Wilhelm Ostwald

Neue Forschungen zur Farbenlehre (New researches in color science)

Physikalische Zeitschrift XVII, 1916, pp. 322-332, Leipzig: S. Hirzel (1899-1945)

An English translation with a biographical introduction by Rolf G. Kuehni and a technical introduction by Michael H. Brill and Rolf G. Kuehni

Wilhelm Ostwald (1853 – 1932)

Friederich Wilhelm Ostwald was born in Riga, in the Russian Empire (today in Latvia) to descendents of German immigrants, Gottfried Wilhelm Ostwald, a master cooper and Elisabeth Lenckel. Ostwald studied chemistry at the University of Tartu (today in Estonia) where he graduated in 1874 and received his PhD in 1878. He taught at Tartu from 1875 to 1881 and at the Riga Polytechnic Institute from 1881 to 1887. In 1887 he was named Professor of Physical Chemistry at the University of Leipzig where he did pioneering work and was the director of the Department of Physical Chemistry which inaugurated a new departmental building in 1897. Ostwald was instrumental in establishing physical chemistry as a strong separate entity of the sciences. During his years in Leipzig he had more than 70 students from the USA. In 1905 he spent half a year at Harvard University lecturing as an exchange professor. After his early retirement from the University of Leipzig in 1906 he received in 1909 the Nobel Prize for Chemistry for his work on catalysis, chemical equilibria, and reaction velocities. He was the recipient of a number of honorary doctorates from universities in Europe and the USA as well as various honorary memberships in learned societies.

In 1880 Ostwald married Helene von Reynen and they had two daughters and three sons. Ostwald was an enthusiastic amateur painter throughout his adult life and left some 4000 works. His range of knowledge and activities was unusually large. It is estimated that in his lifetime he wrote some 20,000 pages. Among these are some 37 books, 11 each on chemistry and color, 3 on philosophy and 12 on general subjects. Many of these have been published in multiple editions and translated into multiple languages. He founded some scientific journals and national and international scientific organizations. In his ontological views he was a monist believing that the basic element of the universe was energy.

During his stay at Harvard University he became acquainted with Albert Henry Munsell with whom he had extended discussions on color. This was a subject of interest to him in

connection with his hobby of painting. After his early retirement from the University of Leipzig he moved to his country estate of Grossbothen, located between Leipzig and Dresden. At the time of his death there were five buildings on the estate, most designed by him for various purposes. Today the estate is the seat of a foundation housing extensive collections of Ostwald's labors. It was at Grossbothen where he decided to devote most of his time to research toward establishing a solid scientific foundation for the subject of color. His predecessors in Germany were Helmholtz and Grassmann, who established, together with Maxwell in England, the trichromatic theory. Ostwald was keenly aware of the battles between Helmholtz and Hering and was convinced that Hering had made important contributions toward understanding of color phenomena. He became convinced that trichromacy did not offer a complete answer. Ostwald was particularly interested in solidifying the science of object colors.

Ostwald established many new empirical facts in experiments that tried to establish the relationship between stimuli and object colors. He also developed and published in 1917 a color order system with 2500 samples, for a long time the largest attempt at an objective color atlas. While he understood the difference between psychological color and physical 'color' he did not hesitate to introduce compromises between the two, while his contemporary Schrödinger separated color science into elementary color measurement, based on judgments of equality, and advanced color measurement based on the results of psychological evaluations.

Retrospective Introduction to Wilhelm Ostwald's "New Researches in Color Science"

Michael H. Brill and Rolf G. Kuehni

Optimal colors are the idealized reflectance spectra that bound the object-color solid in tristimulus space. At the beginning of every bibliography on the optimal colors is Wilhelm Ostwald's "New Researches in Color Science."[1-4] The fundamental theorem of optimal-color reflectances is that such reflectances are 1 or 0 at every wavelength with at most *n* transitions, where *n* is the maximum number of times a straight line in chromaticity space intersects the spectrum locus. The number *n* is taken to be 2 for human vision, based on the observation that our spectrum locus is substantially convex and well-ordered in wavelength.

How far did Ostwald progress toward the modern understanding of the theorem? He surely understood the "1 or 0" concept because of his definition of purity, which he defined through its opposite: impurity is the degree of whiteness in the nominally-0 region of the spectrum plus the degree of blackness in the nominally-1 region of the spectrum. Purity is defined as 1 – impurity. Hence reflectances with greatest purity are those that are 1 or 0 at each wavelength. Additionally, the wavelength (or, more accurately, color-circle angle) regions with 1 and 0 must each be connected. This we can infer from the fact that Ostwald imagines the 1 and 0 regions to comprise a semichrome, defined as follows: The color-circle "angle" is divided in two parts, half with reflectance 1 and the other half with reflectance 0. Ostwald also refers to "pure" and "impure" semichromes, the former referring to theoretical functions with transitions between 0 an 1, the latter to those achievable with real colorants. The color circle traverses a wavelength-like domain comprising the spectrum locus with the line of purples, and "half" means the 1-to-0 transition points are complementary with respect to the illuminant white. However, the "half" in the semichromes is too limiting of the possibilities available with optimal reflectances.

Because the currently translated article contains no discussion of the optimal colors *per se*, it is tempting to conclude that Ostwald had no understanding of them. However, his later book, *Physikalische Farbenlehre* (PF) [5], uses an idealized function in Fig. 49 and in Fig. 51 he shows the four types of real reflectance functions that Schrödinger then shows in his paper in the idealized form. Being an empiricist and not a mathematician, Ostwald understood the optimal colors without voicing a theorem about them.

Koenderink [6] attributed to Ostwald the development of a synthetic color order system that comprises the semichromes and mixtures of black and white. This atlas does not extend all the way to the optimal colors, but fills up two cones in tristimulus space whose common (non-planar) base is the set of semichromes. Such geometric realization (and even the gamut shortfall due to hanging the colors entirely from the semichromes) is surely consistent with the 1916 paper, but manifested more clearly in PF and other works by Ostwald.

