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The vision of Helmholtz

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ABSTRACT

Hermann Ludwig Ferdinand von Helmholtz (1821–1894) began investigating vision at a time when its study was undergoing a revolution. Laboratory experiments were augmenting the long history of naturalistic observations. Instruments of stimulus control enabled the manipulation of time and space in ways that had not been possible previously, and Helmholtz added to their tally. Vision was a central issue in his early years as an academic, and the bicentenary of his birth is here celebrated visually. Much of his research on vision was described in his *Handbuch der physiologischen Optik*, which was translated into English to mark the centenary of his birth. The history of his *Handbuch* is examined, together with illustrating highlights from it. Helmholtz's contributions to understanding the eye as an optical instrument, the sensations of vision, and perception were expressed in the three parts of the *Handbuch*, which became the three volumes of his *Treatise on Physiological Optics*.

KEYWORDS

Helmholtz; ophthalmoscope; physiological optics; rivalry; stereopsis; stereoscope; vision

Introduction

Much has been written about Hermann Ludwig Ferdinand von Helmholtz (1821–1894), in terms of both his life and his science (see Cahan 2018; Koenigsberger 1906; M'Kendrick 1899; Meulders 2010). The centenary of his birth was marked by the translation of his *Handbuch der physiologischen Optik* into English (Helmholtz 1924a, 1924b, 1925), and the centenary of his death saw an assessment of his science (Cahan 1994) and an analysis of his work on vision as it related to his conflicts with Ewald Hering (Turner 1994). Indeed, his contributions to neuroscience have been described in this journal (Finger and Wade 2002a, 2002b).

Science relies on observation, and so vision can be thought of as the sense of science and also of neuroscience. The science of vision was undergoing a revolution when Helmholtz emerged from his medical studies. The long history of naturalistic observations was being enhanced by laboratory experiments. Instruments of stimulus control enabled the manipulation of space and time in ways that had not been possible previously, and Helmholtz added to the tally of instruments with his ophthalmoscope (1851), ophthalmometer (1855), and telestereoscope (1857). His inaugural lecture at Königsberg, delivered in 1852, was on the nature of human perception. Vision was a central issue in his research, and the bicentenary of the birth of Helmholtz is here celebrated visually in terms of portraits and illustrations from his books and articles. More specifically, concentration will be on his writings and research on vision in general and binocular vision in particular. Much of this

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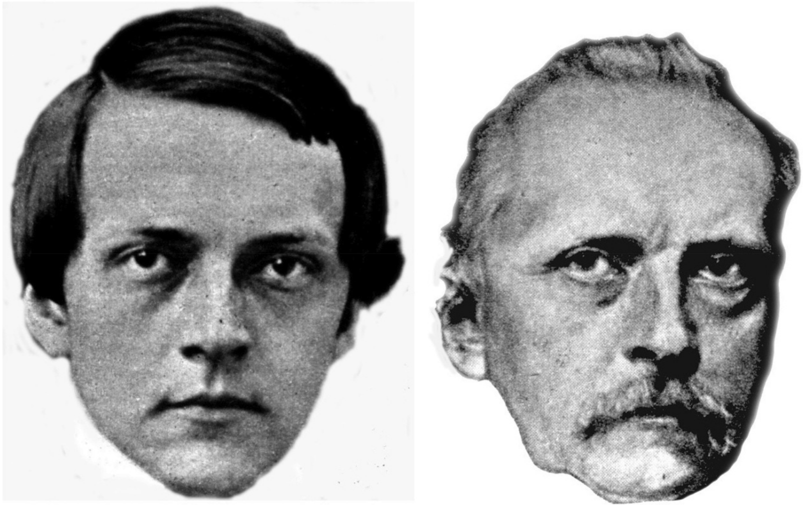

Figure 1. Helmholtz as a young man and in late middle age. Details of portraits after a daguerreotype taken in 1848 and lithograph from 1876. Portraits are derived from illustrations in Koenigsberger (1902).

was described in his *Handbuch der physiologischen Optik*, which was translated into English to mark the centenary of his birth. The frontispiece portrait of Helmholtz in the centennial translation of the *Handbuch* can be compared with a daguerreotype taken almost three decades earlier (see Figure 1); they indicate that his physiognomy changed little throughout his life.

Volume 1 of *Helmholtz's Treatise on Physiological Optics* treats the anatomy and optics of the eye, with consideration of image formation and optical aberrations. Volume 2 examines the sensations of vision, dealing principally with color and contrast phenomena. Volume 3 presents the theory of visual perception and addresses eye movements, visual direction, and binocular vision. Essentially, they were concerned with the physics, physiology, and psychology of vision, respectively. This was stated succinctly in the first volume of Helmholtz's *Popular Lectures*:

> To render what follows understood in all its bearings, I shall first describe the *physical* characters of the eye as an optical instrument; next the *physiological* processes of excitation and conduction in the parts of the nervous system which belong to it; and lastly, I shall take up the *psychological* question, how mental apprehensions are produced by the changes which take place in the optic nerve. (Helmholtz 1873, 199)

Helmholtz is shown in Figure 2 surrounded by his diagram of the human eye, the functions of which he did much to elucidate.

The history of Helmholtz's *Handbuch*

The passage of the *Handbuch* through its various editions reflected Helmholtz's move away from physiological optics toward physics as he progressed from Königsberg to Berlin via Bonn and Heidelberg. Vision was examined progressively with regard to the physics of the stimulus, the physiology of the sense organs, and the psychology of perception. These

Figure 2. *The Eye of Helmholtz* by Nicholas Wade. Helmholtz in 1867, the year in which the three parts of his *Handbuch der physiologischen Optik* were published in a single volume. Portrait after an engraving in Koenigsberger (1902); diagram of the eye after Figure 2 in Helmholtz (1867a).

divisions are represented in the three parts of the *Handbuch*, which were published separately in 1856, 1860, and 1866. In 1867, they were published together in Gustav Karsten's *Allgemeine Encyklopädie der Physik*, with supplements added by Helmholtz. It was translated into French in the same year (Helmholtz 1867b). Despite the impact the *Handbuch* has had on visual science, its history over the three German editions and its translation into English were not straightforward; the title pages of the three editions and the English translation are shown in Figure 3. With publication in a single volume, in 1867, Helmholtz virtually ceased his active involvement in sensory physiology. In 1869 he wrote:

> For the time being I have laid physiological optics and psychology aside. I found that so much philosophizing led to a certain demoralization, and made one's thought lax and vague; I must discipline myself awhile by experiment and mathematics, and then come back later to the Theory of Perception. (Koenigsberger 1906, 266)

When he did eventually revise the *Handbuch*, it took almost as long as its original production: The revisions for a second edition were published separately in nine parts between 1885 and 1895; the final part, published after his death, was edited by Arthur König (1856–1901). These were assembled as a single volume in the second edition of 1896. Most of the revisions were to the physical and physiological parts, with relatively few changes to the third part (on the theory of visual perception). Most of the changes he made to the third part concerned the philosophical aspects of vision in the first section on perceptions in general (see Cassedy 2008).

