1832)

100 years after Newton, Johann Wolfgang Goethe (1749-1832) examined the problems of color and although his "*Theory of Colors"* was intended to attain "a more complete unity of physical knowledge" by including all branches of the natural sciences. Goethe approached the subject primarily to gain some knowledge of colors "from the point of view of art". [9]

When, in 1793, Goethe sketched his *"Color-Circle"*, he did not place this basic pair of yellow (giallo) and blue (blu) opposite each other but extended them into a triangle together with a red, which was originally described as purple (rosso). He described "this red effect" as the "highest augmentation" of the series of colors leading from yellow to blue, and placed green (verde), arising from the mixing of yellow and blue, opposite. The circle is completed by an orange (arancio) on the ascending side and by a blue-red (porpora) on the descending side (often described as violet). [9]

In figure 4.1 and figure 4.2, the Color Circle and the Original Drawing of Goethe are shown.



Firgure 4.1: Goehte´s Color Circle

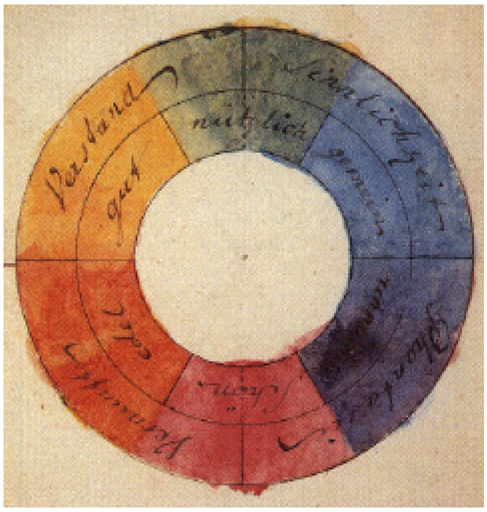


Figure 4.2: Goethe´s Original Drawing

Goethe referred to the part of his circle running from yellow to red as the plus side and its continuation into blue as the minus side, and arrived at the following arrangement. The yellow was associated with "effect, light, brightness, force, warmth, closeness, repulsion", and blue with "deprivation, shadow, darkness, weakness, cold, distance, attraction". It is suggested that Goethe's intention was mainly to ascertain the "sensual-moral" effect of individual colors "on the sense of the eye ... and the eye's imparting on the mind". He understands colors mainly as "sensual qualities within the content of consciousness" and thus transfers his analysis into the area of psychology. The colors on the plus side "induce an exciting, lively, aspiring mood". Yellow has a "splendid and noble" effect, making a "warm and comfortable" impression. The colors on the minus side, however, "create an unsettled, weak and yearning feeling". Blue "gives a feeling of coldness". [9]

4.1 Comparison between Newton´s and Goethe´s Theories

Whoever should compare this short description of Goethe's *"Theory of Colors"* with Newton's preferred approach will soon become aware of two completely different attitudes to the one, single theme. These attitudes do not oppose each other, however; they complement each other — alone, neither of the systems can cover all aspects of color completely. Their relationship can best be described as "complementary", implying a deeper meaning here than the term used for colors. Newton's analysis of colors is to be seen as complementary to Goethe's. Neither of the theories is wrong; each independently reproduces a valid aspect of our world, and substantiates the other. Goethe is only wrong when he maintains that Newton was misled, indeed "twice and three times over". [9]

In order to bring life to this idea of complementarity, we can compare the English scientist's and the German poet's beliefs. What for Newton is simple — pure blue, for example, being light with one wavelength ("monochromatic light") — is complicated for Goethe, since pure blue must first of all be prepared by an extravagant means and is therefore artificial. In contrast, white light is simple for Goethe, since it exists completely naturally and without effort. Newton, on the other hand, sees in white light a mixture of all colors. White light is not simple for Newton, it is a combination. [9]

The essential complementarity of both color theories becomes evident when we consider the role of the subject — the human being. While Goethe, as a matter of course, views the human being as central, Newton omits him totally. Here, two complementary truths meet. Goethe presents the direct truth of sensuary perception as a counterbalance to the remote truth of Newton's science; Newton distances himself from a notion of the world ("the pure human sense" as Goethe would have it). Indeed, Goethe expressively employs such a notion to obtain clarity about the nature of colors. Something troublesome arises here, creating a certain tension. The opposite of one deep truth (in this case from Newton) is not something which is wrong; it is another deep truth (that of Goethe). [9]