Semichromes have their own theorem, to which Ostwald came closer in his 1916 article than to the optimal-color theorem. We can appreciate his understanding once we overcome some difficulties of terminology. On the same page as Fig. 2, Ostwald notes the definition of a semichrome and asserts the essential theorem: "The totality of colors within half of the color

circle must be combined to obtain a saturated color." By a "saturated color," he meant what he in 1918 [5] called "full color" (Vollfarbe[1]) a term also used later by Schrödinger and Luther with expanded meaning: If the object-color solid were examined in parallel projection along the white-to-black axis, the full colors would be on the occluding contour. By "half the color circle" Ostwald meant a connected part of the spectrum whose end wavelengths are complementary relative to a given white. By "totality of colors" he meant a reflectance value of 1 at every wavelength within the aforementioned connected part. This understanding is shared by J. Koenderink [6, 7]. But although Ostwald understands the behavior of semichromes, he does not prove it as a mathematical theorem. He uses empirical means, admitting that "confirmation is fairly incomplete".

In assessing Ostwald's 1916 article, we must be mindful of its original goal and not just of the mathematical implications that revealed themselves later. Ostwald's goal was not to characterize the optimal colors or to prove the optimal-color theorem. He sought a meaningful, empirically accessible set of coordinates for the space of object colors. Dominant wavelength and lightness were two of the dimensions, and purity seemed too ill-defined in literature prior to Ostwald's writing. Ostwald therefore defined purity, and said of his definition, "I do not believe I am guilty of exaggeration by viewing the discovery of absolute purity measurement as the most important progress that color science required for its steady progress and was able to make."

Ostwald's metric of colorimetric purity did not survive into modern practice, but some of his other ideas persisted.

For one thing, he described (perhaps for the first time) the terminology and distinction between related and unrelated ("nonrelated") colors. Ostwald visited Albert Munsell in 1905 and had lengthy discussions with him concerning the latter's color order system. But later he rejected the idea that Lichtstärke (Helmholtz) can be a valid attribute for related colors and decided that the only valid attributes in that case are full color, whiteness, and blackness [5, pp 53, 54]. He concluded that from arguing that brightness applies only to unrelated colors. Lightness as a principle separate from brightness was not yet a generally accepted idea. Ostwald himself used a gray scale to make psychological brightness/lightness measurements.

Ostwald thought highly of Ewald Hering, quoting him verbatim over several pages in PF, and arranged his color system essentially according to Hering's. However Ostwald used complementary opposites which, particularly in the red-green pair, are far from Hering's Urfarben. Hering hoped they might be complementaries but for most people the Urfarben according to Hering's 'neither-nor' perceptual definition are not. His color order system like its modern implementation, the Swedish Natural Colour System (NCS), is based on "average" unique hue percepts of the four chromatic fundamentals.

[1] In the translated paper and in the much longer one of 1917 [8] Ostwald did not use the term 'Vollfarbe.' The term is mentioned in the 1918 first edition of PF. Attached is the graph of the hue circle from PF that shows the relationship between Ostwald's 100 hue numbers and wavelength, where possible (Fig. 35). This circle defines his semichromes, and the idea of the Vollfarbe is also present, albeit in a not-fully-developed form.

Finally, Ostwald [5, p 237ff.][2] introduced the term "metamer" into the color field and defined it as follows: "Color metamers are those that, even though they are composed differently in regard to types of light or wavelengths, have identical appearance. The identical appearance is not limited to hue but is complete, that is, also in regard to white and black content." However, he did not mathematically define the concept, even though he was well aware of König's color-matching functions. Figures 58 and 59 below show sketches of reflectance functions of "double, triple, and multiple grays." Of the many of Ostwald's discoveries, metamerism is one of the few that remains.

In summary, although many people have cited the currently translated 1916 paper as seminal to the theory of optimal-color reflectances, the connection should be extended to other Ostwald works including PF, and we should examine the 1916 paper on its own merits. Ostwald was clearly the first to give the object-color solid extended thought supported by a lot of experiments. He did not represent it in full detail; that was left to Schrödinger and others. But because Ostwald was first, it is appropriate to examine his contribution, perhaps facilitated by the present English translation.

[2] The terms 'Isomerie' and 'Metamerie' (as well as several others) were introduced into chemistry by the Swedish chemist J. J. Berzelius (1779 – 1848). Ostwald applied them in a comparable fashion to the field of color.

[1] E. Schrödinger, Theorie der Pigmente von grösster Leuchtkraft, Ann d Physik 62 (1920), 603-622 (1920). See English translation by R. G. Kuehni on this website.
[2] D. L. MacAdam, The theory of the maximum visual efficiency of colored materials, *J. Opt. Soc. Am.* **25**, 249-252 (1935).
[3] G. West and M H Brill, Conditions under which Schrödinger object colors are optimal, *J. Opt. Soc Am.* **75**, 1223-1225 (1983).
[4] D. Couzin, Optimal fluorescent colors, *Color Res. Appl*. **32**, 85-91 (2007).
[5] W. Ostwald, *Die Farbenlehre, Vol. 2 Physikalische Farbenlehre*, Leipzig: Unesma 1918.
[6] J. Koenderink, Color atlas theory, *J. Opt. Soc. Am. A*, **4**, 1314-1321 (1987).
[7] J. Koenderink, *Color for the Sciences*. Cambridge, MA, 2010: MIT Press.
[8] W. Ostwald, Beiträge zur Farbenlehre, in Vol. 34 of Abhandlungen der Mathematisch-physischen Klasse der Königlich-Sächsischen Gesellschaft der Wissenschaften, No. III, V + 365-572, Leipzig: Teubner, 1917.