Willibald Nagel (1870–1911), together with Allvar Gullstrand (1862–1930) and Johannes von Kries (1853–1928), based the third edition of the *Handbuch* (1909–1911) on

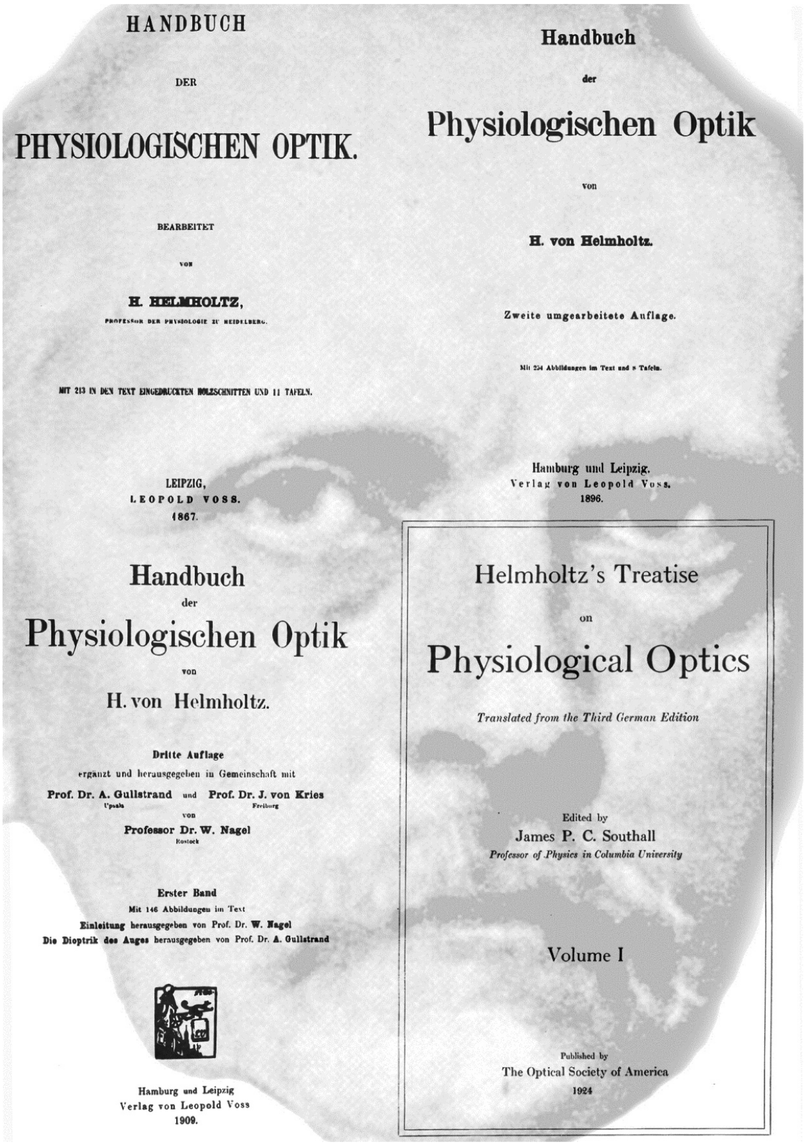

Figure 3. *The Physiological Optics of Helmholtz* by Nicholas Wade. Title pages of the three editions of Helmholtz's *Handbuch der physiologischen Optik*, together with that of the translation into English. The portrait of Helmholtz is derived from a frontispiece lithograph in Southall's translation (Helmholtz 1924a).

Helmholtz's text from the first edition of 1867, rather than on the revised second edition of 1896. Each of the three parts of the *Handbuch* was accorded a separate volume. The editors added footnotes, notes, and additional references to many of the sections and each wrote extensive appendices based largely on their own experimental researches. It was the third edition of the *Handbuch* that was translated into English by James Powell Cocke Southall (1871–1962) as *Helmholtz's Treatise on Physiological Optics* (1924–1925). It was commissioned by the Optical Society of America in 1921 to mark the centenary of Helmholtz's birth. In addition to the revisions by Helmholtz, the second edition contained König's extensive historical bibliography. Thus, Helmholtz's text that was translated into English was from the first edition of 1867, even though it was derived from the third German edition. As Nagel noted in his Preface "The demand for the book has not ceased and will not cease for a long time to come, for no new treatise has superseded Helmholtz's work" (1924a, x).

Helmholtz's *Handbuch* presents a history of research on vision as well as an analysis of it. This history itself changed over the three editions. In the first edition (Southall's translation) it consisted essentially of notes at the end of each section devoted to a particular topic. In the Preface to the first edition, Helmholtz stated that he had relied principally on secondary sources in compiling the references to the early literature. He also noted, "The execution of a really trustworthy history of physiological optics would be of itself an undertaking that would demand the time and strength of an investigator over a long period of years" (1924a, ix).

The skeleton for such an enterprise was undertaken by König for the second edition. He prepared a "Survey over the whole physiological optical literature until the end of 1894" (Helmholtz 1896, ix); the lists of references to historical works are much more extensive than those in the first or third editions and they, together with the name index (*Autorenregister*), occupy about 300 pages as a supplement to the text. The survey was based on the notes made by Helmholtz in the first edition and it consists of numerical and chronological listings (under the original 33 topics) of almost 8,000 references up to the year of Helmholtz's death. König prefixed two general headings, concerned with principles underlying physiological optics and cortical localization, before presenting Helmholtz's topic headings. As König himself noted, the coverage of the German literature is more thorough (and accurate) than that for foreign research, and he also maintained the abbreviations Helmholtz had used for journals. Following the conventions of the day, the manner in which journals were cited often gave greater prominence to the editor than to the journal itself, particularly for the German journals. König made a distinction between the "older" literature and the "newer," with the boundary set at 1866. However, there was relatively little reference to the literature of antiquity; this want has been supplied in books by Lindberg (1976), Park (1997), Smith (1996), and Wade (1998). Southall provided a partial bibliography covering the periods from 1911 to 1924/1925 for the material in Volumes 2 and 3. It is unfortunate that König's survey is not more readily available, and that it was not included in the third edition and its translation; it was included with a reprint of the English translation (Helmholtz 2000).

The plates in the *Handbuch* did change a little over the three editions. In the first edition there were 11, in the second eight, and in the third edition only six. The final six plates were the same in all editions. Those not reproduced in the third edition concerned the gross and microscopic structure of the eye and retina and diagrams of the ophthalmoscope, telestereoscope, and of some entoptic phenomena. Plates 1 and 2 of the second edition were in color and included a representation of the retina as seen with an ophthalmoscope.

