Contemporary teaching materials on colour theory in Germany: Eckhard Bendin's *Kreiselscheiben zur Farbenlehre* (2010)

Chiaki Yamane-Saihoji

Keio University, Tokyo, Japan
Email: chiakiyamane@keio.jp

A colour teaching material *Kreiselscheiben zur Farbenlehre* (*Rotating discs for understanding the theory of colour*), published in 2010 by the German colour scientist Eckhard Bendin (1941-), provides a comprehensive demonstration of the history of special visual phenomena on rotating discs. Also, it newly thematizes the aesthetic value of visual phenomena occurring on rotating discs, which have mostly been regarded as a means of measurement and experimentation. These 18 discs and tasks set by Bendin show us two facts. First, the simple and ordinary hand-spinning top is the only means by which we can continuously experience the process of transformation of phases and phenomena according to the speed of rotation and the elapsed time. Second, as colour is a visual phenomenon, it is not only "to be read" but also "to be done" (Goethe), and in this process, there are still unknown visual phenomena, such as those discovered by Bendin, as well as latent possibilities for new research.

Received 18 August 2022; revised 24 October 2022; accepted 16 November 2022
Published online: 20 January 2023

Introduction

This study examines the colour teaching material *Kreiselscheiben zur Farbenlehre* (*Rotating discs for understanding theory of colour*) published in 2010 by the German colour scientist Eckhard Bendin (1941-). It explains the material's contents and considers its intentions with that development in terms of the aesthetic peculiarities of rotating discs, which have mostly been regarded as a means of measurement and experimentation. Thus, this study re-evaluates Goethe's colour theory in today's German colour research and education.

In 2010, Bendin released a set of rotating discs as part of his anthology *Zur Farbenlehre* (*On colour theory*), which summarises his most important research results. It comprises three parts: the didactic material, including a hand-spinning top with 18 discs; 24 illustrative panels with a prism, which present findings on colour theory under different aspects and the textbook *Zur Farbenlehre: Studien, Modelle, Texte* (*On colour theory - Studies, models and texts*), which provides a scientific context for these illustrative panels [1]. In 2014, this anthology added a DVD titled *Basisexperimente mit Kreiseln: Filmmodule zur Farbenlehre* (*Basic experiments with rotating discs: Film modules on colour theory*) along with a small book, *Historischer Exkurs Farbkreisel* (*Historical excursus on colour tops*), which summarises basic experiments with colour tops, and a CD-ROM with an improved version of *Zur Farbenlehre*. These were published as *Basic box 'Colour cosmos': 50 basic elements for colour theory* (Figure 1) [2]. Simply put, this set functions as a universal colour theory teaching aid through which—based on actual visual experiences with colour mixing experiments—basic knowledge can be conveyed. Its advantage lies in its combination of materials in different learning styles that enable the learner to experience colours intensively or generally according to their interest and learning level. Academically and scientifically, this set is a pioneering study of historical experiments on optical colour mixture and a unique work that incorporates the latest research.

Figure 1: Bendin, new edition of the anthology Zur Farbenlehre *as* Basic box 'Colour cosmos'*, Dresden: Edition Bendin, 2014.*

Development background

After graduating from Hochschule für Architektur und Bauwesen Weimar (now Bauhaus-Universität Weimar), Bendin worked as an architect and architectural sculptor and, in 1983, received a call from Institut für Grundlagen der Gestaltung und Darstellung der Fakultät Architektur (Institute for the Fundamentals of Design and Representation in the Faculty of Architecture) at the Technische Universität Dresden, where he taught design theory until 2006, discussing the theory of colour and form, body and spatial composition, architectural sculpture and visual art. During his tenure as a university lecturer, he made colour research his main concern and, in 1991, published the 'Analogy Model of Colour (AMC; revised in 1994)', which is based particularly on the correlation between brightness and tone of colour. In 1992, he founded the Dresden Farbenforum (Dresden colour forum) at TU Dresden, an interdisciplinary series of conferences and publications focusing on light and colour. Furthermore, almost single-handedly, he collected teaching and research materials on colour theory that would make up the Sammlung Farbenlehre (Colour Research and Theory Collection), which was affiliated with the institute in 2005. This new collection was linked to two existing historical collections at TU Dresden: the Hermann-Krone-Sammlung (Hermann Krone collection), which collects primary materials on photographic technology (Faculty of Applied Photography), and the Farbstoffsammlung (Dye collection), a historical extensive stock of colour dyes (Faculty of Chemistry of Colours and Textiles)[1]. The new collection gathers important archival materials and preserves them as material witnesses to the history of colour theory in Central Germany, including those on the current art of light, colour and images by contemporary researchers and artists. Through these efforts, TU Dresden played a central role as *ein interdisziplinäres Kompetenzzentrum für Farbe-Licht* (an interdisciplinary colour–light competence centre) within the state-funded research project FARBAKS for four years (2014-2017) together with the University of Jena and TH Köln and grew into a leading force in colour research in Central Germany[2].

As previously discussed, Bendin, who synthesised colour research at TU Dresden, now summarised in this teaching resource the visual phenomena associated with optical mixture. Not only has the rotating disc been inherited by Central Germany, the historical centre of modern colour research where Dresden is located [3], but it has also served as an essential experimental tool for colour research as early as ancient Greece. This teaching material is the product of pioneering research on the rotating disc[3], which is also a challenge to present through experience.

Content of discs

Bendin suggests that the following 10 visual phenomena should be observed using the disc set:

1. Flicker and fusion
2. ‘Mach bands’
3. ‘Relief effects’
4. ‘Subjective colours’
5. Visually equidistant gradation
6. Mixture of complementary colours to grey
7. ‘Colour continuum’
8. Goethe’s ‘Urphänomen (primordial phenomenon)’
9. Formation of secondary colours through primary colours
10. Visual specificity of the colour triads RGB (Red, Green and Blue) and CMY (Cyan, Magenta and Yellow)

These tasks are arranged such that if one follows them in this order, they can systematically experience colour phenomena from the theoretical basics to their application. More precisely, the first half (1-5) deals with preparatory knowledge on the experimental application of the rotating disc for

[1] The photographer Hermann Krone (1827-1916), who taught at the TU Dresden, gave his Historical Teaching Museum for Photography to the TU Dresden in 1907. It contains 147 teaching plates and 1100 photographs and 120 daguerreotypes, 600 negatives and primary materials on photographic technology. The dye collection was initiated by the chemist Walter G. König (1878-1964), who also taught at the TU Dresden. This collection contains over 12,000 synthetic dyes and over 500 natural dyes and over 800 sample collections from important European dye manufacturers.
[2] cf. on the results of the project: GesprächsStoff: Farbe, Cologne: Böhlau, 2017 (total 624 pages).
[3] Research work that chronologically predates this material is Kuehni [4].

basic phenomena of visual perception and the second half (6-10) with the formation processes of colours and their conditions. This study follows Bendin's intentions in this order.