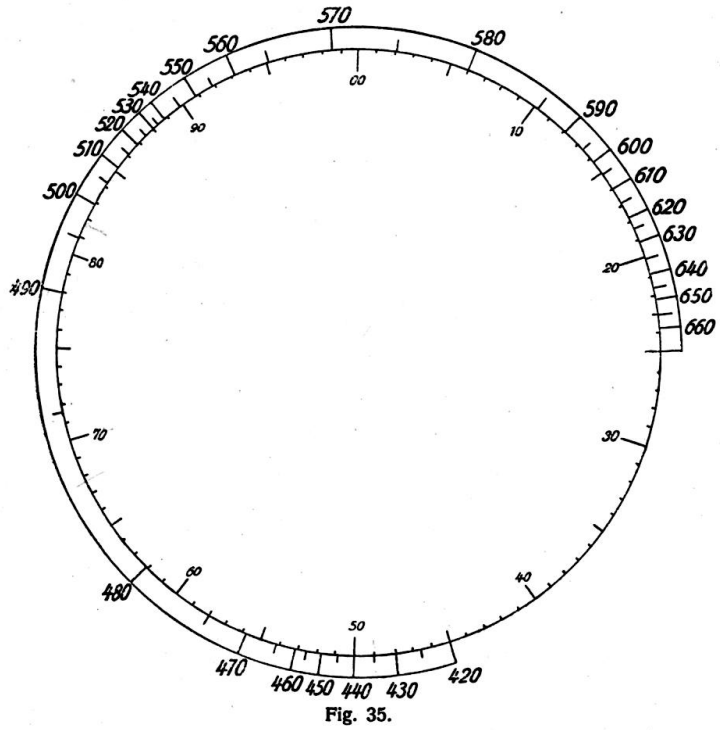

Fig. 35.

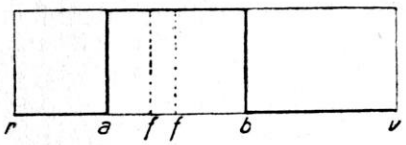

Fig. 49.

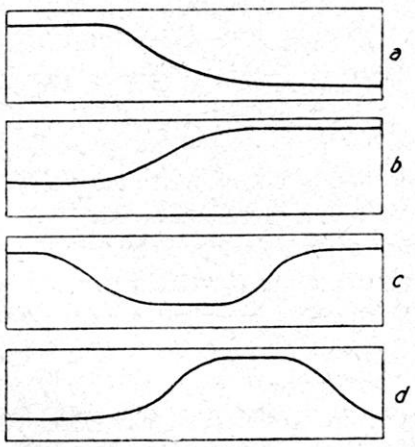

Fig. 51.

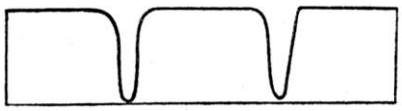
Fig. 58.

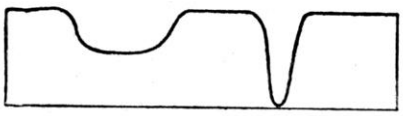
Fig. 59.

Wilhelm Ostwald

New researches in color science (Neue Forschungen zur Farbenlehre)

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Current state of color science

Since its beginning, research in color science has been impaired by the insufficient clarity concerning the question of which more general science it should be part of. As a result, initially it was regarded as a physical or even a chemical problem and its most successful researcher in recent times, Helmholtz, has treated the problems of color science from the standpoint of a physicist and later from that of a physiologist. However, among today's researchers, led by E. Hering, the insight has emphatically moved to the foreground that in the final analysis color science is a psychological discipline, which therefore psychology is the general science in which color science must be placed as a sub-discipline. According to the lawful structure of the totality of sciences the earlier mentioned disciplines, from logic and mathematics (that together I will give the term mathetics) to physics, chemistry, and physiology, play only a subordinate role. It is therefore completely natural that those disciplines whose development, as a result of their relatively greater simplicity, has progressed more rapidly than that of psychology, at first treated the areas of color science in which they found specific application as parts of their own discipline. In particular, an extended physical color science developed in this manner, based on the narrow and definite relationship that exists between the stimulation of the visual apparatus by light of certain wavelengths and color experience. However, these more general sciences can, given the nature of this subject matter, only add materials toward the final solution of the problems of color science, but are insufficient to achieve the solution. In other words, they are necessary, but insufficient components of a science of color.

It is also possible to clearly see in the history of color science the difficulties that result from insufficient clarity concerning these relationships. The passionate battle, for example, that Goethe carried on against Newton was lastly due to the fact that for Goethe color science was properly a psychological problem while Newton only determined the physical conditions necessary for certain color percepts and his successors treated these conditions as the true and final content of color science. In recent times it was especially E. Hering who made the important contribution of pointing out with vigor the true situation while at the same time laying the foundation for a purely psychological color science for which the named other sciences are properly only supporting disciplines.

At any case, also the newer developments have not yet solved the major problems so that color science can become effective. A compilation of what is known up to now indicates large gaps in regard to a number of substantial issues. For example, for a long time the idealistic term of a pure or saturated color has been used to relate impure or dull colors to it. The inquirer into the definition of the term saturated color is usually referred to lights of constant wavelength, that is, the colors isolated in the spectrum. However, a somewhat more penetrating consideration indicates that identification of spectrally pure colors as saturated colors cannot be true. Among the purest colors currently produced by technology are the yellows and a contamination of

yellow with black or gray is especially easy to recognize. All researchers concerned with this matter are in perfect agreement that among pure or saturated colors yellow is the brightest. When, in an attempt to determine the size of the portion occupied by pure yellow wavelengths, a spectrum is carefully considered it is evident that the width of the section is exceedingly narrow and that in the psychophysical sense it represents at most a few percent of the total spectrum. To be identical with a spectrally pure one, the brightness of a saturated yellow can only have the brightness of a few percent of that of a pure white object, which cannot be valid because the brightness of yellow is much higher. As will be shown later it is actually 0.9 [90%] of that of absolute white. The necessary conclusion is that pure yellow most certainly does not consist of spectrally pure rays and also not of closely neighboring rays, for example 580 to 590, but must contain a large number of other rays. Spectral analysis of any kind of pure yellow solutions or paints produces a result in full agreement, i.e., the undiminished presence of all rays from the red long-wave end of the spectrum all the way to blue-green of approximate wavelength 490. The purer the yellow, the more the result of its spectral analysis agrees with the description just given; the presence of partial absorption at any location in this region renders the resulting yellow psychophysically impure when compared to other, purely yellow colors.