Sensory physiology

Sensory physiology was not the primary or principal concern of Helmholtz. He was trained in medicine but was a physicist at heart who made intellectual forays into mathematics. His invention of the ophthalmoscope in 1850 met with instant acclaim. It revealed a new world to ophthalmologists and assisted greatly in the diagnosis and treatment of eye ailments. Helmholtz would take the instrument on his travels and delight his scientific acquaintances by demonstrating its use: "The ophthalmoscope is, perhaps, the most popular of my scientific performances" (Helmholtz 1895, 278). The instrument not only transformed the clinical examination of the eye but also essentially created a new journal: *Archiv für Ophthalmologie*. It was in this journal that Helmholtz announced his ophthalmometer and described its application to measuring the changes in lens curvature that accompany accommodation (Helmholtz 1855).

The ophthalmometer has received far less attention from historians than has the ophthalmoscope (see Godefrooij, Galvis, and Tello 2018). Donders said of Helmholtz's ophthalmometer: "This instrument is one of the great treasures for which we are indebted to his genius" (1864, 17). Further improvements in design were rapidly incorporated, and some were illustrated in the second and third editions of Helmholtz's *Handbuch*. Gullstrand, in his appendix to the third edition, referred to the instrument as "a blessing to practical ophthalmology and to mankind" (Helmholtz 1924a, 301). Helmholtz is shown in Figure 4 with his diagrams of the ophthalmoscope and the ophthalmometer.

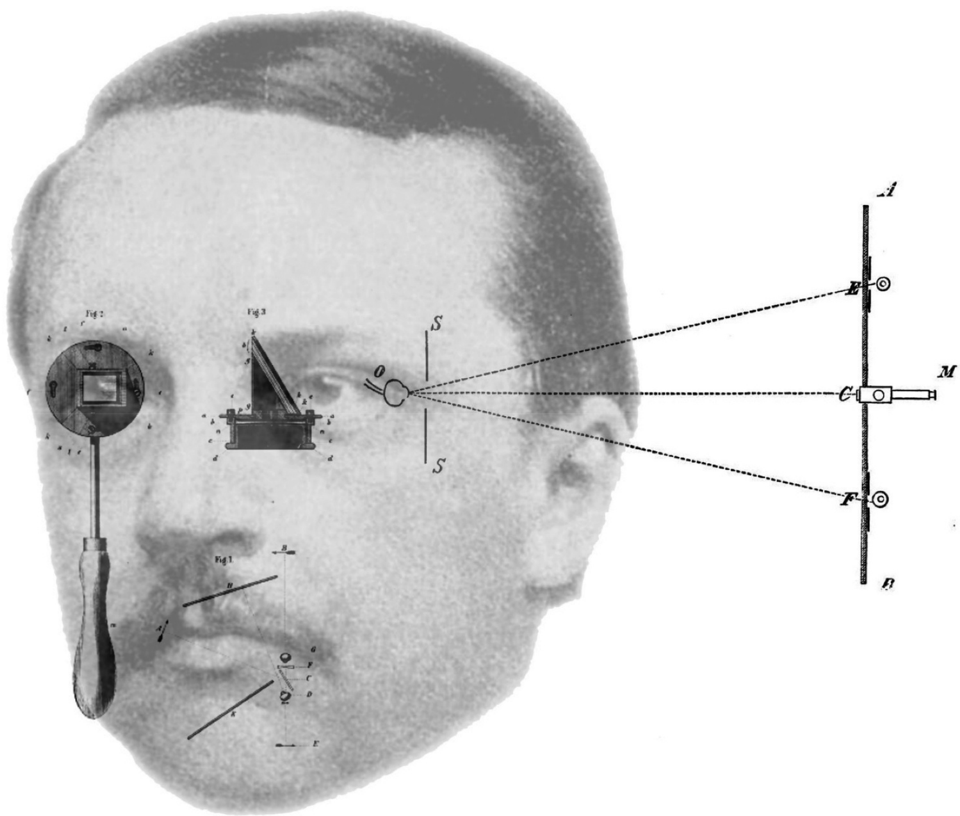

Figure 4. *Helmholtz's Ophthalmoscope and Ophthalmometer* by Nicholas Wade. The portrait is after a photograph taken in 1857. Diagram of the opthalmoscope and its operation is from Helmholtz (1851) and of the ophthalmometer from Helmholtz (1855).

The ophthalmometer enabled Helmholtz to tackle the perplexing problem of accommodation: "The mechanism by which this is accomplished . . . was one of the greatest riddles of the physiology of the eye since the time of Kepler. . . . No problem in optics has given rise to so many contradictory theories as this" (Helmholtz 1873, 205). In order to measure the curvatures of the optical surfaces in the living eye, Helmholtz confirmed the speculations of Young (1793) that the crystalline lens changes curvature during accommodation and Helmholtz proposed a mechanism by which this is achieved:

> On contraction, the ciliary muscle could pull the posterior end of the zonule forwards nearer the lens and reduce the tension of the zonule. . . . If the pull of the zonule is relaxed in accommodating for near vision, the equatorial diameter of the lens will diminish, and the lens will get thicker in the middle, both surfaces becoming more curved. (1924a, 151)

Figure 5 represents an older Helmholtz within the structure of the lens as illustrated in the *Handbuch*.

The ophthalmoscope and ophthalmometer sparked Helmholtz's interests in physiological optics and ushered in almost two decades of research on the senses. They were also part of an instrumental revolution that had engulfed the study of vision during the previous two

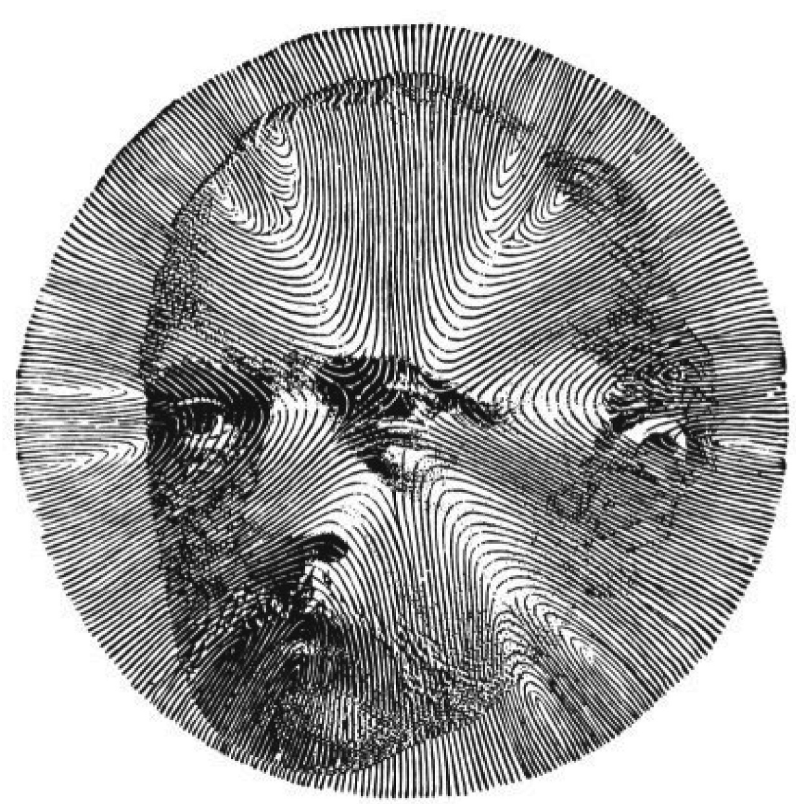

Figure 5. *Helmholtz's Crystalline Lens* by Nicholas Wade. A portrait of Helmholtz in 1881 combined with a diagram showing the "characteristic star-shaped figures . . . from the outer layers of the lens" (Helmholtz 1924a, 33). The portrait is derived from a frontispiece engraving in Helmholtz (1882); the diagram of the crystalline lens is after Figure 20 in Helmholtz (1867a).

decades, and Helmholtz was able to capitalize on it. Experiments could be performed on vision, and its study was transferred from the natural environment to the laboratory, where the methods of physics could be applied (see Wade 1998; Wade and Heller 1997).

