Part I

Research Contributions

A Large Water Prism Ultraviolet Monochromator

Holtsmark, T.; Langeland, T.; Refsdal, I.; Ore, A. (1961), *Physica Norvegica*, 1, Nr. 1: 1-6

Abstract. A description is given of a new high intensity, low resolution water prism monochromator for irradiation work. The instrument yields a vertical emerging beam. It is equipped with concave mirrors for collimation and focusing, and a 60º prism with quartz windows. The focusing mirror has been specially ground to correct for optical defects, in particular coma. Data on the performance of the instrument are given, and the optical system of a modified design is outlined.

In various types of experimental investigation the need for a source of intense, monochromatic ultraviolet radiation often arises. Large water prism monochromators have been described in the past by several authors (Harrison 1934, Fluke & Setlow 1954, Magnus *et al.* 1959).

An instrument which belongs to the same general category has been built in our laboratory for the purpose of studying inactivation of enzymes, photoconductivity, etc. In this report we present a description of the monochromator together with data on its performance. Some ideas related to a modified monochromator design are included at the end.

The completed instrument was constructed so as to give a radiation of high intensity in the near ultraviolet region (down to at least λ = 2200 Å). A resolving power ($\Delta\lambda/\lambda$) of only 1/50 - 1/100 was considered sufficient. In order to facilitate irradiation of free liquid surfaces a construction was preferred which yields an emerging beam of vertical direction.

In our monochromator a 60° water prism with quartz windows serves as the dispersing element, and mirrors are used for collimation and focusing. The number of reflections has been kept at the very minimum of two in order to minimize the energy loss.

As to the mirrors the collimator should have a short focal length to reduce the demand on lamp size. On the other hand, the optical defects, especially the spherical aberration, increase with the aperture ratio. The telescope mirror should make the spectrum appear at a suitable district to give it a convenient length.

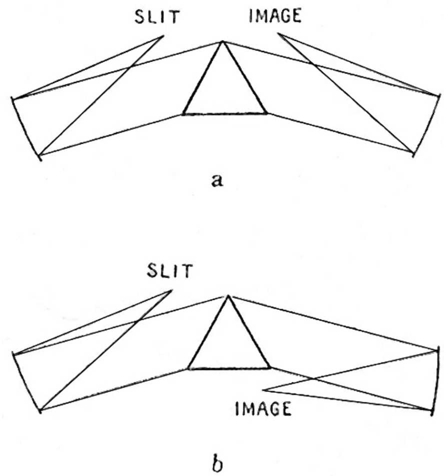

Fig. 1.1 Alternative combinations of reflections: (a) symmetrical and (b) antisymmetrical.

When spherical mirrors are used a certain amount of spherical aberration will always be present and there may also be some coma and astigmatism depending on the angles of reflection. The reflections can be combined in two different ways (Fig. 1.1): In the symmetrical mounting (a) both coma and astigmatism from the two mirrors are additive, while in the antisymmetrical (b) this is the case only for the astigmatism which need not be very harmful in a spectral apparatus. For this reason mounting (b) was preferred. The coma, which makes the image of a spectral line unsymmetrically diffuse, is cancelled under otherwise symmetrical conditions (Czerny & Turner 1930).

The prism windows represent the largest quartz plates readily available and have a diameter of 200 mm and the corresponding smallest feasible thickness of 3 mm.[1] Following Fluke and Setlow (1954), we originally used a collimating mirror with a focal length of 425 mm and a telescope mirror of focal length 850 mm, both spherical and with diameters of 250 mm and front aluminized. The mirrors were mounted so that the reflection obliquities were as small as possible without obstruction of the beam. The mechanical design is

[1] Supplied by Heraeus Quarzschmelze GmbH, Hanau, Germany.

A Demonstration of Additive Color Mixing Rules under the Influence of Color Contrast

Reprinted from Holtsmark, T., *American Journal of Physics*, Vol. 37, Nr. 6, Page 662-664, (1969).

Abstract. A simple slide-projector technique, which demonstrates the process of additive color mixing within areas of relatively low luminance as compared with that of the surrounding area, is described. Under such conditions full-hue circle representations can be obtained by means of two colored, and one uncolored beams of light. Some examples of appropriate pairs of color filters are given.

The following demonstrations may be considered as an extension of the old established phenomenon of the »colored shadows« which were for the first time explained from a physiological point of view by Goethe (1810, Didaktischer Teil, Sec. 62ff). They may also be considered as a modification of the »two-color projection experiments« announced by Land some years ago, which have caused much discussion (Land 1959).[1]

To the best of my knowledge they have not been described before although they deserve serious attention as a supplement to the usual demonstrations of additive color mixing, because they use a somewhat similar method and the observed effect is very stable. A set of color-mixing rules is established which differs in a systematical way from the ordinary rules of additive color mixing.

Additive color mixing is usually demonstrated in the following way. By means of slide projectors, three partly overlapping, circular, illuminated fields are produced on the screen. In our experiments we have used a 500 W projector, with iris diaphragms attached to the objective lens and slide holder serving as aperture and field stops, respectively. The aperture stop which controls the

[1] Land's experiment differs systematically from those described by us in that he restricts himself to the use of two beams only. He also aims at a full colors reproduction of photographic *objects*. Among the many utterances to Land's demonstrations might be mentioned an instructive experimental work (Wilson & Brocklebank 1960).

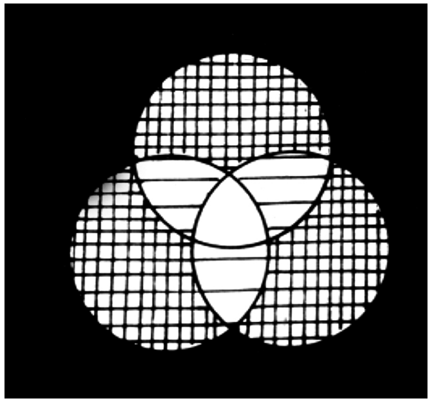

Fig. 2.1 Schematic diagram showing the ordinary distribution lightnesses under additive color mixing.

luminance of the beam could be replaced by a Variac in the power supply of the lantern. Admittedly, a variability of the color temperature of the emitted light is then introduced, but this has proved to have no observable effects in the actual demonstrations. The field stop, which enables quick adjustment of the size of the illuminated area, can be replaced by an opaque plate with a central hole.