Flicker and fusion (Discs 6 and 9; Figure 2)

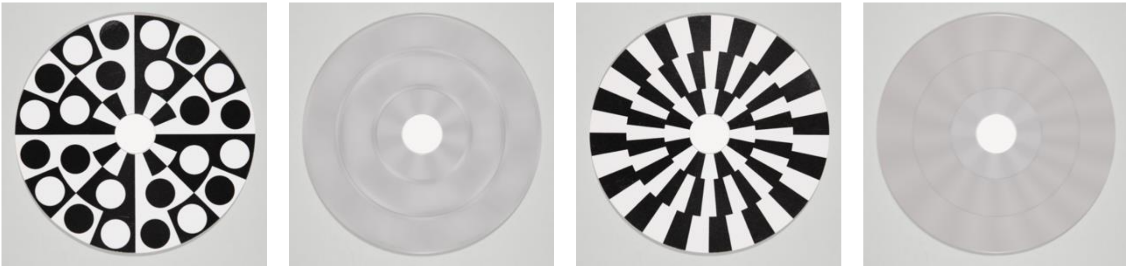


Figure 2: Discs 6 (pair on the left) and 9 (pair on the right).

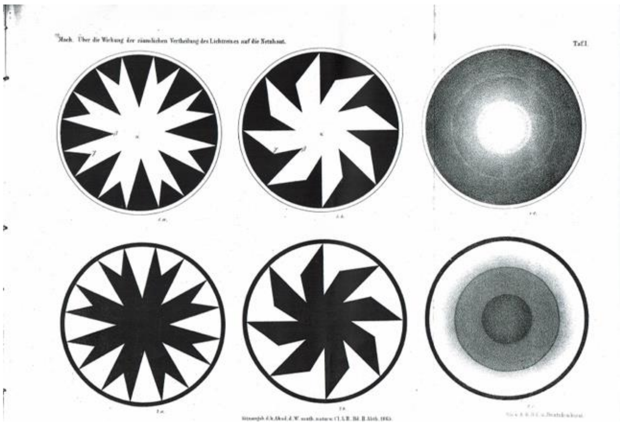
The first task involves the different states of perceptions owing to the movements of the spinning top. The pictorial perception captured when the period is long in one revolution is flickering (*Flackern*). When the period becomes shorter, another flickering (*Flimmern*) begins; when the rotation speed increases and frequency exceeds 70 hertz, it becomes impossible to perceive the stimuli separately, and a fusion (*Verschmelzen*) of pictorial perception occurs [5]. Since optical stimuli are generated quickly and continuously, the ideas of brightness, contours and figures are perceived as a rationally unified sensory impression, confirming a fundamental property of the rotating disc. By verifying these two basic achromatic (black and white) patterns, complicated visual phenomena can be easily observed, as the same basic patterns are later shown chromatically.

'Mach bands' (Discs 1 and 2; Figure 3)

Figure 3: Discs 1 (pair on the left) and 2 (pair on the right).

Bendin's 18-disc set also includes five historically important discs, two of which can demonstrate the 'Mach bands' phenomenon, a special visual event involving ring-like intensifications as a physiologically-conditioned contrast reaction owing to the mutual inhibition of interconnected nerve cells (lateral inhibition), which react to periodically changing brightness stimuli. The Austrian physicist Ernst Mach (1838-1916) published Disc 1 in his treatise *Über die Wirkung der räumlichen Vertheilung des Lichtreizes auf die Netzhaut* (*On the effect of the spatial distribution of the light stimulus on the retina*), in which he first reported his observation of these bands (or stripes or rings; Figure 4) [6]. Disc 1 comprises not only three grey zones (bands) with different brightness, as expected, but also unexpected ring-like darkenings (the actual contrast bands) at both bending points, that is, where the black and white components abruptly change in each case.

Disc 2, by the Swiss physiologist Fritz Burckhardt (1830–1913), is a graphic pattern that he published in 1869 in the treatise *Eine Relief-Erscheinung* (*A relief effect*; Figure 5) [7]. Furthermore, in this disc with spherically curved figures, we can observe ring- to node-like brightening or darkening at the respective bending points. These direct learners' attention not only to the conditionality of visual phenomena but also to their historical origins, which is a strength of these teaching materials.



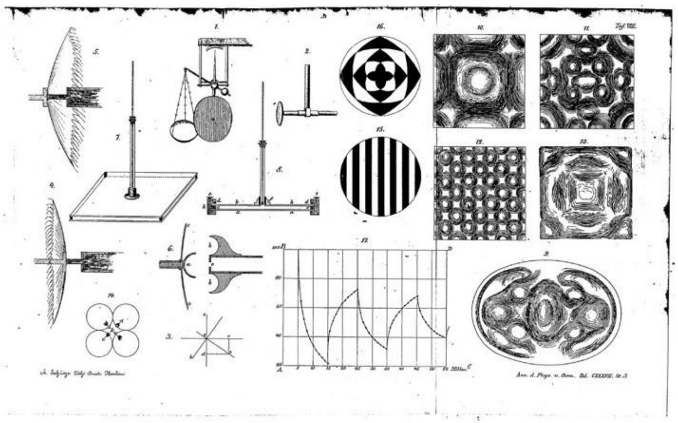


Figure 4 (left): Mach, On the effect of the spatial distribution of the light stimulus on the retina*, 1865.*
Figure 5 (right): Burckhardt, A relief effect*, 1869.*

Relief effects (Discs 2 and 3; Figure 6)

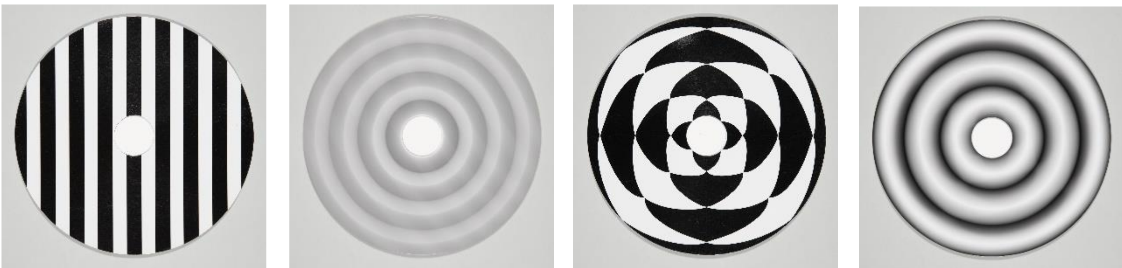


Figure 6: Discs 3 (pair on the left) and 2 (pair on the right).

Relief effects are visual phenomena that allow one to perceive two-dimensional, graphic patterns as plastic during rotation. The two patterns can be traced to Burckhardt. With Disc 3, which has a striped pattern, a relatively flat-looking ring group is observed; with Disc 2, which has a rhythmically figurative pattern, a stereoscopic ring group can be observed (the author observed several bead-like curved rings, with the black part protruding on the right side, providing a visual idea such that of a plate concentrically decorated with relief). Connected with the plastic bulge formations is the impression of so-called free colour (*Freie Farbe*). Free colour, which is caused by the gradual alternation of atmospheric loosening with solidified density, appears connected with the plastic bulge formations. Here, one can observe a relief effect as a mixed form of gradual contrasting owing to lateral inhibition, as in Mach bands, creating the impression of free colour.

The 'free colour' corresponds to the 'film colour' defined in 1911 by the German experimental psychologist David Katz (1884-1953), who distinguished the appearance of colour in relation to the visual space. The surface colour, which resists the gaze through compression, is supposed to transform into a 'film colour' when it is loosened up, which has no fixed spatial reference and, therefore, somehow appears to float[4]. The physiologist Rupprecht Matthaei (1895–1976), known as an interpreter of

[4] Katz [8], S. 6ff.