The material on accommodation was incorporated and enlarged in the first part of the *Handbuch*, but the analysis of color vision was presented in the second part. By that time, Helmholtz had examined several color-blind individuals and had conducted experiments using Maxwell's color wheel. Helmholtz's initial experimental studies, published in 1852, involved the nature of the stimulus to vision; he assessed and repudiated Brewster's (1831) analysis of sunlight into three spectral components. Helmholtz repeated Brewster's experiments, adding more precise controls, and found that the results did not diverge from Newtonian predictions (Helmholtz 1852). Nonetheless, it could well have been an illustration of "the triple spectrum" by Brewster that led to Helmholtz's speculative spectral sensitivity curves (see Figure 6). These are taken as the basis for what has been called the

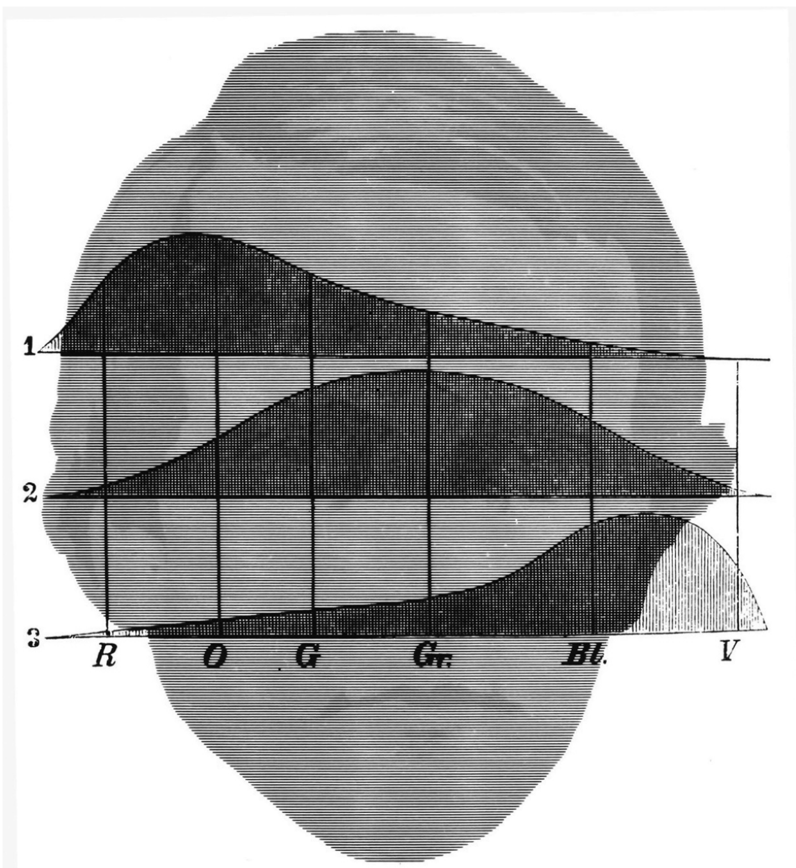

Figure 6. *Young Helmholtz* by Nicholas Wade. A youthful Helmholtz in combination with the curves "taken to indicate something like the degree of excitation of the three kinds of fibres, No. 1 for red-sensitive fibres, No. 2 for the green-sensitive fibres, and No. 3 for the violet-sensitive fibres" (Helmholtz 1924b, 143). The speculative spectral sensitivity curves are after Figure 21 of volume 2 in Helmholtz (1867a).

Young-Helmholtz, or trichromatic, theory of color vision, although Helmholtz did not initially embrace Young's suggestion:

> [I]t is almost impossible to conceive each sensitive point of the retina to contain an infinite number of particles, each capable of vibrating in perfect unison with every possible undulation, it becomes necessary to suppose the number limited, for instance, to the three principal colours, red, yellow, and blue. (Young 1802, 20)

Helmholtz became an ardent proponent of Young's theory following publication of more detailed support for it by Maxwell (1855) using his color disc (see Kremer 1994; Turner 1994). Helmholtz differentiated between additive and subtractive color mixing in the second part of the *Handbuch*.

Helmholtz's knowledge of physics informed his studies in mathematics and physiology. Thus, his systematic treatment of light and sound provided a new, more rigorous understanding of the early stages of vision and hearing. His experimental procedures were precise (although the results were based almost entirely on his own observations) as was his analysis of the ensuing results. Despite his contact with Fechner, who had published his *Elemente der Psychophysik* in 1860, Helmholtz continued to place greater reliance on his own qualitative and quantitative observations than on any generalizations of them to other observers. In common with his contemporaries, the processes of perception were considered to be universal, so that general principles could be derived from particular observations. Much of the polemic surrounding the heated debates in nineteenth-century visual science was based on the conviction that personal perception was pervasive; individual differences were only taken seriously in areas like color blindness. Novel observations were accepted as fact only when they were seen by another investigator. Helmholtz was at his most vulnerable when his observational skills were impugned (see Howard 1999).

Binocular vision

Binocular vision was addressed in Part 3 of the *Handbuch*. Helmholtz commenced by examining visual direction: Monocular vision could signal direction alone, but location required distance, which could be supplied by binocular vision. In this context, he added to the terminology by introducing the term "cyclopean eye" (Wade 2021). The concept is based on the mythological cyclops who forged thunderbolts for Zeus and was a one-eyed giant in Homer's *Odyssey*. The direction in which objects were seen with two eyes was as if the origin was a point between them. The term is now in common parlance, and Helmholtz's use of the German *Cyclopenauge* became the English cyclopean eye.