This situation also touches on another unsolved problem. It is the question concerning the degree of purity of a given color and how it can be measured. So far there have only been timid attempts at a solution by a few researchers based on the rule that the various descendants of a specific hue are the purer the more of their complementary color is required to neutralize them to a pure gray (for example in a disk mixture experiment). As is evident this idea, even when expanded to its limits, only allows for *relative* purity determination related to a specific opposing color used for the compensation. It does not allow a conclusion regarding its absolute purity value and does not allow extending the conclusion from one hue to another. This principle can only provide information about the purity relationship of a pair of complementary colors but cannot be extended to any third hue.

A third example of the current state of color science is the question of the brightness of chromatic colors. The difficulties of practical photometry when comparing light sources of different color have shown themselves to be of a magnitude that several competent researchers deny the comparability of the brightness of different lights, thereby declaring the determination of specific brightness values of differently colored lights being impossible. Using the simple approach of not comparing different chromatic colors directly in regard to their brightness, but each one individually against a gray that produces the same psychological brightness perception the just named difficulties can be resolved in a fundamental manner. In this manner it is possible to find for any presented color a brightness value determined by certain very simple and general laws. However, at the same time it is found that the current inclusion of brightness as one of the definitive coordinates of each color, since Helmholtz generally viewed as being hue, purity, and brightness, cannot be considered effective because brightness shows itself as being a special property of colors, without direct connection to its analysis and synthesis. Instead, in color analysis, aside from hue, the content of black and white must be designated as elements of a given color. They make it possible on one hand to express the result of the analysis without ambiguity, on the other they also make a corresponding synthesis with reconstruction of the analyzed color possible.

A number of other points could be made where current color science has failed or produces wrong answers. One of these is why in the spectrum, regardless of brightness and of mixture, brown, olive green and comparable colors can never be achieved, even if the ratio

between monochromatic and white light is varied in any which way. Also mentioned can be the lack of a principle according to which the continuous and closed sequence of hues can be divided up and numbers attached to them to assign to each hue its unequivocally determined location without subjective arbitrariness or having to fall back on arbitrarily selected samples.

All these facts demonstrate that a fundamental development of color science from its elements is necessary to place this field appropriately within the exact sciences. The need for such progress is particularly urgent today given, for example, the existence of an extensive, worldwide industry of artificial colorants that so far has not been able to identify numerically or by measurement the key property of its products, i.e. their color. Presently, a particular color can be defined only in form of a physical object that has the color in question. Such objects can undergo change in the course of time, a possibility against its occurrence one is essentially helpless.

There is, therefore, the task not only to fill the mentioned holes and correct the insufficiencies just pointed out, but also to generate the missing foundations to the point where color can be defined unambiguously by number and measure and, in the opposite direction, a certain defined color can without doubt and without the help of a reference sample be produced, as it is possible, for example for temperature, electrical current, or volumina. In other words, the goal of a science of color must be the integration of the system of colors into the so-called system of absolute measures. In the following I am attempting to show that these requirements can actually be met today.

Unrelated and related colors

When removing the ocular lens from a spectroscope of conventional build and putting a slit in place of the cross hairs, the image when looking through the slit is that of the frontal plane of the prism filled with a homogeneous color which depends on the orientation of the two slits. By moving the telescope tube or the prism any color of the spectrum can be viewed. By adjusting the instrument so that it displays a specific color, e.g. pure lemon yellow, and adjusting its brightness by opening or closing the slit of the objective within broad limits, the viewed field is always seen as pure yellow. Only in case of very high illumination does the appearance of the yellow field change to a white one due to overexposure of the eye. On the other hand, when the brightness is extremely low the yellowness disappears as the viewed area is no longer perceived. In this case the observer no longer views the object via the fovea but rather in the peripheral regions because they are much more light-sensitive but cannot convey a color difference. The characteristic change in yellow by addition of black, such as can be demonstrated using disk mixture, is not at all experienced in the spectral apparatus; the yellowish gray or olive green colors that can be generated with optical mixture of black and yellow and that for inexperienced viewers present a surprising spectacle of the changes from a saturated toward an achromatic color are non-existent. Comparable phenomena can be produced even more easily by placing at the outer end of a piece of tube that is blackened in its interior a piece of frosted glass or by closing it off with a piece of oil paper and then placing into the resulting bright field in dark surroundings a piece of gelatin, deeply colored with any kind of clearly discernible color. By pointing the tube sequentially toward the window and toward the darkest corners of the room it is possible to change the objective strength of the light passing into the pipe within a very wide range. The light thereby does not change its color at all. If it is red it remains red all the way to the final border of perceptibility and does not turn brown as red does when it is optically mixed

with black in disk mixture. Comparably, it is not possible to perceive with such an apparatus (absent a colored filter) gray when changing the intensity of the light. Either a bright field of view or nothing is experienced, never is it seen as gray with mid-level illumination and white with high illumination.

Here we have a case where a color, despite wide-ranging changes in the objective intensity of light, does not change. On the other hand it is easily possible to generate a case in which the appearance of a color, despite unchanged objective light intensity, can vary within a very wide range. The experiment was devised by E. Hering and must be considered a fundamental experiment of psychological color science. Therefore I recommend very strongly to any reader to perform it as soon as practical. The only materials required are a piece of strongly colored paper (ideally lemon yellow) and a larger piece of opaque white paper with an opening in the center of about 2 cm diameter. Place the paper horizontally on a table, facing toward light and hold the white paper at a distance of 10 to 20 cm above the yellow paper so that for the eye the colored one is completely covered and the yellow color is only visible in the cut-out in the white paper. If the white paper is kept horizontal, the resulting yellow appears normal, i.e., just like that obtained by direct viewing of the yellow paper. If its angle toward the light is changed in a manner resulting in a steady increase of illumination, whereby it is important to assure that no shadow falls on the yellow paper below, the yellow in the opening changes. It becomes steadily grayer and its color can, with a properly selected arrangement, that is, when the illumination of the white paper in the optimal position is much stronger than that of the yellow below, appear different all the way to a blackish olive-green. If the white paper is angled in the other direction so that it is less illuminated the yellow paper at first assumes its normal appearance and with increasing shadowing of the white paper its appearance changes to a luminous light yellow, a yellow that cannot be produced with pigments. [Fluorescent pigments have been invented only later.]