Goethe's theory of colour, gave this 'non-localisable' appearance of colour the new name 'free colour'[5]. He stated, 'it can be proved, firstly, by the transformability of all other appearances into it through a pinhole screen, and secondly, by the observation that the structure of all colour impressions of certain brain-injured persons approaches Free Colour'[6]. In its fusion process, a rotating disc's printed or painted 'surface colour' emerges as 'film colour/free colour'. In spinning tops, this phenomenon occurs as a special feature that is only comparable, for instance, to the floating-colour impression in a 'Ganzfeld', that is, an unstructured and uniform stimulation field of vision, as we can experience, for example, in James Turell's (1943-) spatial installations. In other words, by adopting Matthaei's interpretation of 'free colour' instead of Katz's 'film colour', Bendin elucidates that gyroscopes are also suitable for studying colour that is 'free' from external conditions.

Subjective colour (Discs 4, 6 and 9; Figure 7)

Subsequently, this study will discuss subjective colour, also called the Prévost–Fechner–Benham effect. As its name suggests, this phenomenon was discovered in 1826 by the French monk and theology professor Isaac Bénédict Prévost (1755-1819) and defined in 1838 by the German polymath Gustav Theodor Fechner (1801-1887) in his treatise, following Johann Wolfgang von Goethe (1749-1832), as 'subjective colour' [10]. In 1894, the English journalist and amateur scientist Charles E. Benham (1860-1929) applied this phenomenon to rotating discs and put it on sale [11].

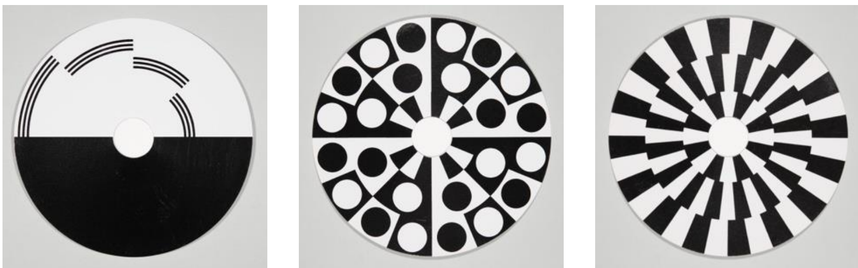


Figure 7: Discs 4 (left), 6 (middle) and 9 (right).

The 'Benham disc' (Disc 4) quickly spread throughout Europe. On this disc, the perceivable phenomenon also arises as a result of rapidly changing, periodic light-change stimuli, which, because of lateral inhibition, produce a 'false' colour impression in the observer. The special feature of subjective colours is that, as the name implies, each observer may have different expressions of colours when the panes are turned. These subjective colours can be best experienced through direct visualisation, which can only be achieved to a limited extent with video recording and reproduction. It is often said that when Benham's disc is rotated clockwise, one can observe a coloured ring group—from the outside to the inside of the red, yellow, blue and green rings—but only one red and one green ring could be seen by the author, who also observed only a reddish coloration in Discs 6 and 9. The 'prismatic-like effects' that Bendin observed on these discs as a novelty—observed on those two discs only with the rotational speed producing a flicker—reiterates the strong connection between the visual phenomenon and conditions under which those stimuli are produced. Although subjective colour is a multi-dimensionally determined phenomenon, the conditions for producing it are not too complicated; it is usually sufficient to vary the phase of the achromatic pattern by rotation speed or illumination. Thus, Bendin hints that

[5] Katz himself wrote in the second edition of his 1911 work *Der Aufbau der Farbwelt* (1930) that 'Matthaei occasionally referred to film colour as "free colour"' (p. 16) and used the term 'free colour' several times in the same essay.
[6] Matthaei [9], S. 7.

one can produce colours simply by changing light stimuli and demonstrates this effect not only through the Benham disc but also through Discs 6 and 9.

Visually equidistant gradation (Discs 5 and 10; Figure 8)

In Discs 5 and 10, the mixing ratio of colours or black and white changes in a geometric sequence. Disc 5 is a colourless pattern designed by the German painter and colour researcher Otto Prase (1874-1956), whereas Disc 10 is a coloured pattern designed by Bendin, which generates equally spaced gradations when spun. The following tasks use discs in which such gradations and other colour phenomena occur simultaneously.

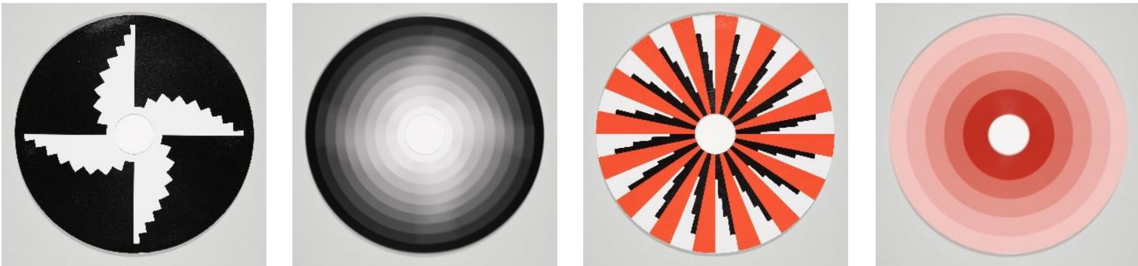


Figure 8: Discs 5 (pair on the left) and 10 (pair on the right).

These spinning tops prompt the learner to turn their gaze back in history to Weber–Fechner's law. In the middle of the 19th century, Fechner, the eponym of subjective colours, established the mathematical connection between stimulus and experience intensity based on the fundamental studies of his mentor Ernst Heinrich Weber (1795-1878), which, at the time, was a fundamental psychophysical finding. Fechner noted that a linear increase in the subjectively perceived intensity of sensory impressions corresponds to the logarithm of the increase in the objectively measurable intensity of the stimulus. His theory allows for an objective measure of one's subjective, inner experience, thereby establishing a principle that applies not only to the sense of sight but also to other sensory modalities.

Through the aforementioned five tasks, this study has reviewed the basic knowledge of experiments with rotating discs: knowledge of the relation between rotational speed and visual ability, lateral inhibition, the subjectivity and locality of colour phenomena and the psychophysical principle essential for measuring and controlling visual phenomena. Equipped with this basic knowledge, we now proceed to colour mixing using rotating discs.

Mixture of complementary colours to grey (Discs 8, 13/14, 15, 16 and 17; Figure 9)

Learners first observe 'a neutral grey' from the additive mixture of paired parts, which confirms that these are complementary ratios. In the outer ring of Disc 8, as expected, the fusion of equal black and white components causes a strongly brightened grey. In the middle ring, however, the circular segments of different complementary colour pairs are equally mixed and fused into a band, resulting not in a neutral grey but in a weak reddish-yellow tone, a trüb (Goethe, meaning 'greyed'), because here the lighter components assert themselves much actively than the darker. In Disc 13, magenta and green mix in the outer ring on a white background to form a neutral, brightened grey because of an equivalent balance between colour components according to their activity. The smaller but more active magenta component outweighs the larger green component here.