> Midway between the two eyes suppose there were an imaginary cyclopean eye which was directed to the common point of fixation of the two eyes, and that it rolled according to the law governing the rolling of the two real eyes. Imagine the retinal images transferred from one of the real eyes to this imaginary eye, so that the point of fixation of the imaginary eye is the same as that of the real eye. *Then the points of the retinal image will be projected out along the line of direction of the imaginary cyclopean eye.* (Helmholtz 1925, 258)

Prior to the invention of the stereoscope, vision with two eyes was considered in terms of singleness rather than depth. Two contrasting approaches were proposed for single vision—suppression or fusion (see Wade and Ono 2012). Helmholtz's mentor, Johannes Müller (1826, 1838), considered that fusion was restricted to stimuli lying on a circle, with its circumference defined by the point of fixation with both eyes and the rotation centers of each of them; it became known as the Vieth-Müller circle because Vieth (1818) gave a similar geometrical description. All points on the circle stimulated corresponding or identical retinal points yielding single vision; all other patterns of binocular stimulation were considered to lead to double vision. This was questioned by the stereoscopic phenomena described by Wheatstone (1838). Helmholtz found precisely the support he needed for his empiricist theory in Wheatstone's stereoscopic phenomena. Indeed, his own stereoscopic experiments added to a negative assessment of Müller's theory of identical retinal points, and to Hering's extension of it:

> The second difficulty for the Intuitive Theory is that, while we have two retinal pictures, we do not see double. This difficulty was met by the assumption that both retinae when they are excited produce only a single sensation in the brain, and that the several points of each retina correspond with each other, so that each pair of corresponding or 'identical' points produces the sensation of a single one. (Helmholtz 1873, 277)

Moreover, Helmholtz emphasized that stereoscopic depth perception is learned, and that the invention of the stereoscope "made the difficulties and imperfections of the Innate Theory of sight much more obvious than before" (Helmholtz 1873, 274). Thus, the stereoscope helped to give Helmholtz precisely what he needed to strengthen and defend his own empirical theory of space perception against attacks on it by Hering (see Lenoir 1993; Turner 1994). He maintained not only that binocular depth perception is learned but that all spatial perception is founded on judgmental acts based in experience. As Helmholtz saw it, space perception is, from a more general perspective, essentially similar to object recognition.

Presenting different stimuli to each eye was transformed by the invention of the stereoscope. It could be argued that the stereoscope heralded the revolution in vision (see Wade 2004, 2016), and the instrument was embraced by Helmholtz. He initiated research on binocular vision in the 1850s and invented the telestereoscope in 1857, although his experiments on binocular vision were undertaken in the early 1860s while he was in Heidelberg. The stereoscope was important to Helmholtz, both for the experimental world it exposed and also for his inferential theory of vision. In prosecuting his experimental enquiries, Helmholtz developed the reflecting stereoscope so that disparities could be enhanced. This was achieved by extending the separations between the mirrors, and he called the instrument a telestereoscope; his diagram of it is shown, together with his portrait, in Figure 7.

Eye movements were implicated in stereoscopic vision by Brücke (1841), a close associate of Helmholtz, in order to reconcile the binocular phenomena with Müller's theory of identical retinal points. If the eyes changed convergence rapidly while viewing solid objects, this could be the basis for perceived depth rather than the combination of slightly disparate retinal points in the two eyes. Although Helmholtz adopted eye movement interpretations of many visual effects, this did not apply to stereoscopic vision. Dove (1841) illuminated stereoscopic pairs with brief electrical sparks, which generated afterimages, and depth was visible with them. Volkmann (1859) presented paired stimuli briefly with a tachistoscope, and this also resulted in stereoscopic depth. Helmholtz confirmed these observations and wrote: "Both these experiments and those with electric sparks show that ocular movements are not necessary for perception of depth; because afterimages move with every movement

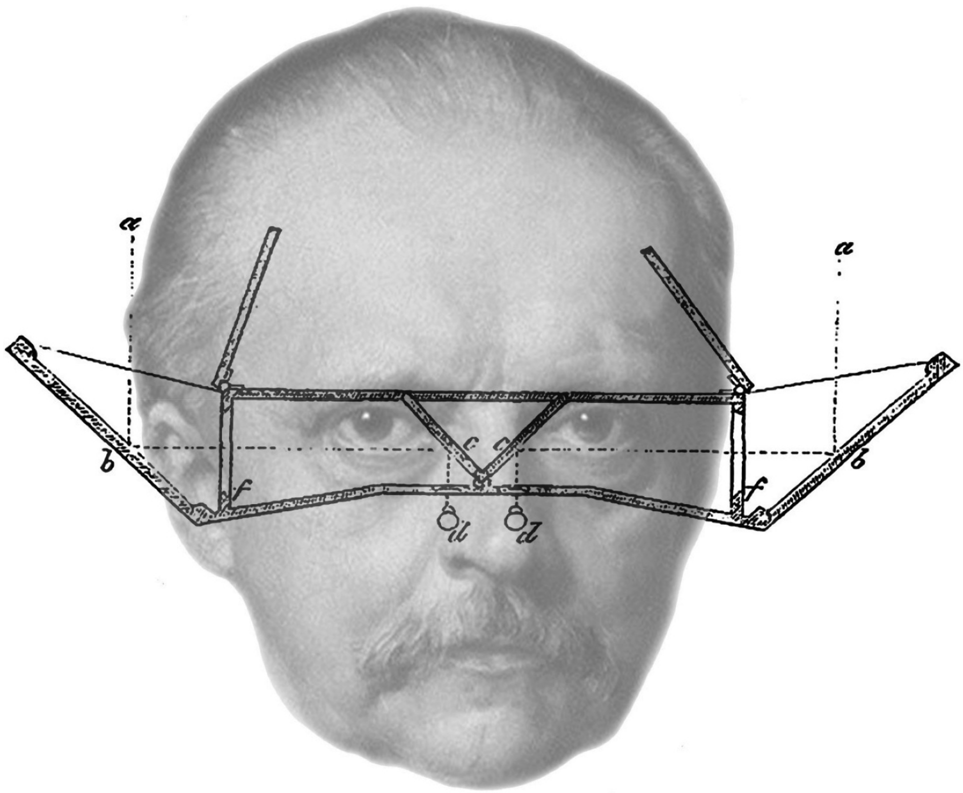

Figure 7. *Helmholtz's Telestereoscope* by Nicholas Wade. Portrait modified from a painting dated 1881. Diagram of the telestereoscope from Helmholtz (1857).

of the eye, and it is simply impossible to make disparate images correspond to each other by any such movement" (1925, 456).