In an otherwise darkened room one will now recognize on the screen a pattern of areas with different degrees of whiteness, within a dark surrounding (Fig. 2.1).

In the next step, the beams are colored by means of transparencies. A complete set of filters for theatrical lighting purposes will be of great use: they are hue-stable, heat-resistant, and cheap. We have used the Cinemoid filters from Strand Electric, England, but in the following we shall refer to the Wratten filters from Kodak.

If the three beams have been colored with the trichromatic primaries, red, green, and blue respectively, for instance Wratten numbers 29, 61, and 47, and if the luminances are properly balanced, the pattern on the screen will exhibit both the primary colors and their mutual mixtures in systematic order. The double-overlapped areas appear colored according to the following rules:

Colour Discrimination and Hue

Holtsmark, T. & Valberg, A. (1969), *Nature*, Vol. 224, Nr. 25: 366-367

During two short stays by one of us (T.H.) at the *Laboratorium für Farbenmetrik* we have measured just noticeable colour differences for pairs of optimal colours, complementary with respect to a white surrounding field. These preliminary observations indicate a correlation between colour discrimination and hue.

Measurements of colour thresholds $\Delta\lambda_d$ as a function of dominant wavelength λ_d have been made in various conditions by several workers. Steindler (1906) recognized minima of $\Delta\lambda$ in the yellow (580 nm) and blue/green (490 nm) transitions, with secondary minima in the far red (630 nm) and far blue (430 nm). The far red minimum was not confirmed by Wright (1934). In measurements by Bedford and Wyszecki (1958) the far blue minimum appeared at 410 nm. Siegel and Dimmick (1962) recognized a 580 nm minimum and a 520 nm maximum $\Delta\lambda$ which corresponded with the »unique yellow« and »unique green« hues respectively. Wright (1946, chap. 14) recognized that the $\Delta\lambda$ minima occur in those regions of the spectrum where there is a rapid change of hue.

It should be remembered that the »inverted spectrum« (Miescher & Rometsch 1950), which consists of the complementaries to the ordinary spectrum, shows a rapid change of hue in the red and violet regions, which are complementary to the blue-green and yellow respectively in the ordinary spectrum. This coincidence called for a more general investigation of the correlation between discrimination and hue.

We have therefore measured just noticeable colour differences for optimal colours within a white surround (»object colours«). For this purpose we used the *Spectral Colour Integrator* developed by K. Miescher *et al.* (1959, 1962, 1965). In the present state of the instrument, three independent channels with dispersion prisms are available and a fourth serves for the white surround.

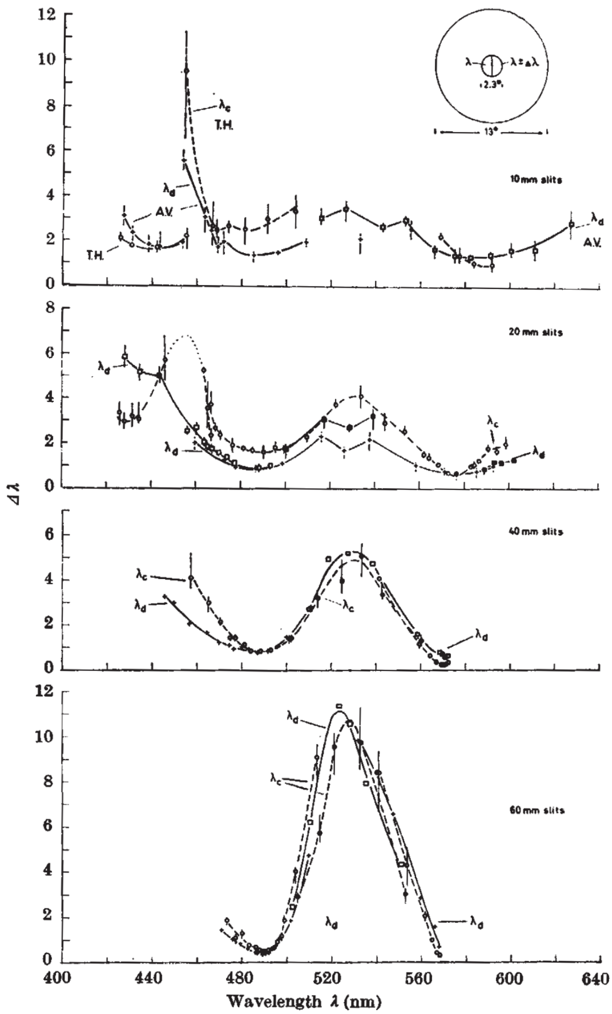

Fig. 3.1 Just noticeable differences in λ for pairs of complementary optimal colours. The solid lines refer to the dominant wavelength (λ_d) of the positive-slit colours. The dashed lines refer to the compensatory wavelength (λ_c) of the negative-slit colours. The various signs apply to measurements at different days. For the +10 mm slit, the separate minima of $\Delta\lambda$ in the 440-450 nm region were obtained with a dark surround. Maximum deviations from the mean of $\Delta\lambda$ are represented by bars. They are of the same magnitude for 40 and 60 mm positive and negative slits, and so only the latter are reproduced here.

Conflicting Implications in Newton's Opticks

Holtsmark, T. (1969), *Tagungsbericht Int. Farbtagung COLOR 69*, Stockholm, 1294-1298

Abstract. Contradictions in Newton's commentaries to the *Experimentum Crucis* reveal an ambiguity in his ideas on the physical significance of color. The same ambiguity appears when he defines the »Ray of Light« as »least part« although he deals with it as the ray of geometrical optics. His implicite definition of color »homogeneity« breaks down in the light of general experiences with colored boundaries under refraction. His experiments with crossed prisms in order to prove the homogeneality of spectral colors must be criticized because of its complexity and the conclusion drawn. Newton's experimental findings are consistent with a more general definition of »Ray of Light«.