5. Johann Heinrich Lambert (1728-1777)

The astronomer, mathematician and naturalist Johann Heinrich Lambert is renowned amongst physicists as the founder of the theory of light measurement, which at that time was known as *"photometria"*. He was strongly influenced by the work of Tobias Mayer, presented the first three-dimensional color-system in 1772. [10]

In about 1760, Lambert originated the law governing the illumination of a surface by a light source which still bears his name. He also studied the ability of surfaces to reflect, and their transparency. In the course of his deliberations, he consulted measurements taken by Tobias Mayer in Göttingen and Lambert recognised that Mayer had discovered a means of constructing and naming many of the possible colors. At the same time he also recognised that, to extend its coverage to include their full abundance, the only element missing from this triangle was depth. [10]

After carrying out his own experiments, Lambert suggested a pyramid, which is shown in figure 5.1, constructed from a series of triangles to accommodate the full richness of natural colors in one geometrical form.

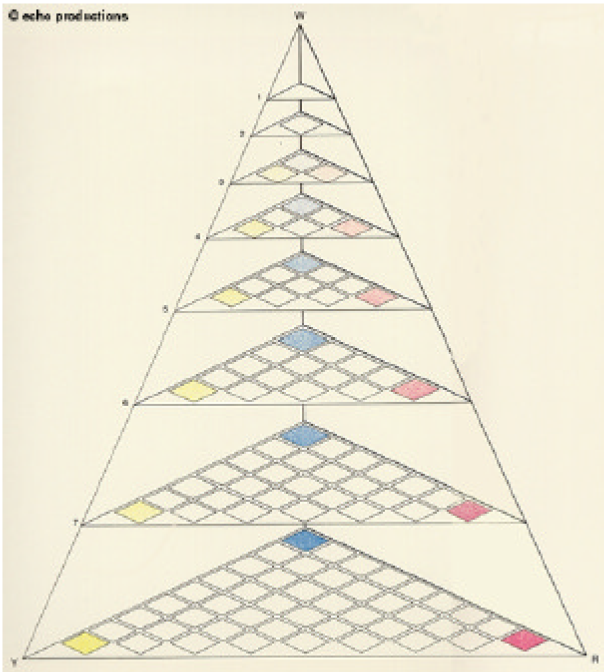


Figure 5.1: Lambert´s Pyramid

As with "*Mayer´s Modell*", the corners of "*Lambert's Base Triangle"* are occupied by King's yellow, cinnabar and azurite. In each case, two basic colors are mixed (with varying proportions) to form seven hues along the sides, while on the inside all three basic colors contribute to the color of each respective surface unit. A total of 45 color-hues are thus formed in the lowest triangle, above which the others rise, tapering and becoming brighter as they proceed upwards. In turn, they contain 28, 15, 10, 6, 3 and finally 1 field.

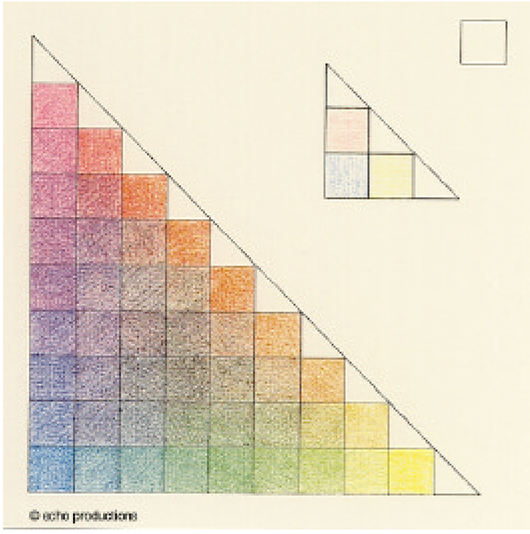


Figure 5.2: Lambert´s Base Triangle

Lambert accommodates a total of 108 colors or their mixtures in his pyramid, the tip of which is white. [10]

This construction succeeds in incorporating the various "tertiary colors" into one system, and logically links them with the neutral grey values appearing along its central axis. The color created by mixing all basic colors — black — is found at the centre of the lowest triangle. More colors can be distinguished on this plane than at the point where white predominates, demonstrating that the system of colors must taper upwards, and is a therefore a pyramid. [10]