Furthermore, Bendin's Discs 14-17 demonstrate that complementary colours do not merge into a neutral grey in equal proportions (Figure 10). The complementary pairs yellow and violet-blue (14), orange and blue (15), orange-red and cyan (16) and magenta and green (17)—each complemented by white and black—are optically mixed here with equal proportions so that four special 'complementary colour mixes' are created. Each of them produces a rich spectrum of specifically coloured grey tones, in which grey tones that appear neutralised also resonate. Based on these phenomena, Bendin refers to the equivalent colour circle, which traces back to Arthur Schopenhauer's (1788–1860) work *Ueber das Sehn und die Farben* (*On vision and colours*) [12] and the quantitative colour harmony theory advocated by the chemist George Field in England in *Chromatography; or, a treatise on colours and pigments, and of their powers in painting* [13]. This suggests that each colour has a specific assertive power that finds its equivalent in a visual complement and must be regulated qualitatively and quantitatively in an appropriate way to produce a neutral grey, as is the case in the outer ring in Disc 13. The learner then gains an understanding of the conditions leading to coloured mixtures and neutralised grey tones.

Figure 9: Discs 8 (pair on the left) and 13 (pair on the right).

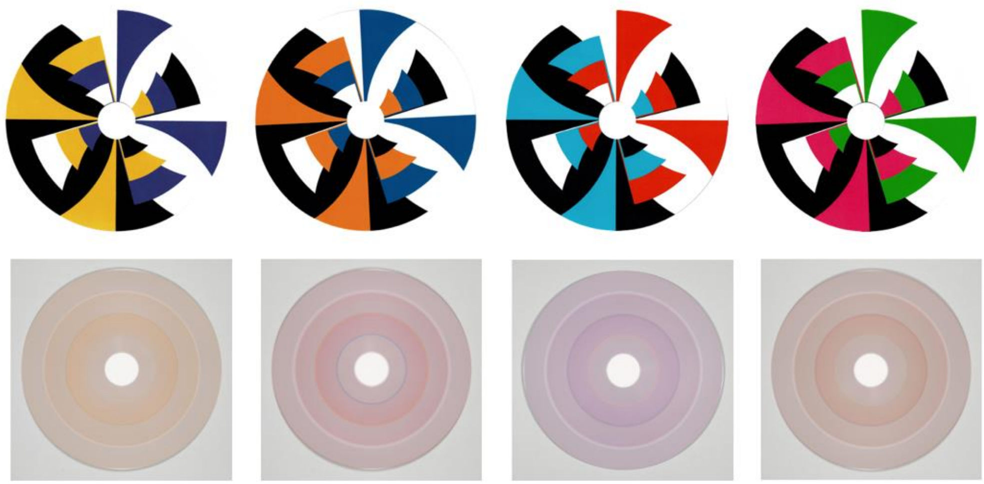


Figure 10: Bendin's Discs 14, 15, 16 and 17 (from left to right).

'Colour continuum' (Discs 7 and 8; Figure 11)

We refer to a 'colour continuum' when a sequence of neighbouring colour tones visually exhibit no demarcations and the tones merge seamlessly, that is, continuously. With rotating discs, these continuous 'colour gradations' are easily created through optical merging, which is demonstrated differently with Discs 7 and 8.

Both discs differ only with regards to the inner and middle rings. While achromatic circular sectors alternate (black and white) in the inner ring of Disc 7, colour-differentiated sectors face each other in neighbouring succession in Disc 8. The middle rings of the two discs differ in in the following ways: in the case of Disc 7, coloured circles are embedded on alternating black and white sectors, while in the case of Disc 8, the number of black and white sectors of the ground is doubled, and the embedded coloured circles are transformed into pairs of opposite coloured semicircles (both a sequence of adjacent colour tones and opposite coloured pairs).

Figure 11: Bendin's Discs 7 (pair on the left) and 8 (pair on the right).

If we first compare the middle rings of both discs as they spin, we notice that in the case of Disc 7, the neighbouring coloured circles merge into a continuous colour gradient at high speed, whereas in the case of Disc 8, only a pale, monochrome coloured band on neutral grey can be observed on merging the complementary semicircles. Here, the impression of a floating band of colour on a grey background also gives the special appearance of free colour. In contrast, the optical merging of the 16 directly neighbouring colour sectors into a colour continuum in the inner ring of Disc 8, even at a low rotational speed, offers a vivid comparison to the clearly more difficult merging processes in the middle ring of Disc 7.

Here, the learners are also introduced to the continuous order of colours, that is, to the concept of colour order. To emphasise this, Bendin designed Disc 8 such that the inner ring creates a continuum of colours, highlighting the contrast with the coloured grey in the middle ring. The colour phenomenon is actually a continuous whole as the rainbow already demonstrates. To clearly grasp this whole through differentiations and classifications, various colour orders have been designed since Greek antiquity hitherto. These order models are immensely different in their design, including a straight line, triangle, square, circle, tetrahedron, square pyramid, circular cone and sphere, but they all encompass the phenomenon in its wholeness. Therefore, they share an inner continuity and are topologically in the same space. The pioneer work on the colour order based on the colour concept of the 'totality of manifolds' is *Zur Farbenlehre* (*Theory of colours*) written by Goethe in 1810[7]. Goethe wrote, 'Colour is an elementary natural phenomenon in nature adapted to the sense of vision [...] which, like all others, exhibits itself by separation and contrast, by commixture and union, by augmentation and neutralization, by communication and dissolution'[8]. Because of the general dynamic properties of natural and colour phenomena, Goethe understood colours as an order, constantly changing in their dynamic relation to each other, each being 'divided' differently and not as a system corresponding to a 'super-temporal static "classification"'[9]. Consequently, he summarised the totality and inner dynamics of the colours and developed the six-part colour circle, demonstrating not only six colours in a spatiotemporal context but also the phenomenon of coloured increase. When yellow and blue move downwards, they merge into green; when they move upwards, they produce purple. Goethe, who had abundant knowledge of his predecessors' works, deliberately chose a simple circular colour arrangement to exclude the black and white axes that divide colours linearly, unambiguously and comprehensively because he wanted to clearly emphasise the phenomenon in which colours transform

[7] Maeda [14], p. 8.

[8] Goethe [15], p. xl.

[9] Maeda [14], p. 9.

limitlessly in spatio-temporal movements—increasing, uniting, mixing and attracting one another—in their totality[10]. Goethe's idea of colour is based on the 'Urphänomen' that will be discussed in the next section.

Goethe's 'Urphänomen' (Disc 11; Figure 12)

Figure 12: Bendin's Disc 11.

Goethe's 1791 paper titled 'Beyträge zur Optik (Contributions to optics)', which recounts Goethe's experience that gave Goethe the decisive impetus to develop his own colour theory. In 1791, Goethe recreated the Newtonian spectroscopic experiment using a prism borrowed from Christian Wilhelm Büttner (1716-1801), a famous collector and adviser to the court in Jena, and was surprised when the white wall viewed through the prism remained white; contrary to expectations, no rainbow appeared. However, when he looked through the prism in the direction of the window, he observed the formation of coloured edges on the window bars, that is, orange and yellow upwards, violet-blue and cyan downwards. Goethe considered these *Randfarbe* (edge colours), which appear on the border between light and dark, *Urphänomen* (primordial phenomenon) that represent 'the limits of experimental knowledge'[11]. Through this experiment, he discovered the insight that colours are not created by light alone, as Newton claimed, but are rather created in the space between light and shadow. This was the beginning of Goethe's colour studies.