In the popular image of the successful development of modern physical science Newton's *Opticks* (1704) plays a most distinguished, if not mythical part, representing the ideal case of experimental deduction and proof. Newton's experimental arguments, such as his demonstration of the »homogeneality« of spectral colours have dominated the textbooks to this day. Part of this astonishing success may be due to the circumstance that a fundamental undeterminability that is always attached to the colour phenomenon insofar as it is no physical object, has been so well hidden behind the seemingly consistent system of *Definitions, Axioms and Experimental Arguments*, that it was overlooked even by Newton himself and his successors, such as Helmholtz (1867, 268). Nevertheless, the uncertainty is reflected from the contradictions of occasional utterings by Newton about the nature of the very *Experimentum Crucis* itself. To Hooke, for instance, he declared that

> … y^e designs of it [Experimentum Crucis, T. H.] is to show that rays of divers colours considered apart do at equall incidences suffer unequal refractions, without being split, rarefied, or any ways dilated … (Newton 1959, Vol.1, 187)

But later on he uttered himself to Lucas thus:

> … you think I brought it, to prove that rays of different colours are differently refrangible: whereas I bring it to prove (wthout respect to colours) y^{t} light consists in rays differently refrangible … (Newton 1959, Vol. 2, 257)

The aim of Newtons's *Opticks* is the establishment of a *physical science of light*, and according to the classical pattern, the treatise rests upon a system of *Definitions and Axioms*. The *Definitions* exhibit the fundamental terms and operations involved, whereas the *Axioms* state certain elementary laws of geometrical optics. Seemingly Newton recognized three observable actions of light which were significant from the physical point of view, namely the »Ray of light«, the »Colour of Light« and the (optical) »Picture«. Whereas both definitions and axioms deal extensively with the ray of light, the picture and the colour are left more or less undetermined.

According to *Definition I* the »*Ray of Light*« results from certain operations with shuts and stoppers:

> The least Light or Part of Light, which may be stopp'd alone without the rest of the Light, or propagated alone, or do or suffer any thing alone, which the rest of the Light doth not or suffers not, I call a Ray of Light.

Although Newton's terminology is influenced by his atomism, the ray does not represent any specific model of the elementary light quantum itself. In fact, Newton has taken over the old established ray of geometrical optics which was developed in order to serve the construction of seen pictures. The ray of geometrical optics is no physical object, only in certain limiting cases do we meet with an optical phenomenon that illustrates the behavior of the rays of geometrical optics. For instance, the geometric-optical ray is illustrated equally well by a narrow beam of light as by a narrow beam of shadow. This ambiguity was overlooked by Newton, who made all his experiments with beams of light only. As we shall see later on, Newton's ray concept has to be taken in a still more general sense.

The ambiguity of the ray concept is demonstrated once more by *Axiom III* which states the principle of reversibility:

> If the refracted Beam be returned directly back to the Point of Incidence, it shall be reflected into the Line before described by the incident Ray.

Newton's *Experimentum Crucis* Reconsidered

Reprinted from Holtsmark, T., *American Journal of Physics*, Vol. 38, Nr. 10, Page 1229-1235, (1970).

Abstract. Certain terminological inconsistencies in the teaching of optical theory at the elementary level are traced back to Newton's *Opticks* and shown to derive from an uncritical application of the terminology of the old, established Euclidean geometrical optics to experiments which are primarily concerned with the establishment of a physical theory of light. The »ray« of Euclidean geometrical optics should be considered as a geometrical operator, the working rules of which are laid down in a set of axioms. If the Euclidean ray concept is adapted to those dispersion experiments put forward by Newton in favor of his hypotheses, some general class properties of dispersion phenomena are revealed. From the insight in those class properties, certain counter experiments can be easily recognized which demonstrate that it makes no sense to connect a certain color of the ray with its degree of refrangibility. There is a brief discussion of the significance of such experiments for insight into the part played by pure observation in scientific theory making.

In the public image of the development of physical sciences, Newton's *Opticks* (1704) plays a distinguished part, representing an ideal case of experimental verification of hypothetical assumptions (Newton 1704, Lohne & Sticker 1969[1]). Nevertheless, a closer examination of the hypothetical-deductive structure of the *Opticks* reveals a terminological ambiguity which has greatly influenced later textbooks. As a consequence, a general class property of dispersion phenomena has been overlooked.

This terminological ambiguity also lies behind the obvious contradictions in occasional commentaries by Newton himself to the so called *Experimentum Crucis (Experimentum VI)*:

[1] This work contains numerous historical as well as bibliographical references.

> … y^e designe of it is to show that rays of divers colours do at equall incidences suffer unequall refractions without being split, rarefied, or any ways dilated (Newton 1959, Vol. 1, 187)
>
> … you think I brought it, to prove that rays of different colours are differently refrangible: whereas I bring it to prove (w^{th}out respect to colours) y^t light consists in rays differently refrangible (Newton 1959, Vol. 2, 257)

In the *Opticks* itself a number of postulates which are logically independent of another, are not properly distinguished. For instance:

1. »White« light is »heterogeneous«, i.e., it is a mixture of »spectral lights«.
2. Spectral lights are »homogeneous«.
3. Spectral lights are specifically refrangible.
4. Spectral lights are specifically colored (in the sense that they give rise to specific color sensations in the eye).

In what follows we shall be concerned with the interpretation of the introductory experiments of the *Opticks* which are usually referred to by the textbooks:

Experimentum III: A beam of light from a narrow circular opening in the window shutter enters a triangular glass prism in the main section position, being therewith transformed into a divergent bundle of »spectral rays«, which give rise to the image of a »spectrum« on the opposite wall (Fig. 5.1).