Binocular rivalry can involve competition between colors or contours, and both were investigated before the invention of the stereoscope (see Wade and Ngo 2013). The combination of different colors presented to corresponding regions of each retina became an issue of theoretical importance following experiments on color mixing: Are colors combined by either eye as they are when selected from the spectrum? Helmholtz, like Wheatstone, embraced color rivalry as evidence in favor of an inferential theory of vision. On the other hand, Hering (1861) argued for a physiological interpretation of rivalry, and much of his dispute with Helmholtz surrounded the visibility of yellow from dichoptic combinations of red and green. This reflected the disputes between them over trichromatic and opponent process theories of color vision (see Turner 1994). Helmholtz used the stereoscope to examine binocular color and contour rivalry, and it also assisted in his personal rivalry with Hering. Panum (1858) and Hering (1861) considered that binocular rivalry was physiological, whereas Wheatstone and Helmholtz maintained that it was psychological. In his *Handbuch* of 1867, Helmholtz discussed the rivalry in some detail and also emphasized that changing, complex mixtures of the two stimuli tend to be visible most of the time, with only occasional periods in which the stimulus in one eye alone dominates:

> [I]n the various parts of the field, one image will prevail more than the other, whereas in other parts the other image will predominate. Sometimes there will be alternations, so that, where for a while only parts of one image were visible, presently parts of the other image will emerge and suppress portions of the first image. This fluctuation, in which parts of the two images mutually supplant each other, either side by side, or one after the other, is what is usually meant by *the rivalry between the visual globes*. (Helmholtz 1925, 494)

Helmholtz placed great importance on eye movements in binocular rivalry and made a modification to Panum's orthogonal gratings configurations: He placed two small squares at the center of both gratings to facilitate common fixation by each eye (see Figure 8), because otherwise "it is difficult to concentrate the attention on one of the systems of lines" (Helmholtz 1925, 498). Thus, Helmholtz also assigned rivalry to attention: "The extraordinary influence exercised by contours in the rivalry between the two visual globes is also essentially a matter of psychological habit, in my opinion" (Helmholtz 1925, 501).

The crossed diagonal figure was used by Helmholtz to support his theory that rivalry is a psychological rather than a physiological process, because he could control which stimulus was visible:

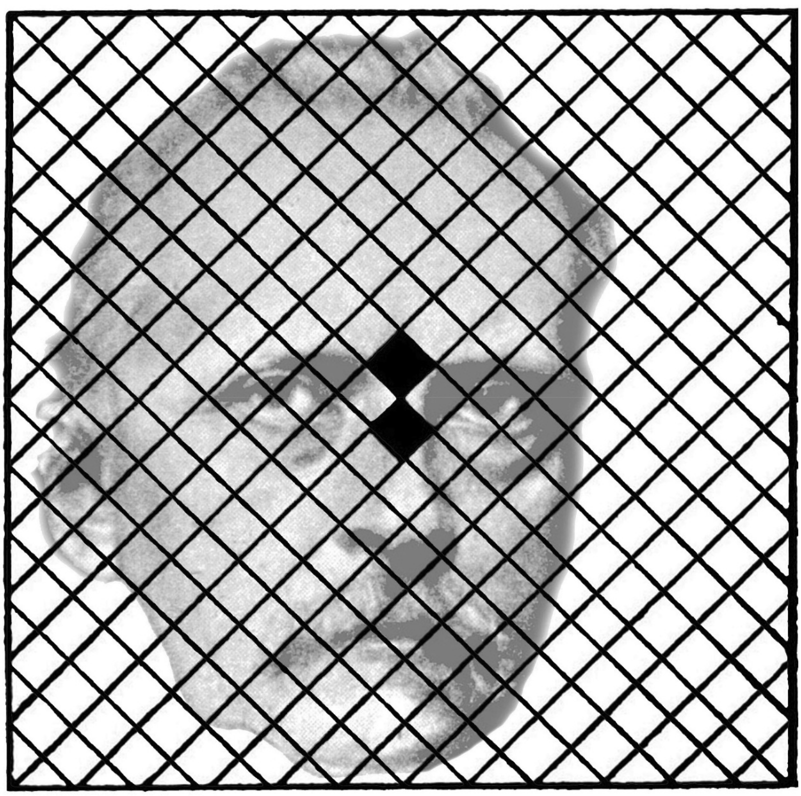

Figure 8. *Helmholtz in Rivalry* by Nicholas Wade. Helmholtz in combination with the crossed gratings he illustrated in Plate 2 of his *Handbuch* (Helmholtz 1867a).

> These experiments show that man possesses the faculty of perceiving the images in each eye separately, without being disturbed by those in the other eye, provided it is possible for him . . . to concentrate his whole attention on the objects in this one field. This is an important fact, because it signifies, that *the content of each separate field comes to consciousness without being fused with that of the other field by means of organic mechanisms*; and that, therefore, *the fusion of the two fields in one common image, when it does occur, is a psychic act*. (Helmholtz 1925, 499)

In 1839, the year following the announcement of the stereoscope, photography was introduced to the public. Soon after, paired photographs from slightly different positions were taken which could be viewed in a stereoscope to yield apparent depth. It was also possible to present a positive image to one eye and a negative of the same image to the other. However, the initial studies of binocular luster by Dove (1851) used drawings of geometrical figures either as black on white or as white on black. Helmholtz examined this aspect of binocular vision, which he called "stereoscopic lustre," and stimuli inducing it were accorded the status of a Plate in his *Handbuch* (see Figure 9).

Perception

However, Helmholtz's lasting influence in visual neuroscience has related to neither his physical rigor nor his observational precision but, rather, to his epistemology as it was enunciated in Part 3 of the *Handbuch* (see Hatfield 1990; Turner 1994). The final section of the volume, reviewing theories of vision, posed him the greatest problems and required the most protracted preparation. Although little he wrote on the issue was novel, he marshaled the arguments over a wider range of phenomena than others had done before. He summarized his position succinctly: "The sensations of the senses are tokens for our consciousness, it being left to our intelligence to learn how to comprehend their meaning" (Helmholtz 1925, 533). The German text for this carries Helmholtz's portrait in Figure 10.

In developing the theory that sensory tokens rather than images are the basis for perception, Helmholtz was guided by Müller's doctrine of specific nerve energies (see Cassedy 2008; De Kock 2016; Finger and Wade 2002b). Müller (1826) argued that the particular sensations experienced are dependent on the nerves excited, no matter how those nerves are stimulated. For Helmholtz, these sensory tokens were processed rapidly, unconsciously, and inferentially in what came to be called "unconscious inferences." A similar concept was advanced by Berkeley (1709) and employed by Wheatstone (1838) to interpret stereoscopic phenomena. Helmholtz's many debts to Wheatstone were acknowledged in his *Handbuch*. Not only did Wheatstone provide the instrument with which Helmholtz would challenge the nativism of Hering, he also supplied the theoretical framework, including the concept of unconscious mental processes, that were used to support the stereoscopic observations. Wheatstone effectively reunited binocularity with space perception, and he employed Berkeleyian empiricism to cement the union. Space perception had remained the province of philosophers for centuries, but it was clear to both Wheatstone and Helmholtz that the methods of physics could be applied in an effective way to study space and depth perception; they were not, as Kant (1781) had contended, outside the realm of experimental enquiry.