In this situation, the composition and intensity of the light rays reflected from the yellow paper into the eye has not changed during the experiment; only the surround in which the yellow color appears has changed in its brightness. Nevertheless, the color of the objectively unchanged yellow has changed within very broad limits and in particular has demonstrated all those changes that can be experienced when the same yellow and a black are mixed in various ratios on a disk mixture apparatus.

While the first experimental sequence showed that despite wide-ranging changes in the objective brightness of a color its perceived color character can remain the same, the second one shows that despite unchanged objective brightness and composition of a light stimulus its perceived color can vary within widest limits.

We have here a profound problem urgently requiring a solution. The solution is found in that there are two substantially different classes of colors involved, one of which to be named *unrelated* colors and the other *related* colors.

Unrelated colors are defined by the fact that they lack a large range of colors that we otherwise know in detail, i. e., all browns, olive-greens, etc., in short all desaturated colors. The cause is the fact that unrelated colors only have two variables, on the one hand their hue, on the other the amount of white that, of course, also can be zero. If a focusing screen and a mechanism to continuously change the illumination intensity are attached to the spectroscope tube containing the wavelength scale any desired amount of white light can be combined with the homogeneous light that the earlier described arrangement makes possible. This exhausts all possible variations of unrelated colors that can appear in the spectroscope. Only by admixture of white light can the

color of a particular hue be made continuously paler until it has completely lost its chromatic character; but it is not possible to slowly convert it to black by continuous diminution of its absolute brightness, as this is possible in disk mixture by the addition of black.

The deciding condition that defines unrelated colors has its basis in the fact that *always only a single color is present in an otherwise lightless field of view*. The observed color is therefore all by itself and there is no possibility to compare it to another, simultaneously perceived color. Whenever such a condition exists, realizable for specific reasons in almost every optical instrument, the result is a color from the system of unrelated colors, with its only variables hue and white ratio.

That in these conditions absolute intensity does not have any effect on the appearance of the color derives from the situation that for biological reasons the eye contains devices that compensate for objective light intensity to the degree possible. These are adjustability of the iris and changes in the light sensitivity of the retina. For this reason the variable of objective light intensity (except in extreme cases) is not effective in perception, i. e., for what we call color and, as some time ago Helmholtz proved, it is only possible hue and white ratio to vary. He showed that the color of any desired mixture of wavelengths can be matched with a mixture of a homogeneous kind of light with white light, with exception of the purple region where *two* kinds of homogenous light are necessary.

Most researchers in color science have made use of spectral or similar colors of the unrelated kind. As a result color science has been largely built on this very special information and thereby is to a high degree incomplete. Neither Helmholtz nor any of his successors has, as far as my knowledge of the literature tells me, pointed to the fundamental difference between unrelated and the more common related colors and the disappearance of one of the three variables belonging to the latter. Clarity in this matter is of essential importance for the further development of color science.

In comparison, the nature of *related colors* is made abundantly clear by Hering's experiment. In this case, because the white paper surround of the constant yellow area is changeable, the related color percept, that is, the related psychological product, undergoes a whole series of changes of a kind that under other conditions can be produced only by objective changes in the stimulus.

The conditions responsible for our perceptions of related colors can be summarized as follows. We recognize the objects of the outer world primarily on basis of the light they reflect from their surface. Discounting mirror-effect reflection, resulting in terms of color in the special perception of gloss, and assuming the surface to be completely scattering, that is to be free of any oriented reflection, there are in the first instance two ideal limiting cases, one in which all light arriving at the surface is scattered, the other where none of that light is scattered. A surface of the first kind is ideally *white*, one of the second ideally *black*. Neither of these two ideals is technically realizable; but they can be increasingly approached. It is not surprising that investigations of the ideal white surface with modern tools, where the *absolute value of whiteness* of a well-defined white surface or its *albedo* was determined, are lacking. Based on my own investigations of white matte surfaces of various kinds I consider myself justified to assume that a paint application of precipitated barium sulfate, also recommended by other authors, has an albedo that deviates from unity by not more than a few percent. Such a layer is somewhat whiter than any other that I was able to produce. At the same time other similar white layers approach in whiteness that of barium sulfate ever more closely so that a convergence to an end point is clearly apparent. It must be considered to be an urgent task of a laboratory with the

required tools, primarily our imperial physico-technical laboratory, to determine the albedo of any kind of reproducible surface so that it becomes possible, using simple photometric measurements, to relate in absolute units any kind of white surface to the standard.

We are much better informed concerning the other end of the sequence white-gray-black because the corresponding investigations have uniformly shown that even our blackest pigment still reflect a few percent of white. However, an ideal black can be technically generated by a small opening in a box blackened in its interior. Highest quality black silk velvet has a reflectance[FN] (this term introduced by Hering is to be used to indicate in general the light scattered by a matte surface) of only a fraction of a percent (in a material I measured the value was 0.2%).

The reflectance of all other object surfaces lies between the borders of white and black. Some reflect light without favoring or disfavoring a particular range of wavelengths and, depending on the fraction of the reflected light appear light *gray* or dark *gray*. In other, much more frequent, cases there is a selective reflectance that in the final analysis depends on absorption in the surface layers of the object and as a result the objects appear *variously colored*.

Reflectance data are highly characteristic constants of the objects surrounding us. Within the range of light energy we are able to produce there is no "saturation" of any kind and as a result the intensity of the reflected light is within a very wide range strictly proportional to the intensity of the light falling on the object. It follows that the biological adaptation of our visual system is not for the purpose of determining *absolute* brightness that changes all the time and thereby does not produce anything absolute for the distinction of the surrounding world but for the determination of the *differences in reflectance* that are completely independent of light intensity and by themselves make recognition of given objects possible.