Experimentum V (The crossed prism experiment): A second prism is placed behind the first one, the length axes of both prisms being mutually perpendicular. The »spectrum« reappears on the wall, being only displaced and turned a certain angle. This indicates, according to Newton, that the spectral rays are »homogeneous«, giving rise to no secondary order dispersion. The greater refrangibility of the blue rays as compared with the red ones explains the tilted position of the spectrum (Fig. 5.2).

Experiment V may be criticized because of its unnecessary complexity. The cross refraction occurs because the planes of two successive refractions do not coincide, but this may equally well be obtained by means of one single prism

Das Experimentum Crucis und die Theorie der Dispersion

Holtsmark, T. (1971), *Journal of Modern Optics*, 18, Nr. 11: 867-873, Abdruck mit freundlicher Genehmigung des Herausgebers

Zusammenfassung. Die Newtonsche Auslegung des berühmten Experimentum Crucis hat auf die Entwicklung der Optik einen starken Einfluss gehabt. Trotzdem zeigt eine genauere Untersuchung des Versuches, dass das Verhältnis zwischen einem »weißen Strahl« und seinem »Spektrum«, das durch das Experimentum Crucis beschrieben wird, allgemein auch für die Beziehung zwischen einer Kante und ihrem auseinandergezogenen Bild gilt. Die Gesetze der geometrischen Optik sind unabhängig von einer besonderen Annahme über die Natur des Lichtes aufgestellt worden.

In dem allgemeinen Bild der Entwicklung der optischen Wissenschaft spielt Newtons *Opticks* (1704) eine wichtige Rolle. Dieses Werk hat auch die Terminologie der optischen Literatur bis heute weitgehend geprägt. Besonders wird das »Experimentum Crucis« als Musterbeispiel induktiver Methode gerühmt (Westfall 1962 und 1966, Lohne 1968, Lohne & Sticker 1969). Die folgenden Sätze eines klassischen Lehrbuches der Spektroskopie hätten ebensogut heute geschrieben werden können:

> Der experimentelle Beweis dafür, dass das Sonnenlicht aus einfachen Lichtarten zusammengesetzt sei, denen eine bestimmte Brechbarkeit zukomme, ist stets als eine der schönsten Leistungen Newtons bewundert worden. Seinen Fundamentalversuchen hat auch die Folgezeit nichts Wesentliches hinzufügen vermocht, und sie sind in fast unveränderter Form in die Lehrbücher der Experimentalphysik übergegangen (Kayser 1900, 239).

Es wird wenig beachtet, dass die Terminologie Newtons nicht eindeutig ist. Sie enthält eine verborgene Unsicherheit, die sich bisweilen zu scheinbaren Widersprüchen steigert, z.B. wenn Newton selber gelegentlich das Experimentum Crucis kommentiert.

> ... y^{e} designe of it (Experimentum Crucis) is to show that rays of divers colours do at equall incidences suffer unequall refractions without being split, rarefied, or any ways dilated (Newton, Vol. 1, 187) ...
>
> ... you think I brought it, to prove that rays of different colours are differently refrangible: whereas I bring it to prove (wthout respect to colours) y^{t} light consists in rays differently refrangible (Newton, Vol. 2, 257).

Es scheint als ob sich Newton in der zweiten, und späteren Aussage von dem distanziert, was er früher ausgesprochen hat. Durch die erste Aussage bleibt noch die hypothetische Möglichkeit offen, dass eine funktionelle Beziehung zwischen Farbe und Brechbarkeit besteht, während nach der späteren Aussage das Experiment sich grundsätzlich nicht auf die Farbe bezieht. Dieses begriffliche Schwanken hängt mit der doppelten Voraussetzung der *Opticks* zusammen. Erstens wurzelt das Werk in der überlieferten geometrischen Abbildungsoptik, deren Formalismus es inkorporiert. Auf der anderen Seite wird die Grundlage gelegt für eine neue Wissenschaft, die wir unter dem Namen »physikalische Optik« kennen.

Die erste vorbildliche Darstellung der geometrischen Abbildungsoptik kennen wir als die »pseudoeuklidische« Katoptrik (Euklid 1959). Sie wurde dann später vor allem durch Kepler in eine moderne Abbildungslehre weiterentwickelt (Ronchi 1939). In ihrer ersten Fassung, und mehr oder weniger auch bei Kepler, erschien die geometrische Optik als eine Lehre von dem Raum der Sehdinge. Von den euklidischen Behauptungen werden keine Folgerungen in Bezug auf die physikalische oder physiologische Natur der Abbildung gezogen. Im Sinne der heutigen Sprechweise wäre der »Licht-« bzw. »Seh«-Strahl als ein Operator zu verstehen, dessen Form von den Eigenschaften des Sehdingraumes bestimmt wird. Deshalb wird z.B. das Reflexionsgesetz von einer allgemeinen axiomatischen Aussage über die Symmetrie des Sehdingraumes abgeleitet (Holtsmark 1970).

In *Opticks* wird der Strahl als individuelles, physikalisches Gebilde mit bestimmten, messbaren Eigenschaften gedeutet. Deshalb wird auch das Reflexions- bzw. das Brechungsgesetz als axiomatisches Naturgesetz dem deduktiven Teil vorangestellt. Als messbare Eigenschaft des Strahles kommt vor allem seine *Brechbarkeit* (»refrangibility«) in Betracht, dann aber auch seine *Farbe*. Die Begründung einer Metrik der Brechbarkeit sowie einer Metrik der

On Complementary Color Transitions Due to Dispersion

Reprinted from Holtsmark, T. & Valberg, A., *American Journal of Physics*, Vol. 39, Nr. 2, Page 201-204, (1971).

Abstract. The often mentioned indifference of geometrical optics towards particular interpretations of the physical nature of light is discussed from the standpoint that geometrical optics operates in a line continuum. It is shown that, in dispersion experiments, the concept of specific refrangibility applies to pairs of rays in so far as mutually complementary boundary conditions at the aperture are considered. Such pairs of rays are projecting mutually complementary colored images. Finally, some lecture room experiments are proposed, which demonstrate complementary color transitions due to complementary boundary conditions at the aperture.