The image-based theories had long been dominant following Kepler's (1604) analysis of ocular dioptrics: An inverted and reversed image of external objects was focused on the back of the eye. Kepler referred to it as a picture and set in train an approach to vision that

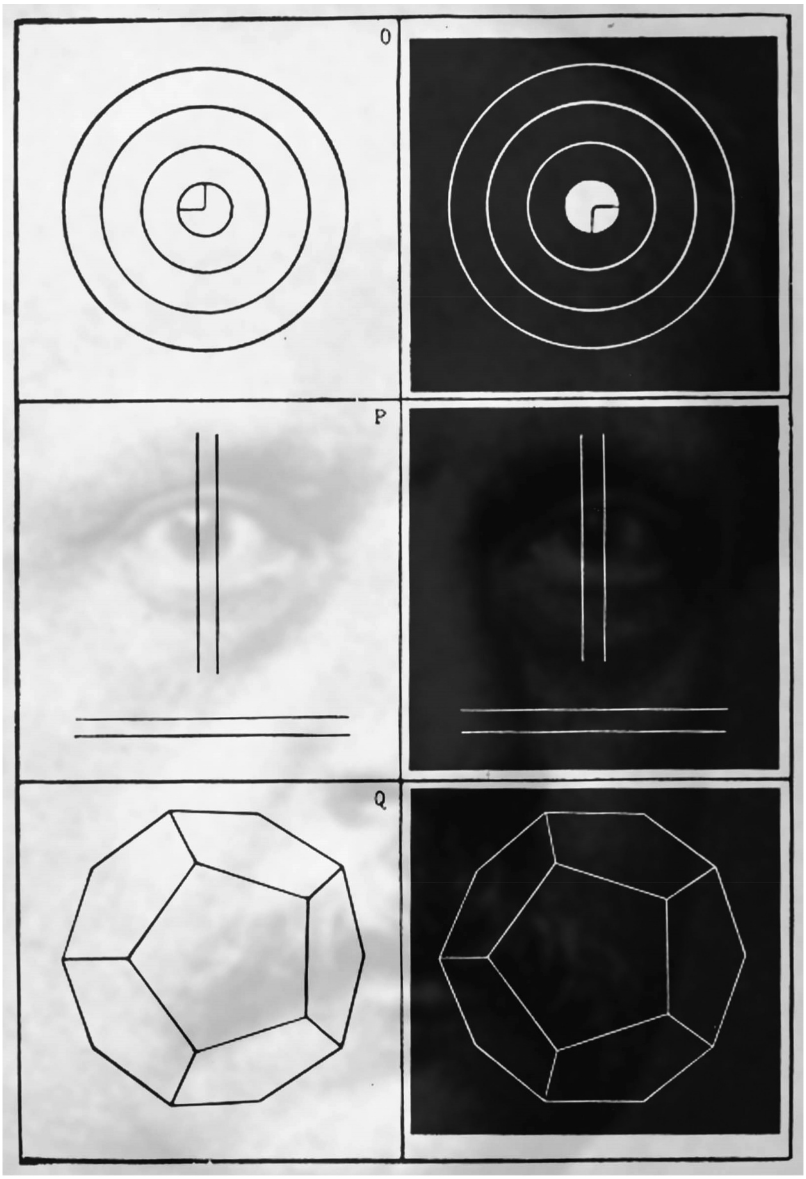

Figure 9. *Helmholtz and Stereoscopic Luster* by Nicholas Wade. The portrait is derived from a frontispiece lithograph in Helmholtz (1910), as are the diagrams that induce stereoscopic luster (Plate 4). The plate is numbered 9 in the first edition (Helmholtz 1867a), 6 in the second (Helmholtz 1896), and 4 in the third edition (Helmholtz 1910).

involved processing this picture. This created problems like relating upright vision to an inverted image. As was the case with two retinal images, such problems were bypassed when considering sensory tokens:

> These two difficulties do not apply to the Empirical Theory, since it only supposes that the actual sensible "sign," whether it be simple or complex, is recognised as the sign of that which

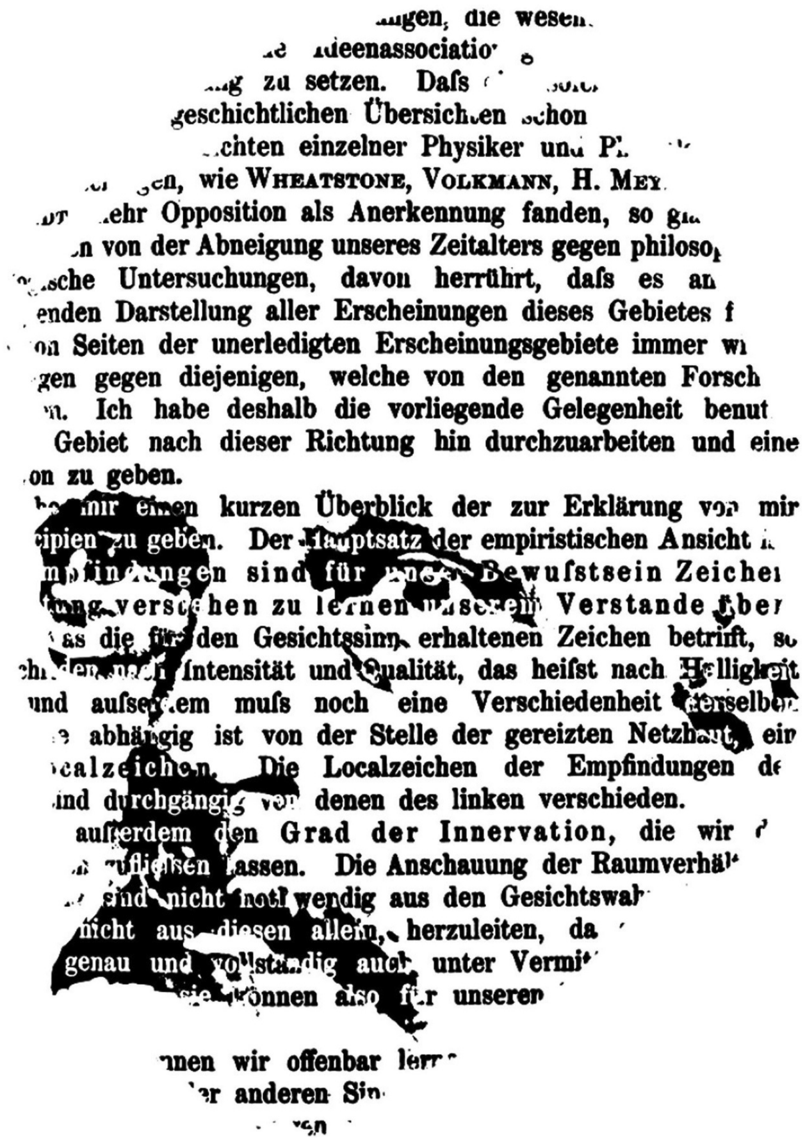

Figure 10. *Tokens of Ssensation* by Nicholas Wade. A portrait of Helmholtz (after an engraving in Koenigsberger 1902) embedded in text from the *Handbuch* (1896, 947). The text (a translation of which can be found on pp. 532–533 of Helmholtz 1925) is drawing attention to the intelligence of perception, and the reader is required to exercise inference in order to extract Helmholtz's portrait from the text.