Related colors are determined by how much light is reflected and are assessed on that basis.. The yellow in the opening of the white surround in the earlier described fundamental experiment is implicitly taken to be a part of the white area and the light conditions that exists in the opening are judged as if determined by a reflecting area located in the opening, that is, they are related to the reflectance of the surround of the yellow area, that of the white paper. If the surround reflects much more light than the yellow paper, the opening creates the impression of being covered with a yellow pigment that additionally causes a corresponding amount of general absorption, i.e., contains an amount of black the magnitude of which depends on the brightness of the surround compared to that of the enclosed field. Conversely, if more light is returned from the enclosed area than would be from the lightest yellow pigment if the illumination conditions would result in the appearance of a white surround, the enclosed field appears to emit light because only self-luminous bodies have surfaces reflecting an amount of light larger than a surface of albedo 1.0. In this case our perception of the color (it must be particularly emphasized that it is not the result of a conscious judgment but of an automatically operating relational assignment) is the result of a specific relationship between reflectances. To define such relationships is in the field of related colors currently the fundamental task of color science. The reason is that not only the characteristic properties of colorants depend on these reflectance relationships but our complete assessment of the world of optical appearance is essentially determined by it.

In the field of related colors we encounter the three characteristic variables of the totality of colors. Here we can study in all their diversity olive-green, brown, and other colors, absent among unrelated colors. The evident reason, we notice, is that *black*, non-existent in unrelated

FN Hering's German term is 'Remission' which remains the standard German term for 'reflectance.'

colors, begins to play a role as an independent percept or psychological fact. Accordingly, we first gain from its mixture with white the various kinds of gray and from its mixture with the pure colors and those tinted with white a large number of dark and dull colors that can in general be defined as a mixture of a pure color with some kind of gray. As a result it also is apparent that unrelated colors are a special case of related colors, caused by the loss of one variable, black. Investigating related colors will tell us everything we need to know about unrelated colors.

A kind of graphic representation, later to be used generally, will make the fundamental difference between the two even more clear. For a defined hue line *w*−*r* (Fig. 1), where white is located at *w* and the pure color at *r*, represents the totality of all possible derivates of a given hue as long as we limit ourselves to unrelated colors. Any color can be quantitatively expressed by a linear the equation $w + r = 1$, where *w* represents the fraction of white and *r* the fraction of pure color. If the units of length of the line are defined all possible relationships between the two variables can be represented as a point on the line.

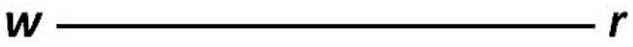

Fig. 1

In case of *related* colors black is added as a third independent component and in place of the line of unit length an equilateral triangle *w r s* with length of side equaling 1.0 is used (Fig. 2). As is known, in such a triangle any point has the property that three lines drawn parallel to the sides of the triangle through it are together of unit length, the length of a side. Because, as will be show later in more detail, for every related color the equation $w + s + r = 1$ is valid, any set of these three components can be represented as a point in the triangle and the area of the triangle represents the totality of all possible combinations of the three components of related colors. Comparing the triangle *w r s* with the line *w r* the relationship between unrelated and related colors is immediately apparent: the former are limited to the border line *w r* of the triangle *w r s*, i.e. the isochromatic area that represents the multiplicity of the latter.

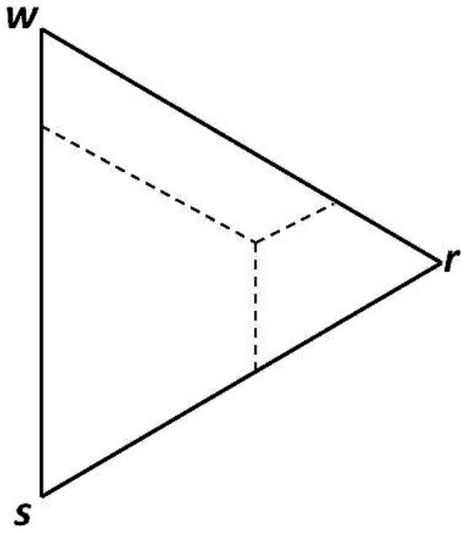

Fig. 2

Saturated colors

In the introductory remarks I have pointed out that there is a very large difference between homogenous light and saturated colors. Investigations to be discussed later concerning the purity of specific color chips have shown that in the area of warm colors a purity of up to 80-90% can be achieved. When such color chips are measured spectroscopically it will become evident that what has been discussed earlier in regard to yellow is also applicable to all other colors. In every case, the pure or saturated color contains in addition to its characteristic wavelength a large number of neighboring wavelengths on both sides.

The borders of these accompanying wavelengths demonstrate a specific and very remarkable conformity to a natural law. It is most readily noticeable in case of saturated yellow. The kinds of wavelength that combine to form this color extend in one direction to the most extreme red [700 nm] and in the other to a certain blue-green that can be identified with the wavelength of approximately 490. This blue-green color happens to be the complementary of the most extreme red and this conjunction results in a general rule that is confirmed in all cases of other saturated colors. The rule is the following: *the totality of colors within half of the color circle must be combined to obtain a saturated color.* As a result, the totality of these colors is limited due to the need for pairs of complementary colors and the resulting saturated color is that which in the effectively divided hue circle is symmetrical to the two diagonally opposed border points, i.e., it forms a right angle with the corresponding diameter. If the totality of all colors of an effectively divided color circle that are limited by a pair of complementary or opposing colors is named a *semichrome* [*Farbenhalb*], it can be said that to form a saturated color in each case the totality of colors of a semichrome must interact.