In the development of optical science, the dispersion of visible light in a glass prism has played a considerable part, and the theory of the prism experiments has become standard content of optical textbooks. Nevertheless, the usual theoretical introductions reveal certain terminological ambiguities which point to the origin of optical science in a geometrical theory of directional seeing on the one hand and in a physical theory of the optical medium on the other. These two tracks of optical thinking have crossed each other only occasionally, but admittedly, those occasions belong to the turning points in the development of physical science as a whole.[1]

A few examples may illustrate the conflict. In the excellent and much used textbook by Pohl, a simple model of a spectroscope is drawn, and the theory of it is outlined (Pohl 1958, 93). The appearance of a »spectral line« is then discussed, and it is shown that, depending on whether the entrance slit is wide open or narrow, the spectral line may be explained as the geometrical image of the entrance slit or as the diffraction figure of the prism aperture.

[1] A detailed analysis of the axiomatic-historical origin of geometrical optics as well as a particular case history would be found in (Holtsmark 1970).

Later on, the well-known formula for the resolving power of the prism spectroscope is introduced (after application of the Rayleigh criterion) :

$$\lambda/d\lambda = |dn/d\lambda|B$$

where B is the length of prism basis, n the refractive index, and $d\lambda$ the resolved wavelength difference. Seemingly this formula determines the resolving power as a linear function of the dispersion $|dn/d\lambda|$, although the dispersion cannot be determined without knowledge about the resolving power.

On the other hand, since the number n refers to measurements of the deviation of rays due to refraction, the equation might equally well be interpreted as a transition between the terminologies of ray and wave optics, respectively.

A different approach to the conflict is offered by *The Feynman Lectures* (Feynman 1964, Vol. I, Chap. 26-1). Initially they state that the ray model, the wave model, and the quantum model represent three successive steps of approximation to the exact treatment of optical phenomena, but this assumption does not correspond well with a later statement in their text:

> In this chapter our discussion is limited to the geometrical optical region, in which we forget about the wavelength and photon character of the light, which will all be explained in due time. We do not even bother to say what the light *is*, but just to find out *how* it *behaves* on a large scale compared with the dimensions of interest.

In the classical works of geometrical optics, one will find several references to the indifference of geometrical optics towards particular physical interpretations of the nature of light.[2] But the reason for this indifference has never been explicated. One reason, at least, seems to be that geometrical optics is concerned with the formation of images, according to the laws of a line continuum.

The transition from physical optics to geometrical optics occurs when it is assumed that the physical nature of light may be formally represented on a line continuum. In Hamiltonian optics, this transition is guided by a semiphysical principle, namely that of the least action (Fermat's principle) together with the principle of superpositions of actions. The concept of »action« is a crucial

[2]See for instance (Hamilton 1931, Vol. I, 10; Bruns 1895; Klein 1901).

Similarities between JND-Curves for Complementary Optimal Colours

Valberg, A. & Holtsmark, T. (1971), *Helmholtz Memorial Symp. on Color Metrics*, Dreibergen[1]

Introduction

Recently we have described a simple lecture room experiment, in which pairs of mutually complementary colour stimuli distributions are projected on a screen (Holtsmark & Valberg 1971). The stimuli distributions derive from pairs of mutually complementary apertures (Fig. 8.1), which are projected through a prism.

Complementary colours are opposing each other in the two »spectra«, and it appears that rapid change of colour occurs at corresponding positions in the spectra. This circumstance raises the question about a possible correspondence between discrimination curves for pairs of complementary colour stimuli distributions.

Method and Apparatus

This report is concerned with an extension of earlier measurements of just noticeable colour differences (*JDN*) for pairs of optimal colours, complementary with regard to a white surround (Holtsmark & Valberg 1969).

The colour stimuli were established by means of a *Spectral Colour Integrator* developed at this laboratory (Gasser *et al*. 1959, Weisenhorn 1965) (Fig. 8.2).

The main principle of the instrument is a combination of two image formations. The entrance slit (*Esl*), which is illuminated by the collimated light

[1]This work has been supported by Grant 2.17369 to K. Miescher from Schweiz. Nationalfonds zur Förderung der wissenschaftlichen Forschung and by a grant to T. Holtsmark from Norges Almenvitenskapelige Forskningsraad.

Fig. 8.1 A »positive« and a »negative« aperture giving rise to complementary colour stimuli distributions.

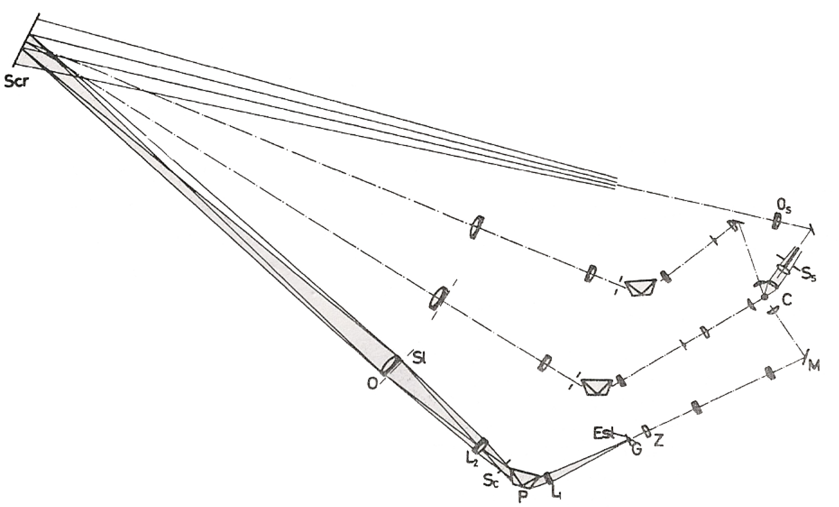

Fig. 8.2 The principle of the *Spectral Colour Integrator*.