The actual appearance of the edge colours through a prism easily illustrates the validity of Goethe's insight. On a light background, cyan and yellow emerge; on a dark background, violet-blue and red emerge, and where cyan and yellow overlap, green emerges. Furthermore, magenta develops when violet-blue and red mix additively at the two edges. Simply put, one recognises in the edge colours a relation that universally applies to the modern primary colours—the four physiological complementary colours (yellow, red, blue and green), the three primary colours of the additive model (red, green and blue) and cyan, magenta and yellow on a light background[12].

In the 19th century, Fechner referred to Goethe's work; the German physiologist Hermann von Helmholtz (1821–1894) also recognised Goethe as a physicist [17]. However, Goethe's achievements in both physics and optics were often and for a long time considered dilettantish even though he used various scientific angles to comprehensively examine the phenomenon of colour. In recent years, however, physicists have intensified their re-examinations. In 2011, the nanostructures of the DNA distribution became visible in localisation microscopy after photoactivation; this confirmed that the positions of individual molecules can be determined according to the light–dark-colour principle and not according to the shape principle [18]. This finding corresponds to Goethe's assumption that '[...] the

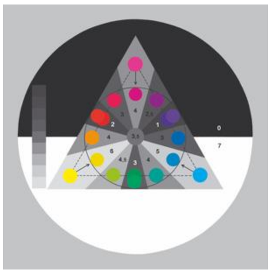
[10] Maeda [16], pp. 36f.

[11] Goethe, [15], p. 73.

[12] Bendin [1], S. 76.

eye sees no form, in as much as light, shade, and colour together constitute that which to our vision distinguishes object from object, and the parts of an object from each other' [13]. Furthermore, the symmetry of spectral phenomena to which Goethe had attributed the mutual complementarity of colours was proven in 2017. The result is a re-evaluation of Goethe as an optical physicist [19].

Anticipating the current state of evaluation, Bendin postulated the coherence between Goethe's colour theory and modern colour theory as early as 1991/1994 in 'Models for the generative grammar of colour tones (AMC; Figure 13)'. These models emerged from his studies in which he arranged the edge colours in terms of the ground (light or dark), the inherent brightness of the colour and the secondary colour produced by additive mixing. On the border between light and dark are orange and blue[14]. With Disc 11, Bendin encourages learners to experience this 'generative grammar'. Among the edge colours, which are primordial colour phenomena (i.e. the optical world), the two neighbouring orange-red and yellow or violet-blue and cyan merge into an orange and a blue, respectively, when rotating. By observing this phenomenon, learners can recognise the coherence of 'generative grammar' and its meaning.



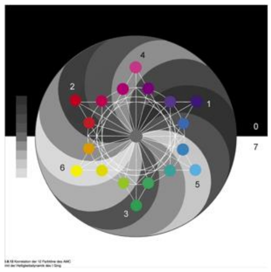


Figure 13 (left): Bendin, 'Models for the generative grammar of hues' (AMC), 1993.
Figure 14 (pair in the midde): Disc 18.
Figure 15 (right): Bendin, AMC - I Ching - correlation model, 2010.

Disc 18 demonstrates the culturally overlapping appropriateness of the 'generative grammar of colours' (Figure 14). Here, magenta and green as well as white and black are arranged in opposite directions, with an evenly distributed grey gradation between these four poles. Although the disc has no stated learning objective, its pattern reminds observers of the yin-yang symbol, which summarises the thought world of the ancient Chinese text *Yi Jing*, with colours developing from yin (dark) and yang (light). Here, Bendin identifies the vertical colour and horizontal brightness axes of his generative grammar with the brightness gradation of the yin–yang symbol. Thus, Bendin not only points to his AMC – I Ching correlation model inspired by architect and colour scientist Hans Peter Maier (1932-2008; 2010; Figure 15) but also to the inner correspondence between Goethe's colour theory and the yin–yang symbol[15]. With a high rotation speed, the disc demonstrates a neutral grey. However, it is remarkable here how the complementary pair (magenta and green) emerges from the gradation of the grey series at low rotation speed in different ways depending on the rotation direction. In other words, with Disc 18, Bendin refined the colour phenomenon in its entirety into a colour artefact. By using the yin–yang symbol, he resolves the opposition into an infinitely atmospheric movement.

Notably, Goethe's optical experiments also involved the rotating discs he had made himself, which he set in rotation on a flywheel[16]. Moreover, there was a correspondence between Goethe and the painter

---

[13] Goethe [15], p. xxxviii.
[14] Bendin [1], S. 77.
[15] Bendin [1], S. 86.
[16] Matthaei [20], p. 147.

Philipp Otto Runge (1777-1810), who also experimented and was particularly interested in the mixing differences between 'opaque' and 'transparent' colours[17]. Half a century later, Helmholtz explained the difference between additive and subtractive mixing (RGB and CMY)[18], which is the next task

Creating the secondary colour by merging the primary colours (Disc 13; Figure 16)

Figure 16: Disc 13.

With regards to Disc 13, Section 2-6 already established that the complementary colours, magenta and green, in the outer ring neutralise each other and merge into grey. Magenta is a primary colour in the four-colour printing (subtractive mixture/CMYK), and green is a primary colour on the screen (additive mixture/RGB). Furthermore, Bendin used the other primary colours of these opposite mixing processes as starting points for his three inner mixing rings to create the 'secondary colours' orange, green and violet. For the optical mixtures on this disc, he chose two types of red (orange-red and magenta-red) and two types of blue (violet-blue and cyan-blue) in addition to yellow (Y); that is, he used the modern primary colours of the four-colour printing CMY and the primary colours of light mixing RGB. The latter corresponds more to the primary colours that Field illustrated in 1841 in *Chromatography* and differ qualitatively from the primary colours red, yellow and blue[19], which originated in painting, as they were still at the centre of colour theory at the Bauhaus.

Painters consider red, yellow and blue as traditional primary colours, but these colours ultimately cannot be the primary colours of all paints based on subtractive mixing. Certainly, the modern colour pigments for 'red' are tinted near magenta and for 'blue' near cyan [24], and before the advent of these chemical pigments, it was long argued since ancient Greece that green was also necessary as a primary colour because these three primary colours could not produce a bright green [25]. Learners become aware of this primary colour illusion and are surprised that 'subtractive' secondary colours (orange, green and violet) can be observed using different red and blue tones even with additive colour mixing.

Through this surprise, Bendin reminds us of several points. First, the 'red' in the middle ring is actually orange-red, which differs from physiologist Ewald Hering's (1834-1918) basic 'red' sensation as well as from painter and art educator Adolf Hölzel's (1853-1934) 'high red' (Hochrot) and is closer to the secondary colour by the subtractive colour mixing of orange-red and yellow as Field demonstrated in 1841. Second, Bendin strengthened the mixture to green in the second ring by an additional green sector to counteract an excessively strong brightening of the additive-proportional mixing result owing to the high intrinsic brightnesses of yellow and cyan-blue. The green would be perceived as extremely pale. Conversely, to increase the brightness of the grey, white was added to the outer rings. Thus, the learner familiarises themselves with the relation between the traditional primary colours used by

[17] Maltzahn [21], S. 69-83; Matile [22], S. 186ff.

[18] Helmholtz [23], S. 4.