As a naturalist, Lambert used his pyramid in his efforts to identify and classify all the colors which occur in animals and plants. Of course, this objective can only be achieved if a mixing system, operating with the three colors yellow, red and blue, is capable of creating each color. Unfortunately, this is not possible. In nature, there are many tints of very colorful green, orange or violet which cannot be created by subtractive mixing of three primary colors. Many colors in a butterfly, for example, are formed not by a mixture of this kind or specific dyes, but through the physical properties of light: interference, in other words, through thin leaf-like structures. The abundance of colors thus created reaches far beyond the pyramid in which Lambert wished to confine them. [10]

6. Thomas Young (1773-1829)

Thomas Young, while advancing his theory of light as undulations in a luminiferous elastic ether, brought Newton's observations on the perception of color back into public awareness with the observation that *"The sensation of different Colors depends on the different frequency of Vibrations, excited by Light in the Retina"*. Young further suggested that the retina might be sensitive to only three principal colors and that all appearance of color might be attributable to varying degrees of excitation of these three receptors. [11]

Now, as it is almost impossible to conceive each sensitive point of the retina to contain an infinite number of particles, each capable of vibrating in perfect unison with every possible undulation, it becomes necessary to suppose the number limited, for instance, to the three principal colors, red, yellow, and blue, of which the undulations are related in magnitude nearly as the numbers 8, 7, and 6. Furthermore each of the particles is capable of being put in motion less or more forcibley by undulations differing less or more from a perfect unison. For instance the undulations of green light being nearly in the ratio of 6.5, will affect equally the particles in unison with yellow and blue, and produce the same effect as a light composed of these two species. Each sensitive filament of the nerve may consist of three portions, one for each principal color. [12]

While Young made an interesting and prescient guess about the nature of color perception, his choice of the three subtractive primary colors would continue to confuse color researchers for another fifty years.

7. James Clerck Maxwell (1831-1879)

Jame Clerk Maxwell, the physicist, presented his *"Theory of Color Vision"*, acknowledged as being the origin of quantitative color measurement (Colorimetry). In this work, Maxwell demonstrates that all colors arise from mixtures of the three spectral colors — red (R), green (here abbreviated to V [verde]), and blue (B), for example — on the assumption that the light stimulus can be both added and subtracted. He allocates each of the three main colors to a corner of a triangle, into which we have then placed a curve of spectral colors which is provided with technical data. [13]

The wavelengths of visible light are now known to lie in a range between 760 nm for red and 380 nm for blue, with green at approximately 550 nm. These values are located along the length of the curve. In the following figure 7.1, *Maxwell´s Triangle with the curve of wavelenghts* is shown.

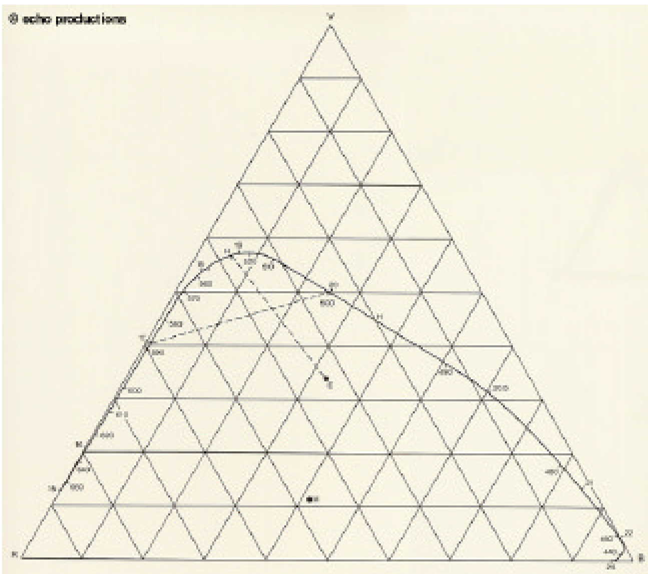


Figure 7.1: Maxwell´s Triangle with Wavelenghts

Maxwell's observations of colors are based on propositions made by Thomas Young, who had already noted that no more than three colors of the spectrum were required in order to bring all others into being. At the time when Young submitted his trichromatic theory, many artists had long known that they could mix all color shades by using three primary pigments. Physicists, however, were still influenced by Newton's claim that the seven colors emanating from a prism are elementary (and therefore not mixable). [13]