Das Weltbild der Physiker: Ein Selbstporträt?

Holtsmark, T.; Wold, J. (1994), *Symmetri* 1, Nr. 2/3: 5-13, Übersetzung aus dem Norwegischen von Dagmar Mißfeldt, gefördert von NORLA, Abdruck mit freundlicher Genehmigung des Herausgebers

Zusammenfassung. Der Bruch der Quantenmechanik mit dem klassischen Determinismus hatte in erster Linie Konsequenzen für die mechanische Weltbeschreibung, obwohl die Zeit für ein Umdenken in der Determinismusproblematik in seit längerem reif war. Die Vorstellung von einer deterministischen Naturwirklichkeit muss als eine Projektion der einzigen deterministischen Wirklichkeit verstanden werden, die wir tatsächlich kennen, nämlich die unseres eigenen planmäßigen Handelns im Leben, z.B. als Billardspieler. Der Erfahrungsausschnitt einer angenommenen kausalen Naturwirklichkeit wird sich darum immer im Rahmen von akausalen Elementen im Stil von Newtons Apfel, Galileis schwingender Kirchenlampe, der Farbe des Lichts usw. abspielen. Eine genauere Untersuchung des Erfahrungsausschnittes bei so unterschiedlichen wissenschaftlichen Persönlichkeiten wie Goethe, Balmer und Bohr kann die Doppelnatur des Weltbildes erhellen. In dem Maße, wie es das Bild des Menschen von der Welt ist, ist es notwendigerweise ein Bild des Menschen von sich selbst. Vor diesem Hintergrund schauen wir uns Balmers Ableitung seiner berühmten Formel und einige weiterentwickelte Versuche zu Goethes »physiologischen Farben« genauer an.

Im Rückblick auf die Entscheidungsjahre der Atomphysik 1911-1918 schildern zwei Mitarbeiter Bohrs seinen Bruch mit der klassischen Physik:

> According to classical physics, an electron moving around a nucleus should continually emit light of a colour determined by the period of the motion, that is the time the electron needs to make one circuit around the nucleus. Therefore the colour – in contradiction to all experimental evidence – should continually change as the electron, emitting energy, comes nearer to the nucleus, and thereby revolves more and more quickly. In the first place the occurance of ›stationary states‹ is thus completely precluded by the classical theory of electrodynamics. Secondly, it is clear that according to Bohr's theory, in which light is emitted when the electron jumps from one orbit of define period to another with a quite different period, there cannot be the relation between colour and period required by the classical theory. The condition Bohr enunciated

> for the determination of the colour of the light, the so-called *frequency condition*, thus differed in principle completely from the classical one. It was this above all that so much disturbed the physicists of the time – that the colour of the light should not correspond to the period of the electron seemed to them completely inconceivable – and it required the courage of a genius to break with such a firmly anchored conception. (Rosenfeld & Rüdinger 1964, 52f)

Dass es Physiker »erschüttern« kann, dass »die Farbe des Lichts nicht genau der Umlaufzeit des Elektrons entsprach«, muss verstanden werden vor dem Hintergrund einer Verflechtung von zwei deterministischen Paradigmen, nämlich dem, dass die Farbe des Lichts von dieser Frequenz bestimmt ist und dem, dass ein um einen Kern kreisendes Elektron Energie durch Strahlung verliert und darum kein Licht mit stabiler Frequenz aussenden kann. Das letztere Paradigma brach in sich zusammen, während das erste dem Anschein nach das Erdbeben unbeschadet überstanden hatte. Was kann der Grund dafür sein? Ist die Annahme berechtigt, es bestehe ein Ursache-Wirkungsverhältnis zwischen der Frequenz des Lichts und seiner Farbe? In einem seiner Vorträge vor einem breiten Publikum legt Bohr das klassische Verständnis des Determinismus auf folgende wohlbekannte Weise fest:

> Die Prinzipien der *Newton*schen Mechanik bedeuteten vor allem eine weitgehende Klärung der Probleme von Ursache und Wirkung, da mit ihrer Hilfe aus dem durch meßbare Größen bestimmten Zustande eines physikalischen Systems zu einem gegebenen Zeitpunkt die Voraussage seines Zustandes zu jedem beliebigen späteren Zeitpunkt möglich wurde. (Bohr 1985, 77f)

Die logischen Operationen, die dem Nachweis der Kausalitätsrelation zu Grunde liegen, werden von Bohr wie folgt beschrieben:

> Die Entwicklung der sogenannten exakten Naturwissenschaften, die durch die Auffindung numerischer Zusammenhänge zwischen Messungen charakterisiert ist, wurde entscheidend gefördert durch die Anwendung abstrakter mathematischer Methoden, die oft ohne Rücksicht auf eine solche Anwendung entwickelt wurden und einzig und allein dem Streben nach einer Verallgemeinerung logischer Konstruktionen entsprangen. (ebd.)

Imitation of spectral and boundary colours on visual display units and colour printers

Vistnes, A.; Holtsmark, T. (1998), *Proceeding of the Oslo International Colour Conference: Colour between Art and Science*

Have you ever tried to photograph a spectrum of colours and compared the result with the colours seen? If so, you have probably also noticed that colour spectra reproduced in various books and journals differ quite a lot, and that they show some shortcomings compared with the perceived spectrum itself. In this paper we present a technique to imitate a spectrum by means of a computer. The result is presented on a visual display unit (VDU) or on a colour printer. The procedure can also be used in order to imitate the whole group of so-called »boundary colours« among them the »inverted spectrum«. The procedure is very flexible, and the results are at least as good as for any method of reproduction we have seen of these colour phenomena.

An ordinary colour spectrum is often produced by sending a narrow beam of white light through a triangular glass prism. The narrow beam is created by placing a so-called »mask« between the light source and the prism; the mask will in this case consist of a slit in an opaque object. The colour spectrum is in reality the image of the slit when projected on a white screen.