[19] Field [12], p. iii.

painters (red, yellow and blue) and the primary colours of modern printing technology (CMY) and the importance of colour-specific brightness in additive/intermediate colour mixing.

Visual peculiarities of the colour triads RGB and CMY (Disc 12; Figure 17)

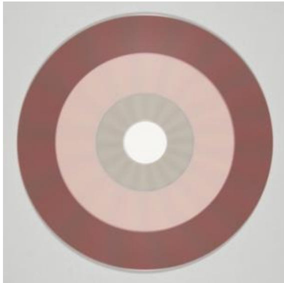
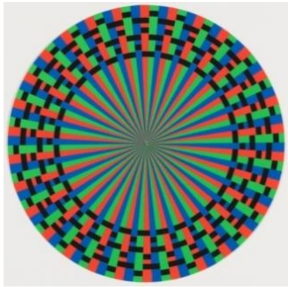




Figure 17 (left and middle): Disc 12.
Figure 18 (right): RGB-Drehscheibe by Andreas Hofer.

After establishing the difference between RGB and CMY, this last task compares the results of the two optical colour mixes. Disc 12 is based on the concept of an 'RGB-Drehscheibe (RGB-rotating disc)' developed by the Swiss artist Andreas Hofer (1956-; Figure 18).

From the three main components of additive colour mixing (red, green and blue), Hofer also created the three main colours for colour printing (cyan, magenta and yellow) through additive means[20]. More precisely, the colours are distributed externally such that RGB merges into a grey, red and blue into a magenta, green remains green, green and blue merge into cyan, red remains red, red and green merge into a yellow and blue remains blue. As already known, spinning tops as instruments for experiments have been common since the 19th century both in laboratories and in artists' ateliers. In particular, in the 1960s and afterwards, there was a great interest in the genre of op-art (optical art) in motion effects that could be used artistically. Bendin refers learners to the use of Hofer's spinning top as an example of how visual phenomena can be artistically applied. In Bendin's Disc 12, the red–green–blue colour triad on a dark background is embedded in the outer ring, and the cyan–magenta–yellow colour triad on a light background is embedded in the middle ring. When the disc is rotated, a lightened and darkened reddish brown appears as a mixed result of the same colour tone. Although equal amounts are mixed, no achromatic colours are created because bright and active yellow and red are optically more prevalent here. A dark and brightened red-brown appears as an expression of the visual predominance of the more active colours. As already noted in the earlier section on "Mixture of complementary colours to grey", each colour has its specific activity. Simultaneously, the tonal equality of the two colour triads RGB and CMY when they merge shows that these triads are equal in their expression of colour distances and proportions. Furthermore, learners can experience here that the modern primary colours are equally spaced[21].

We have seen that the first half of the tasks set by Bendin intended to provide learners the opportunity to observe movement and colour phenomena inherent in the rotating discs, whereas the second half helped them learn, via the rotating discs, the process of creating colours and its conditions—colour-

[20] Andreas Hofer, RGB-Drehscheibe 2005, Disc with RGB colours to create the optical mixtures, https://www.andreashofer.ch/rgb-drehscheibe/ (last accessed 23 July 2022).

[21] One can consider 'incidentally also demonstration example of simultaneous contrast (greenish impression of the inner black-white mixture by the reddish surroundings)' (in Mr. Bendin's letter to the author on 20. 11. 2020).

inherent tone, the relation between composite colours and the mixing result and properties of both basic colour triads of modernity (RGB and CMY) in connection with the historical background.

Rotating discs as an occasion for design

Rotating discs: from measuring instrument to a means of visual art

The rotating discs, commonly used as a means to observe colour phenomena, were historically only measuring instruments, first to elucidate the colour vision mechanism and later for colour design. The first step was taken in 1762 in *Introductio ad philosophiam naturalem* (*Introduction to natural philosophy) by the Dutch natural scientist Pieter van Musschenbroek* (1692-1761)[22], who was impressed by Newton's lectures in England[23]. Following the method of colour mixing with a hand-spinning top, the basis of which was created by Musschenbroek, painter Philipp Otto Runge (1777-1810) developed a colour system in Germany[24], and Goethe, a friend of Runge, also tried to explore the laws of colour mixing. In the 19th century, spinning colour discs were already indispensable as instruments for experimentation in physical or physiological optics laboratories, which aimed to elucidate colour vision. After Helmholtz proved that the experiments of mixing spectrum colours could be conducted using the rotating disc [27], additive colour mixing became a commonplace in science. The Scottish physicist James Clerk Maxwell (1831-1879) used the rotating disc to study colour vision and discovered the principle of colour mixing [28]. Maxwell's rotating disc enabled the colorimetric determination of mixing ratios of the composite colours of a body colour. This paved the way from conventional qualitative research, which analysed and described the perception of colours, to quantitative research, which quantified the perception of colour. The rotating discs now found an application in colour design. For example, Ernst Wilhelm von Brücke (1819–1892) proposed 'Maxwell'sche Scheiben (Maxwell's discs)' for calculating and confirming a colour combination that is in harmony artistically rather than physiologically[25]. The U.S. physicist Ogden Rood (1831–1902), who had studied in Germany, also introduced the 'Maxwell discs' in *Modern chromatics* (1879); thus, experiments with rotating discs became the basis for Neo-Impressionist theory in France[26]. Around 1900, the U.S. painter and art teacher Albert Henry Munsell (1858-1918) strove to systematise colours based on 'Maxwell's rotating discs' and published as *A colour notation* in 1905. Wilhelm Wundt (1832-1920), who founded the first institute for experimental psychology, introduced the rotating disc to the field of experimental psychology; in 1917, his colleague, the physical chemist Wilhelm Ostwald (1853–1932), published a

---

[22] The first documentation of visual colour mixing by rotation can be found in the second volume of Claudius Ptolemy's *Optics in* ancient Greece. Building on this, the Islamic scientist Ibn al-Heithem (in Ateinic Alhacen) expanded Ptolemy's theories in the 11th century and also carried out experiments on colour mixing with rotating discs. His work *Kitab al-Manazir (Opticae Thesaurus or De aspectibus; Book of optics)*, which contains an account of the results of experiments in colour mixing, laid the foundations for European science in the Middle Ages, but none of the researchers on the sense of sight at the time followed him with regard to colour mixing by rotation (Kuehni [4], p. 112).

[23] Musschenbroek [26], p. 728.

[24] Philipp Otto Runge, Letter to Goethe, 23 Oct. 1807, in: Maltzahn [21], S. 71f.

[25] Ernst Wilhelm v. Brücke, *Physiologie der Farben für die Zwecke der Kunstgewerbe*, Leipzig, 1866, S. 33ff. 'Furthermore, one can make use of the rotating disc, Fig. 4, with good success, if one gives it such an arrangement as Maxwell has given it (S. 40)'. *The Farbenlehre im Hinblick auf Kunst und Kunstgewerbe* (1874) by Wilhelm von Bezold, Brücke's successor, later attracted the attention of Franz Marc and many other painters in the 20th century.