In his experiments into the measurement of color, Maxwell engaged test subjects, who judged how the color of a sample compared with a mixture of the three basic colors. Nowadays, the test subjects are themselves allowed to change the mixture of red, green and blue (with the aid of standardised light sources) until the impression of the color corresponds to that of the sample ("color match"). The respective proportions of the mixture can be recorded using three numbers, identified as R, V and B and known since Maxwell's time as "tristimulus values". [13]

Maxwell now became aware that the brilliance of a multicolored surface is relatively insensitive to changes in brightness, and was able to totally eliminate this as a determining factor by introducing new parameters r, v and b, arrived at by dividing each tristimulus value by their total value: r = R/(R+V+B), v = V/(R+V+B), and b = B/(R+V+B). These new color coordinates fulfil a simple condition; their sum is one (r + v + b = 1). This means that all their possible combinations can be represented as the points of an equilateral triangle; the *Maxwell Triangle*. A few examples can be seen in the series of Figure 7.2. [13]

Since their tristimulus values, or their colour coordinates, add up to one, the triangle enables us to predict the result of a mixture of two colours . All possible combinations of any two colours will lie on the line connecting their respective positions within the triangle. Naturally, Newton's circle had already specified the results of colour mixing. But Maxwell's achievement was that the geometrical relationship and spacing between the colours in his triangle have a precise meaning, based on psychophysical measurements. [13]

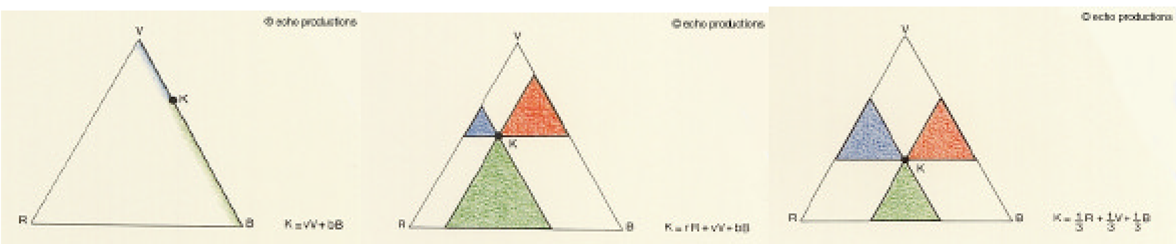


Figure 7.2: Maxwell´s Triangles

In his colour mixing experiments, Maxwell was able to demonstrate that Newton's circle of seven colours, with white as a middle point, implicitly satisfied the trichromatic theory since it equates to a model which allocates a point within a three-dimensional space to each colour. [13]

References

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[3] Stratton, G.M. 1917. Theophrastus and the Greek Physiological Psychology before Aristotle. New York: Macmillan. Page 133-135

[4] Virtual Color Museum. Pythagoras, Aristotle, Platon
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[5] Wade, N.J. 1998. Light and sight since antiquity. In: Perception. – London:Pion Page 640

[6] Stratton, G.M. 1917. Theophrastus and the Greek Physiological Psychology before Aristotle. New York: Macmillan. Page 141

[7] Virtual Color Museum. Isaac Newton
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[8] The Representation of Color Metrics and Mappings in Perceptual Color Space
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[9] Virtual Color Museum. Johann Wolfgang von Goethe
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[11] Young, T. . On the theory of light and colors\ Philosophical Transactions of the Royal Society, 91, Page 12-49.

[12] Young, T. . On the theory of light and colors\ Philosophical Transactions of the Royal Society, 91, Page 21.

[13] Virtual Color Museum. James Clark Maxwell
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Further Literature and Links

Internet:

- The Representation of Color Metrics and Mappings in Perceptual Color Space
  Link: http://kiptron.psyc.virginia.edu/steve_boker/ColorVision2/node1.html

- Color Museum Link: http://www.colorsystem.com/grundlagen/aad.htm

- The Bases of Color Vision Link: http://www.psych.ucalgary.ca/PACE/VA-Lab/Brian/default.htm

- Johann Wolfgang von Goethe: Schriften zur Farbenlehre Link: http://www.steinerschule-bern.ch/goethe/farbenlehre.htm

- Florian Merz: Studienarbeit zum Thema Farbbildverarbeitung
  Link: http://www.fh-offenburg.de/vorlesungen/bildverarbeitung/assignments/Topic13.2/FARBBILDVERARBEITUNG.PDF

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- Wade, N.J. 1999. A Natural History of Color