it signifies. An uninstructed person is as sure as possible of the notions he derives from his eyesight, without ever knowing that he has two retinae, that there is an inverted picture on each, or that there is such a thing as an optic nerve to be excited, or a brain to receive the impression. He is not troubled by his retinal images being inverted and double. He knows what impression such and such an object in such and such a position makes on him through his eyesight, and governs himself accordingly. But the possibility of learning the signification of the local signs which belong to our sensations of sight, so as to be able to recognise the

> actual relations which they denote, depends, first, on our having movable parts of our own body within sight; so that, when we once know by means of touch what relation in space and what movement is, we can further learn what changes in the impressions on the eye correspond to the voluntary movements of a hand which we can see. In the second place, when we move our eyes while looking at a field of vision filled with objects at rest, the retina, as it moves, changes its relation to the almost unchanged position of the retinal picture. We thus learn what impression the same object makes upon different parts of the retina. (Helmholtz 1873, 278)

After 1867, Helmholtz continued to give popular lectures on vision and, although he did not acquire any further evidence for his empiricism, his opposition to nativism was undiminished. Nonetheless, Boring dedicated his history of sensation and perception to the long-dead Helmholtz with the prefatory defense that, "If it be objected that books should not be dedicated to the dead, the answer is that Helmholtz is not dead" (1942, xi).

Helmholtz lived in an era when science was believed to illuminate the path to truth, and he did much to chart its course. He searched for principles that would unify the sciences, and these he considered to have their basis in the senses. He early recognized "that knowledge of natural processes was the magical key which places ascendency over Nature in the hands of its possessor" (Helmholtz 1895, 272). There was little room for doubt in this approach, and the uncertainties of modern physics lay in the near future. Ironically, it was one of his own students, Max Planck, who laid the foundations for this transformation. Physiology received a radical revision in the late-twentieth century with the technical innovations that resulted in single-cell recordings, and it has provided support for both Hering's nativism and Helmholtz's empiricism (see Turner 1994).

However, it is neither in the provinces of physics nor in physiology that Helmholtz's ideas have lingered longest, but in his theory of the psychology of the senses, as it was enunciated in the third part of his *Handbuch*. Perhaps this is because it led Helmholtz into the metaphysical domain he had assiduously avoided in his physical and physiological endeavors: "Philosophy, it is true, has been for nearly three thousand years the battleground for the most violent differences of opinion, and it is not to be expected that these can be settled in the course of a single life" (Helmholtz 1895, 286).

However, an explicit distinction was made between metaphysics and philosophy, and Helmholtz had less regard for the former than the latter. He considered that the relationship between them was comparable to that between astrology and astronomy, noting, "[P] hilosophy, if it gives up metaphysics, still possesses a wide and important field, the knowledge of mental and spiritual processes and their laws" (Helmholtz 1895, 233).

Conclusion

We conclude, as we began, with reference to the unchanging facial characteristics of Helmholtz, but this time they are presented binocularly. Figure 11 is intended for binocular viewing, but it involves binocular rivalry rather than stereoscopic depth. It is composed from two portraits of Helmholtz, one from 1857 and the other from the year in which he died, 1894. The upper part of the figure is an anaglyph that requires red/cyan glasses to view, because the two components are presented to different eyes. The first anaglyphs were made by a German inventor (Rollmann 1853) at the time Helmholtz was in Königsberg, and they were mentioned in his *Handbuch*:

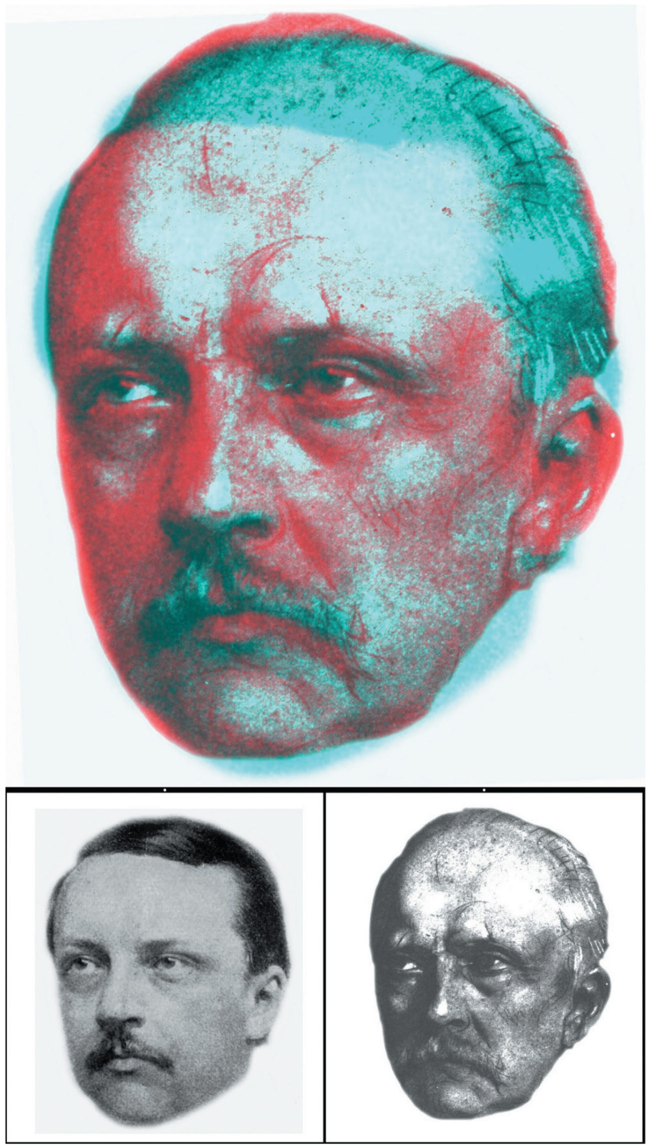

Figure 11. *Helmholtz Through the Ages* by Nicholas Wade. Portraits of Helmholtz in 1857 and 1894 combined as an anaglyph (above) and shown separately (below).

> He [Rollmann] draws two projections on the same black card, one with red lines, the other with blue. Then he takes a red glass in front of one eye and a blue glass in front of the other and only sees the red lines with that eye, with this only the blue ones, which can then be combined to form a relief. (Helmholtz 1867a, 685)

That is, the red lines are seen as black through the blue glass as are the blue lines through the red glass. This was incorrectly translated by Southall, who wrote, "[H]e can see only the red lines through the red glass and the blue lines through the blue glass" (Helmholtz 1925, 356). Beneath the anaglyph, the two portraits are shown separately in black and white.

Combining them by crossed or uncrossed convergence will yield binocular rivalry and fusion, as in the anaglyph.

Although Helmholtz's physiognomy changed little throughout his adult life, the subjects he examined, like physiological optics, were transformed by his analyses of them.

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