[26] The painter Camille Pissarro wrote: 'To seek a modern synthesis of methods based on science, that is, based on M. Chevreul's theory of colour and on the experiments of Maxwell and the measurements of N.O. Rood (quote. in: Phoebe Pool, *Impressionism,* London: Thames and Hudson, 1991, p. 243-244)'.

colour system in *Farbenfibel*, with which he believed that he could oppose Munsell's system[27]. Similar to Munsell, Ostwald also used optical colour mixing to calibrate colour patterns and distances. Rotating discs were used as indispensable experimental instruments, from the colour chart maker Otto Prase (1874-1956), a contemporary of Ostwald's who had published his own colour system a few years earlier, to Manfred Adam (1901-1987), Ostwald's former assistant and colour organist, who synchronised the aforementioned systems in the 1960s, to the colour artists Jakob Weder (1909-1990) and Wolfram Jaensch (1940-), who later used computers to calibrate their colour organs [30]. Also for educational purposes, rotating discs continue to be welcome instruments that can be used to provide learners with vivid insights.

Bendin's 'sound discs' (Discs 14, 15, 16 and 17; Figure 19)

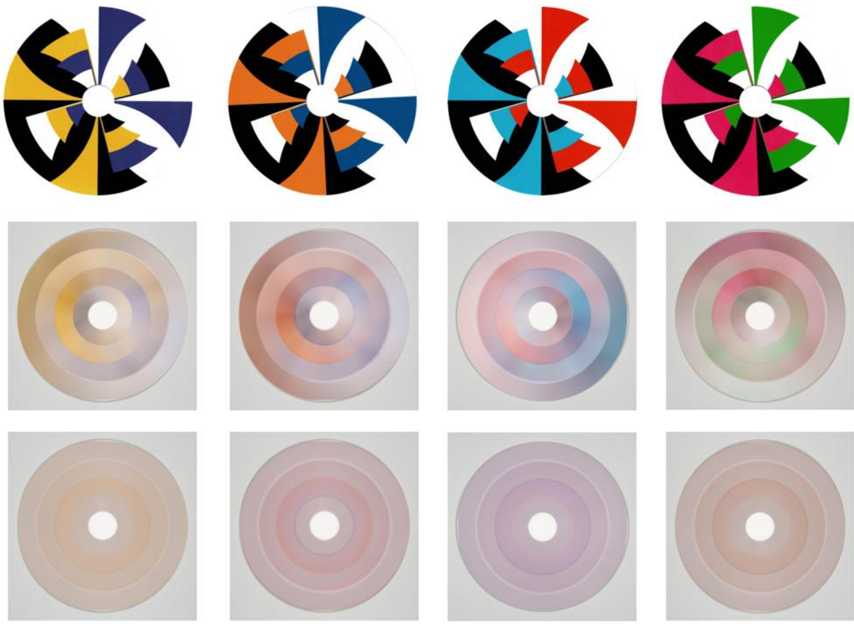


Figure 19: Discs 14, 15, 16 and 17 (from left to right).

In contrast to the rotating disc as an instrument for measurement and observation, where it is important to demonstrate only a visual phenomenon, Bendin's 18-disc set has an additional function. That is, the set is designed such that the learners experience not only each phenomenon with the respective discs but also other visual phenomena through comparisons. For example, Discs 11 and 12 are about a different learning task, but learners can also experience simultaneous contrast through comparison. In particular, the inner rings in both discs show a neutral grey when rotating, but in both cases, a simultaneous contrast can be observed, namely a bluish impression of the inner grey owing to the yellowish surroundings of Disc 11 and a greenish impression owing to the reddish surroundings of Disc 12.

Discs 14-17 show complex visual phenomena, which were already noted in the earlier section on "Subjective colour" even more clearly. Bendin calls these discs 'sound discs' (Klangscheibe), although the name has two meanings. The first meaning of the word 'sound' suggests a complex visual structure in which the colours and shapes appear rhythmically alternately, with flickering still occurring (Figure 19, middle row). The second meaning of the word 'sound' refers to specific coloured grey structures in

[27] Ostwald [29], S. 550.

search of a neutral grey, which was considered 'failed' in the task in the earlier section on "Mixture of complementary colours to grey" (Figure 19, bottom row). However, Bendin highlights the importance of those coloured greys for designers as welcome, rich tones:

> For years, in the colour theory for architects and landscape architects here in Dresden, we only did the classical mixing exercises, i.e. starting from two antagonistic colour poles, we did a mixture, a mixture of colours, with the aim of arriving at grey. And the designer is of course particularly interested in the very rich grey tones in addition to the neutral grey. Also the painter. [31]

In fact, Bendin used the sound discs as visual aids in opaque colour mixing exercises with architecture students not only to 'develop a finely graduated colour series with grey-enshrouded mixed tones from two freely selected solid colours that the student perceives as being of opposite colours, which ideally finally neutralise into grey' but also to reveal 'a specific "colour world" created from complementary tension, each with its own impression'[28]. That is, each of the four different grey tone structures reveal a coherent, aesthetic structure produced by the mixed legality of the complementary colours. Bendin states that because rotation is characterised in particular by the fact that colour fusions come about, that is, soft, rich situations, atmospheric situations, which already become quite similar to the painterly[29].

This 'sound' produced with the colour phenomena occurs through the interaction of two impressions of special appearance: free colours—a loosened-up colour impression without a fixed spatial reference— and the relief effect. Since the patterns on these four discs create a relief effect, a complementary-coloured, three-dimensional sound is produced shortly before the fusion at a speed at which one can still distinguish the composite colours from each other.

However, 'the sounds of complementary colours, produced with the sound discs, not only expresses the characteristic play of colours between the polar output quantities, which through an "atmospheric resolution can relax in each case in fine nuances up to coloured grey values, but also illustrates the harmonious merging of opposing colour qualities into special, coherent sounds"' [33]. Here, Bendin also refers to the special feature of the rotating discs in which the structural impressions change with the passage of time of the rotation speed. Simply put, the rotating discs are a medium with which one can experience how colours temporally and spatially transform in a short period. Goethe investigated and emphasised the correlation of the colours in the circle, particularly the complementary colours, as well as their temporally and spatially boundless changes. Furthermore, Bendin revealed the manifold correlations between colours and movements with this set. Using the rotating discs, he can also vividly demonstrate that depending on the speed of rotation and the duration of the course, the colours show different kinds of phases towards boundless transitions. In contemporary art, especially in media art, one would find numerous works of art or installations that work with these colour phenomena. Bendin, who, in contrast, has chosen these simple colour discs to demonstrate his scientific findings, thus thematises the inherent spatiality and mobility in colours and manifests the obvious visual value of rotating discs. Moreover, this disc set with the aforementioned special features is considered an attempt to re-evaluate Goethe's colour theory system, from which the theory of colours found its origin in terms of art didactics. Goethe once said, "It [Theory of colours] is very hard to communicate [. . .] for, as you

[28] Bendin [32], S. 602f., see also Fig. 4-7.

[29] Ibid. From the fact that the concept of 'atmosphere' plays a major role in the German art world, one can conclude that Bendin probably considered the ecological aesthetics of nature by Gernot Böhme (1937-) in the process.

know, it requires not only to be read and studied, but to be done, and this is difficult"[30]. With this disc set, we can finally 'do' and 'pass on' Goethe's theory of colours, which until now could only be imitated by several laborious works, such as those of Rupprecht Matthaei (1895-1976).