With other kinds of masks (black and white images), other colour patterns arise (see Figure 10.1). The pattern discussed so far, namely that of a narrow slit between opaque areas, was the one used by Newton. We therefore often talk about a newtonian spectrum for the resulting colour pattern. If we instead use a mask that is transparent all over except for a narrow band, we obtain an inverted spectrum. And if we project a simple black-and-white boundary, we obtain the so-called boundary colours. There are two different main types of boundary colour transitions, corresponding to whether the image is refracted towards the white side or to the black side. In everyday life, boundary colours can be observed in thin films, iridescent clouds, in the supernumerary bands of the rainbow etc.

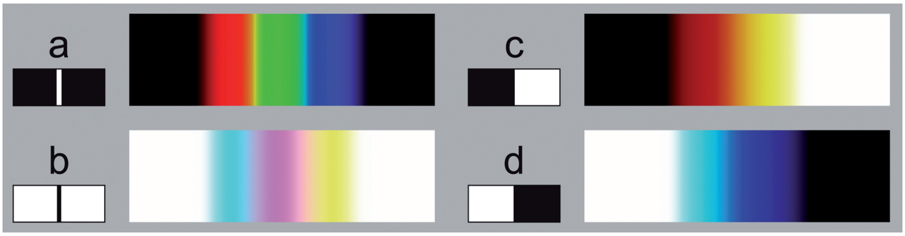

Fig. 10.1 Some colour patterns created when a light beam, shaped by a mask (often a black and white image on a slide), is projected through a glass prism: a) A »newtonian« spectrum, b) an »inverted spectrum«, c) and d): The two main types of »boundary colours«. The corresponding masks are shown.

The various patterns given in Figure 10.1 were created by a procedure which we will now explain in some detail. The starting point for all the simulations was chosen to be an imitation of the newtonian spectrum created by a very narrow slit. We used a trial and error procedure in order to simulate a spectrum that, when displayed on a VDU, was judged by the human eye to be as close as practically possible to the visual picture seen in a real experiment. In the computer programme the underlying data were given as a five-dimensional array (see Figure 10.2). One »direction« in the array represented the spatial distribution, the other »direction« represented the colour/intensity parameters red, green, blue, »violet red«, and intensity. »Violet red« was used in order to simulate violet (even though the final result only appears as degrees of purple). Both »violet red« and »red« contributed on equal foot to the »R« in the final simulated picture (ordinary 24 bit RGB picture in .tiff format), but they are treated differently when several spectra are added to each other (see below). The eight bit values for each point in the five-dimensional array used as the starting newtonian spectrum are given in Figure 10.2.

From the basic spectrum, all other colour schemes were generated by a procedure of integration as outlined in Figure 10.3. We start out with an arbitrary one-dimensional mask array, consisting of opaque or transparent areas (a graded transparency between 0 and 100 % is also permitted). For a straight forward boundary colour simulation, for example, the mask allows full transmittance of light in the first half of the array and no transmittance (»black«) in the second half.

The system of boundary colours

Holtsmark, T. & Sällström, P. (2000), in: *Synergie, Syntropie, Nichtlineare Systeme*, Hrsg. von W. Eisenberg, U. Renner, S. Trimper u.a., Leipzig: Leipziger Universitätsverlag. Abdruck mit freundlicher Genehmigung des Herausgebers

Abstract. When a regular pattern of black and white stripes is looked at through a triangular glass prism, at some distance, it appears as a series of alternating purple and green stripes, separated by grey ones. With successively increasing distance the purple and green stripes become desaturated, finally fusing into a homogeneous grey. The phenomenon may be said to complete the system of boundary colours. Newton observed it, but left an incomplete description. Goethe left the analysis of it to the polemic part of his *Farbenlehre*. The phenomenon may be considered in connection with the pronounced band structure of the boundary colour transitions in general. Ernst Brücke, in his investigations of varying colour fullness in the ordinary spectrum dealt with one aspect of this phenomenon. The experiment is shown to be analogous to a comb-filtering of white light, and the loci of the actual colours in the CIE chromaticity diagram have been calculated.

A regular pattern of black and white stripes seen through a triangular glass prism, at some distance, appears as a many-coloured band, where all the hues of the hue circle appear in a sequence, which repeats itself along the band. With increasing viewing distance the sequence reduces to alternating purple and green stripes, separated by grey ones, the whole sequence in turn fusing into homogeneous grey. According to the relative width of the white and black stripes, the grey will be lighter or darker. The phenomenon is essentially the same with all light sources that have a continuous spectrum (daylight, incandescent light etc.). The light from fluorescent tubes, whose spectrum is more broken up, does not produce a fusion into homogeneous grey.

This phenomenon completes the system of boundary colours, which Goethe so carefully and enthusiastically expounded in his *Beiträge zur Optik* (1790) and used as one corner-stone in his *Farbenlehre* (1810).

The boundary colours were known before Goethe, and after him they have been dealt with several times, Schrödinger showed that due to the rectangular form of their spectra of relative intensity they are optimal, compared with naturally occurring surface colours, in that they represent the greatest luminance attainable at a given hue and saturation, and inversely, the greatest saturation attainable at a given hue and luminance. He established the term *optimal colours* (Schrödinger 1920). In colour space they are represented by points on the surface of the colour solid. Kirschmann saw in the boundary colours the most complete example of complementarity found in natural phenomena (Kirschmann 1917). Matthaei, profound knower of Goethe's work, and the chief editor of the Leopoldina-edition (Goethe 1951), dealt with Goethe's experiments and the systematic of the boundary colours (Matthaei 1939). Bouma calculated their loci in the CIE chromaticity diagram and discussed their properties at some length (Bouma 1971, §§ 48-52). In Ostwald's colour solid the hues were referred to a particular class of optimal colours, the »full-colour circle«, namely those consisting of one half of the spectrum of white light (Ostwald 1923, 118). Born (1963), Heisenberg (1949), v. Weizsäcker (1961), Heitler (1966) and others have been interested in Goethe's experiments with prismatic colours. The optics of boundary colours has been discussed by one of the authors (Holtsmark 1970).