That this is factual can be shown by investigating the absorption properties of filters of pure color after adjusting them so that their coloration matches as closely as possible that of the purest painted color chip of the same hue. I have investigated a series of such cases and found confirmation of the general law in all of them. However, it must be said that the confirmation is fairly incomplete because the absorption transitions of the colorants, even the purest ones, are not sharp but of fairly broad form. It therefore is not easy to determine the border of absorption in the wavelength scale of the spectroscope, resulting in all cases in a degree of arbitrariness in the determination. For this reason it is currently as yet impossible to make a claim for absolute validity of the indicated rule or to exactly determine the limits of its validity. I have no doubt, however, that in general it represents the facts correctly.

It becomes apparent that with this new definition of saturation the earlier mentioned difficulties are eliminated. Saturated yellow consists of red, orange, yellow, yellow-green, and blue-green. It reflects all of the brightest parts of the spectrum and absorbs only the dark parts of blue and violet. This explains why its specific lightness is only 1/10 less than that of pure white. In addition, spectral analysis of the most beautiful and purest object colors we can find in nature in form of flowers and the wings of butterflies always shows the presence of broad, continuous ranges of reflectance, with similarly broad ranges of absorption and never is there even the slightest indication of a narrow, line-like spectrum, required if the usual identification of saturated colors with the homogeneous, spectral ones would be even approximately correct. The obvious objection that a semichrome cannot result in a saturated color because it consists in part of complementary colors and as a result of their interaction contains of necessity whiteness can be eliminated by pointing out that the complementary colors at the ends of the semichrome by definition represent only an infinitely small portion of the total color effect.

By the way, also in this matter does the definition represent an ideal limiting case that in reality can be approached but never reached. For object colors the reason is that the borders between the reflecting and the absorbing range is never sharp but because of gradual changes they slowly transition from one into the other. For this reason the resulting color of necessity contains black if the borders are within the reflecting region, i.e., the absorbing region extends over the opposing semichrome, or white if the opposite is the case. If the borders are located such that the transition region partly falls in one or the other semichrome both kinds of contamination take place simultaneously; the color contains black as well as white, i.e., gray. This is the most common occurrence.

The question of how the borders of semichromes are arranged in the spectrum is most directly connected with the question of how wavelengths of the spectrum are related to the effectively divided color circle and will be later addressed.

However, at this point another matter has to be addressed because it is the cause of a number of psychophysical peculiarities of colors. It is the gap shown by the spectrum in comparison to the color circle. If the latter is arranged, as I have proposed and will substantiate below, into 100 steps with the brightest color, lemon yellow, numbered zero, followed by orange, red, purple, violet, blue, and green back to yellow, the color cinnabar red, comparable to spectral red, is placed at position 25. Position 50 is occupied by a somewhat reddish ultramarine blue and located at position 75 is blue-green with wavelength 490, which is the complementary color of spectral red. In this arrangement the spectrum ranges, if begun with the shortest wave lengths in violet, from approximately position 46 in the color circle, via violet, blue, green, yellow, orange, and red, crossing 99 to 0, to position 25 (Fig. 3). Between 25 and 46, i.e. approximately $1/5^{th}$ of the color circle, there is no homogeneous spectral color of the same hue as those in the color circle. The corresponding colors can only be obtained from mixture of red with violet and blue. The heavy line segment in Fig. 3 represents the spectral component of the hue circle.

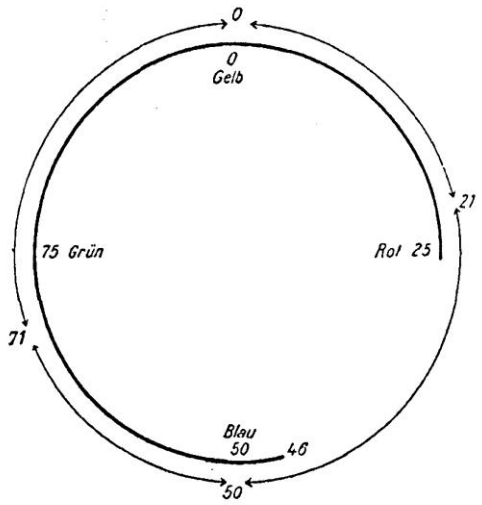

Fig. 3.

Correspondingly, there are relatively few saturated colors (in the green region) with the property that their semichromes consist of spectral colors only. Colors of this type are located between 71 and 100 or 0 because the corresponding semichromes are limited by the pairs 46-96

and and 25-75. All other semichromes have the spectral gap as a component, either partially or completely, and in the spectral analysis have narrower bands.

This incompleteness of the semichromes is of two types. Either a longer or shorter piece is missing on one end of the semichrome. The extent of the gap is in the extreme case 21 units, i.e., more than $2/5^{th}$ of the total semichrome. The gap can also be located within the semichrome, dividing it into two separated sections. They are located at the two ends of the spectrum and as such, in regard to their wavelength and all properties depending on it, have the largest difference that can exist between homogeneous lights.

In summary, the classification of these three kinds of semichromes is as follows. Green and yellow-green colors between positions 71 and 100 or 0 have gap-free semichromes. The saturated colors between 0 and 21, yellow, reddish yellow to approximately red-lead color, and those between 50 and 71, blue colors all the way to the beginning of greens, have an end gap. In the former case the gap is located at the red end, in the latter at the violet one. Finally, the saturated colors between 21 and 50, i.e., saturated reds, purples and violets all the way to blue have a middle gap. This special property is very likely the reason for the special psychological impression they have made since ancient times, in particular on more primitive people. An example of this effect has been preserved in the Russian language by the circumstance that the identical word is used for red and beautiful. With the help of Fig. 3 the just described relationships can be envisaged and compared. Remarkably, most of the colors where it as yet has not been possible to generate high saturation colorants are located in the region with complete semichromes. In case of blue, blue-green and green, all the way to light yellow-green, it has as yet not been possible to obtain a purity higher than approximately 0.6. Presumably, this represents a fundamental phenomenon that is related to the fact, noted by Helmholtz and his disciples, that in the green region wavelengths that are positioned relatively closely together when mixed appear, compared to the spectral color, whitish, i.e., no longer pure. As a result it may in the future become necessary to separate in this region the theoretical definitions of pure and saturated colors. Here I want to limit myself to this hint because systematic research in this field has not yet been initiated.