Acknowledgements

This research was supported by a grant-in-aid for scientific research from the Japan Society for the Promotion of Science: the Grant-in-Aid for Early-Career Scientists (20K12866). This study is based on the manuscript of the online course titled 'Teaching materials for colour theory in Germany today - Eckhard Bendin's *Basic box "Color cosmos": 50 basic elements for colour science 2014*', which was organised by the Color Science Association of Japan on 14 November 2020. Once again, I express my sincere gratitude to the adviser of this organisation, Mr. Yasuhiro Nagata, who supported the formulation of the course, and all the team members who helped produce the flywheel. Furthermore, I would like to express my sincere thanks to the representative of Calo-works AG, Ms. Kei Muramatsu, who kindly accommodated my extraordinary requests and accordingly made video and photo recordings of the rotating discs in motion, and to Mr. Takeshi Kishi, who conjured up a wonderful rotating apparatus from my fan, which caused problems with rotation stability.

References

1. Bendin E (2010), *Zur Farbenlehre: Studien, Modelle, Texte*, Dresden: Die Verlagsgesellschaft GbR.
2. Bendin E (2014), New edition of the anthology '*Zur Farbenlehre*' as *Basic Box 'Color Cosmos'*, Dresden: Edition Bendin.
3. Bendin E (2020), *Zur Geschichte der Farbenlehre im Mitteldeutschen Raum: Ein Beitrag zur Sammlung Farbenlehre*, Dresden: Edition Bendin.
4. Kuehni RG (2010), A brief history of disk colour mixture, *Color Research and Application*, **35** (2), 110-121.
5. Bendin E (2014), Modul 2: Farbe aus periodisch wechselnden visuellen Reizen, *Basisexperimente mit Kreiseln: Ein Lehrfilm zur Farbenlehre*, Digipak with DVD and accompanying booklet *Historischer Exkurs Farbkreisel*, Dresden: Edition Bendin, (*for Basic Box 'Color Cosmos': 50 Basiselemente zur Farbenlehre*, Dresden: Edition Bendin).
6. Mach E (1865), Über die Wirkung der räumlichen Vertheilung des Lichtreizes auf die Netzhaut, in *Sitzungsberichte der mathematisch-naturwissenschaftlichen Classe der kaiserlichen Akademie der Wissenschaften*, Bd. 52.
7. Burckhardt F (1869), Eine Relief-Erscheinung, in *Annalen der Physik*, Bd. 213, Heft 7, 471-474.
8. Katz (1911), *Die Erscheinungsweisen der Farben und ihre Beeinflussung durch die individuelle Erfahrung*, Zeitschrift für Psychologie, Ergänzungsband 7, Leipzig: J.A. Barth.
9. Matthaei R (1926), Die Welt der Farbe.Vortrag gehalten am 12. Mai 1926, in *Verhandlungen des naturhistorischen Vereines der preussischen Rheinlande*, Bd. 83.
10. Fechner GT (1838), Ueber eine Scheibe zur Erzeugung subjectiver Farben, in *Annalen der Physik*, Bd. 121, Heft 10, 227-232.
11. Benham CE (1894), The artificial spectrum top, *Nature*, **51**, 200.
12. Schopenhauer A (1816), *Ueber das Sehn und die Farben. Eine Abhandlung*, Leipzig: Verlag von Johann Friedrich Hartknoch.
13. Field G (1835), *Chromatography; or, a treatise on colours and pigments, and of their powers in painting*, London: Charles Tilt, Fleet Street.

[30] Eckermann [34], p. 561.

14. Maeda F [ed.] (2013), Materials I: Glossary, in *Modern Art and Colour: from Goethe to the Present*, Tokyo: Sangensha. [in Japanese]

15. Goethe JW (2019), *Goethe's Theory of Colours*, translated by Charles Lock Eastlake, London: Routledge.

16. Maeda F (2004), Coherence and gradation. Ostwald's physicochemical colour theory and Goethe's colour theory, in *Morphologia*, **26**, Tokyo: Nakanishiya. [in Japanese]

17. von Helmholtz H (1892), Goethes Vorahnungen kommder naturwissenschaftlicher Ideen, in *Vorträge und Reden*, Bd. 2, Braunschweig: Vieweg, 335-361.

18. Cremer C (2018), Goethes Farbenlehre und die moderne Optik, in *Taten des Lichts-Mack & Goethe*, Steingießer B (Hg.), Hamburg: Hatje Cantz Verlag, 253-265.

19. Grebe-Ellis J and Passon O (2018), Goethes Farbenlehre aus Sicht der heutigen Physik, in *Steingießer*, 18, 125-137.

20. Matthaei R [ed.] (1971), *Goethe's Colour Theory*, London: Studio Vista.

21. von Maltzahn HF [Hg.] (1940), *Philipp Otto Runges Briefwechsel mit Goethe*, Verlag der Goethe-Gesellschaft.

22. Matile H (1979), *Die Farbenlehre Philipp Otto Runges*, München; Mittenwald: Mäander Kunstverlag.

23. von Helmholtz H (1852), *Ueber die Theorie der zusammengesetzten Farben. Physiologisch-optische Abhandlung*, Berlin: Gebr. Unger.

24. Kamishina Y (1987), A study of pigment colour, *Communications of the Faculty of Education*, Simane University (Natural Sciences), **21**, 71-83. [in Japanese]

25. Gurney J (2010), *Color and Light*, Kansas City: Andrews McMeel Pub.

26. van Musschenbroek P (1762), *Introductio ad philosophiam naturalem*, Leiden: Apud Sam. et Joh. Luchtmans.

27. von Helmholtz H (1852), *Ueber die Theorie der zusammengesetzten Farben. Physiologisch-optische Abhandlung*, Berlin: Gebr. Unger, 45-66.

28. Maxwell JC (1855), Experiments on colour as perceived by the eye, with remarks on colour-blindness, *Transactions of the Royal Society of Edinburgh*, **XXI** (Part II), 275-298.

29. Ostwald W (2003), *Lebenslinien: Eine Selbstbiographie*, revised by Karl Hansel, Leipzig: Verlag der Sächsischen Akademie der Wissenschaften zu Leipzig.

30. Bendin E (2014), Begleitheft *Historischer Exkurs Farbkreisel*, Dresden: Edition Bendin (*for Basic Box 'Colour Cosmos': 50 Basiselemente zur Farbenlehre*, Dresden: Edition Bendin).

31. Bendin E (2014), Zum Filmprojekt: Lisa Ewald mit Eckhard Bendin im Gespräch, *Basisexperimente mit Kreiseln: Ein Lehrfilm zur Farbenlehre*. Digipak with DVD and accompanying booklet *Historischer Exkurs Farbkreisel*, Dresden: Edition Bendin (*for Basic Box 'Color Cosmos': 50 Basiselemente zur Farbenlehre*, Dresden: Edition Bendin).

32. Bendin E (2017), Kreiselscheiben als historische und didaktische Instrumente, in *GesprächsStoff: Farbe*, Cologne: Böhlau, 599-607.

33. Bendin E (2014), Modul 3: Die Besonderheiten der Kreiselmischung, *Basisexperimente mit Kreiseln: Ein Lehrfilm zur Farbenlehre*. Digipak with DVD and accompanying booklet *Historischer Exkurs Farbkreisel*, Dresden: Edition Bendin (*for Basic Box 'Colour Cosmos': 50 Basic Elements for Colour Theory*, Dresden: Edition Bendin).

34. Eckermann JP (1874), *Conversations of Goethe with Eckermann and Soret*, translated from the German by John Oxenford, London: G. Bell & Sons.