The system of boundary colours

For didactical purposes Goethe put a certain emphasis on what he called the »subjective experiments«, in which the investigator looks through a prism towards certain black-and-white patterns. Certainly, with the light sources and projection facilities available today the »objective experiment«, in which the black and white patterns are projected onto a screen, through a glass prism, have some advantages, but in the following we shall restrict ourselves to the subjective mode. The reader is therefore invited to look at certain black-and-white patterns, shown in Figure 11.1, through a triangular prism (preferably flint glass), being held in such position (called »vertical« hereafter) that the refracting edge is parallel with the right and left edges of this sheet. Due to the refraction the image seen will then be displaced in a horizontal direction (to the right or the left). In the following the phenomenon will be considered in three steps (Figure 11.1):

Historisch-didaktischer Blick auf das Verständnis von Bewegung und Geschwindigkeit

Holtsmark, T.; Wold, J.; Østby, I. (2001), *Fra fysikkens verden*, 63, Nr. 4: 100-104, Übersetzung aus dem Norwegischen von Dagmar Mißfeldt, gefördert von NORLA, Abdruck mit freundlicher Genehmigung des Herausgebers

Die Unterteilung der Bewegungslehre in Dynamik und Kinematik kann vor dem Hintergrund eines Konfliktes verstanden werden, den die griechische Wissenschaft hinterlassen hat: zwischen einer von Platon inspirierten geometrisierenden Lehre, welche die Himmelsbewegungen in einer kosmischen Ordnung ruhen lässt, und der aristotelischen Lehre von Bewegung als irdischer, von innewohnenden oder äußeren Kräften angetriebener Ortsveränderung. Bei Kepler verschmelzen diese beiden Wissenschaften, wobei Bewegung als Komplex einer dynamisch begründeten Ortsveränderung und einer Richtungsänderung im System der Himmelsrichtungen verstanden wird. Eine Hauptaufgabe im Elementarunterricht der Physik besteht darin, ein ganzheitliches Verständnis des Bewegungs-Phänomens zu vermitteln. Dies vor Augen, haben die Autoren einen Demonstrationsapparat entwickelt, der einige Aspekte der Bewegung hervorhebt, die leicht übersehen werden können.

Erfahrung von Bewegung und Ruhe

Fragt man in der Einführungsveranstaltung zur Kinematik die Studierenden, was sie unter »Bewegung« und »augenblicklicher Geschwindigkeit« verstehen, besteht die Gefahr, dass ratlose Stille aufkommt. Dies, obwohl die Alltagssprache sich auf eine Vielfalt von bestimmten, wiedererkennbaren Bewegungsqualitäten bezieht, wie z. B. dass Gegenstände »sich bewegen«, sei es dass sie »langsam«, »schnell«, »plötzlich«, »anhaltend« … sind, dass sie »fallen«, »steigen«, »sich drehen«, dass Bewegung »stattfindet«, »beginnt«, »endet« usw.

Die Frage ruft ferner eine Gegenfrage darüber hervor, was wir unter »Ruhe« verstehen. Zwischen »Bewegung« und »Ruhe« besteht ein dialektisches Verhältnis, wobei »Ruhe« als »Nicht-Bewegung« oder »Abwesenheit von Bewegung«, d.h. die Abwesenheit von bestimmten möglichen Bewegungen, charakterisiert werden muss. Insofern Ruhe mit Verbalformen wie »ruht«, »liegt/steht still« etc. ausgedrückt wird, ist Ruhe auch etwas, das »dort und dann«, »im Augenblick« stattfindet.

Die Trennung von Bewegung und Ruhe ist im visuellen Zusammenhang von der Möglichkeit bedingt, den Blick »ruhen«zu lassen oder ein abgegrenztes Objekt zu »fixieren«, so dass es mit dem Eigenrahmen des Blickfelds fest verbunden scheint, der von der Nasenspitze repräsentiert sein kann. Die Wahrnehmungen von Bewegung und Ruhe sind bedingt durch ein Zusammenspiel von Muskelwahrnehmung, verbunden mit der Bewegung des Kopfes und der Augen, wobei wir das Objekt mit dem Blick festhalten.

Die Bewegungserfahrung ist im Ausgangspunkt eine Sinnesqualität und hat als solche bestimmte allgemeine Züge mit anderen Sinnesmodalitäten gemeinsam. Es besteht z.B. eine Analogie zwischen »Dunkel« als Abwesenheit von Licht und »Ruhe« als Abwesenheit von Bewegung. Jedes für sich ermöglicht die Abgrenzung von Licht bzw. Bewegung als wieder erkennbare Vorstellungselemente. Ebenso wenig wie wir uns Licht ohne Verweis auf Dunkel *vorstellen* können, können wir uns Bewegung ohne Verweis auf Ruhe *vorstellen*.

Die Verunsicherung der Studierenden bei der Frage nach Bewegung und augenblicklicher Geschwindigkeit ist wohlbegründet. Die gleiche Verunsicherung ruft z.B. die Frage hervor, was wir unter »Farben« verstehen, die ja auch eine Vielfalt von wiedererkennbaren Sinnesqualitäten (Blau, Rot usw.) ausmachen. Als solche bedeuten sie nichts Bestimmtes, aber gerade darum steht es uns frei, sie in einen möglichen verständnismäßigen Zusammenhang zu stellen, so dass wir z.B. ausgehend von einem Blick auf die Ampel die Möglichkeit haben, in dem Augenblick richtig zu reagieren. In Ermangelung einer Ampel legen wir vielleicht die Wahrnehmung von der Fahrt und der Richtung des Autos zu Grunde dafür, wie wir reagieren sollen. Mit anderen Worten: Mit Hilfe wiedererkennbarer Sinnesqualitäten *modellieren* wir eine Wirklichkeit,