Purity

As can be seen, all future progress in color science depends on the solution of the problem of how to determine the purity of a given object color. The state of the art in this matter has already been described and we can move on toward its solution as it presently exists. When considering an objective spectrum of a certain extension and a related paint chip taken to be saturated, it is evident that anywhere according to well-known laws it can only show the color of the light that falls on it. If it has the property of absorbing the light of half of the color circle and reflecting the other half (whereby the "gap" needs to be appropriately considered) it will behave as follows. In the parts of the spectrum that are reflected the reflection is complete, i.e., it will appear as light as an ideal white surface. In the absorbing parts the absorption is complete, i.e., there it will appear completely black.

An actual paint chip will deviate from this theoretical ideal concept as follows. First, its reflection in the reflecting region will not be complete and as a result it will not appear as white as an ideal white object but somewhat darker. Based on a comparison of measured gray paint chips with the chromatically colored one in question it is possible to quantitatively determine the magnitude of the component of light that is not reflected, how much black is in the color.

Equally, the absorption in the related region will not be complete and in that part of the spectrum the paint chip will reflect a fraction of the incoming light. Also in this situation is it possible to determine by comparison with a suitable gray chip that is illuminated with the same light how large the reflected fraction is. This region of the spectrum makes it possible to recognize how much white is in the chip.

Summing the two fractions, the black and the white one, and subtracting the sum from the unit value results in the amount of chromatic light reflected by the chip. *By this means an absolute measure of the purity of the chip's color is obtained*.

It must be kept in mind that, as earlier mentioned, the borders of the reflecting and absorbing regions are not sharply defined, with the consequence that the borders of the spectral regions of the chip, where it appears light and where it appears black, are connected by continuous, more or less steep transitions. This situation narrows the spectral regions in which measurements of the reflecting and the absorbing values can be made.

In addition, the analysis assumes that the fraction of the absorbed or reflected light is practically constant across the remaining area. This apparently general requirement is in most cases found to be met to a sufficient degree. Because, as is well known, the absorption and reflection properties of solid objects are, when compared to those of gases and also those of liquids, highly diffuse and over broad regions their low and high values are therefore quite uniform. It is also possible to make local lightness determinations at different places in the reflecting and absorbing regions of the spectrum to show if and to what degree the basic requirement is met. In most cases a totally sufficient approximation is found.

As is evident, this method of purity determination is based on two conventional photometric measurements, one in the absorbing, the other in the reflecting region. The eye is only used to determine equality of lightness within the same color and it can evidently be replaced without problem with any kind of radiometer with sufficient sensitivity for the radiation in question. Spectra from different light sources with different intensities across the spectrum must produce the same result because only homogeneous light can be used, its absolute intensity having no effect on the relative measurement. These facts produce the remarkable result that purity determination according to this method is of the *absolute* kind, i.e., it depends neither on the nature of the light employed nor on the specific sensitivity of the eye. Identical purity values will be obtained independent of the illumination and it also must be immaterial if the determinations are made by a person with normal color vision or one partially color-blind. The only effect of these variables is one of a larger or smaller *sensitivity* in the corresponding region, i.e., resulting in a larger or a smaller degree of error. I have been able to convince myself of the validity of one part of these conclusions, independence from the nature of the light; lack of means has so far made it impossible to test the validity of the second part. But based on the general situation a positive result of a corresponding experiment cannot be doubted.

In regard to the practical execution of such measurements it is much more convenient to use in place of the objective spectrum color filters that make subjective evaluation possible. I convinced myself that it is possible to produce without difficulties color filters of sufficient narrowness and purity of the transmitted region to conduct the analysis. Only the extra-spectral purple and red-violet colors require special measures; the related difficulties have already been largely resolved. The measurements are reduced to the following simple tasks. First, a gray scale of photometrically measured neutral gray color chips is prepared, with the reflected light changing in specific steps. My scale has steps of 5% between 100% and 10% whiteness and between 10 and 2% (the darkest black that can be generated with conventional means) steps of

2%. According to Fechner's law the distinction between steps at the light end is rather difficult; the steps are perceived as increasingly larger the closer one gets to the dark end. For this reason the difference in the last section has been reduced from 5 units to 2 units. With the eye looking through the appropriate light filter the gray scale is moved up and down alongside the color chip and in such a manner one finds without any difficulty the gray that appears as light as the sample. After gaining some practical experience it becomes possible to interpolate 5 intermediate grades between two sequential steps, so that it becomes possible to estimate the absolute lightness down to 1%.

Purity is the difference between two values, each with a possible error of at least 1% and therefore has an increased margin of likely error. With the difference determination the more difficult the closer one approaches the light end of the gray scale, the margin of error increases accordingly. Purity determinations of light color chips have therefore a lower absolute accuracy than those of darker chips. This is in agreement with subjective experience where the ability to discriminate colors of different purity is much reduced in the light range compared to the dark one.

I do not believe I am guilty of exaggeration by viewing the discovery of absolute purity measurement as the most important progress that color science required for its steady progress and was able to make. Because not only was it shown in the earlier discussions that purity measurement is fundamental in regard to all quantitative questions of color science but the same situation will be encountered in even clearer fashion when considering the effective partition of the color circle. For this reason the additional conclusion that compellingly is the result of the described methodology of purity determination, i.e., that it is free of any subjective and accidental influences, is of particular value because it secures for all obtained values a correspondingly more general and larger significance.

I would like to add that an independent evaluation of the absolute purity determination method is possible by using the initially mentioned method of relative purity determination that makes use of the principle of neutralization with the complementary color. I have made a number of test measurements of this kind and convinced myself that there are nowhere contradictions and that therefore the possibility of a fundamental flaw in reasoning in the method of determination of absolute purity can be considered to have been excluded. There are, of course, experimental difficulties and corresponding errors; however, in the natural progress of science they can be determined with increasing accuracy and increasingly eliminated.