Figure 1. The connected series of tuning-fork resonators that Helmholtz used to combine partial tones, creating tones indistinguishable from those produced by musical instruments. See the discussion on page 300. From Hermann Helmholtz, Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik, 5th ed., (Brunswick: Vieweg & Sohn, 1896), p. 633.
Helmholtz and the Materialities of Communication

By Timothy Lenoir

ONE OF HERMANN HELMHOLTZ’S PRIMARY CONTRIBUTIONS to physiological optics was the experimental elaboration of the three-receptor hypothesis for explaining color vision, a theory first proposed by Thomas Young. Early in his career, however, Helmholtz had publicly rejected the Young hypothesis. My concern in this paper is with the role of experiment and instrumentation in Helmholtz’s reversal of position on this issue and more specifically with the positive contribution made by a variety of new media technologies, particularly electric, photographic, and telegraphic inscription devices. These media devices served Helmholtz as analogues and as models of the sensory processes he was investigating. They did not merely assist him in understanding the operation of the eye and ear through measurement; more to the point, Helmholtz conceived of the nervous system as a telegraph—and not just for purposes of popular presentation. He viewed its appendages—sensory organs—as media apparatus: the eye was a photometer; the ear a tuning-fork interrupter with attached resonators. The output of these devices was encoded in the form of an n-dimensional manifold, a complex measure to which a sign, such as Rot, Blau-grün, or ü was attached. These materialities of communication were important not only because they enabled theoretical problems of vision and hearing to be translated, externalized, and rendered concrete and manipulable in media technologies but furthermore because in this exteriorized form analogies could be drawn between devices; linkages could be made between different processes and between various aspects of the same process. Crucial to Helmholtz’s theorizing were analogies between sound and color perception. Indeed, I will argue that a crucial step in his development of the trichromatic receptor theory of color sensation came through analogies between the technologies of sound and of color production. The juxtaposition of media enabled by the materialities—the exteriorized forms—of communication was a driving force in the construction of theory.

Essentially my claim is as follows: Helmholtz’s model of representation was that of an abstract system of relations among sense data. Like Bernhard Riemann, working independently at almost exactly the same time, Helmholtz treated the mental

* Program in History and Philosophy of Science, Stanford University, Stanford, California 94305-2024.

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The notion of “materiality of communication” I refer to throughout this study is an adaptation of proposals made by Hans Ulrich Gumbrecht and Ludwig Pfeiffer in the introduction to their edited volume Materialität der Kommunikation (Frankfurt am Main: Suhrkamp, 1988).

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representation of sensations as n-dimensional manifolds. Different modalities of sense were characterized as manifolds obeying different metric relations. The sense data were organized into symbolic codes by a system of parameters due to the physical properties of each sense and adjusted by experience. These ideas about representation emerged out of three fields of investigation—color, sound, and electrotelegraphy—familiar to Helmholtz during 1850–1863, the period spanning his work on the speed of nerve transmission, physiological color mixing, and physiological acoustics and culminating with the publication of Part II of the *Physiological Optics*. For my purposes the most innovative character of Helmholtz's work derived from his adapting a number of interrelated technical devices employed in telegraphy to the measurement of small intervals of time and the graphic recording of temporal events in sensory physiology. From as early as 1850 he drew analogies between the electrical telegraph and the process of perception. The telegraph began to serve as a generalized model for representing the processes of sensation and perception. In light of this telegraph analogy Helmholtz, so I hypothesize, imagined the virtual image cast on the retina as dissolved into a set of electrical impulses, data to be represented by symbols as an "image" in the brain through a perceptual analogue of Morse code.

Between 1850 and 1855 Helmholtz was working intensively with the myograph and a variety of electrical devices adapted from the telegraph industry to measure the speed of nerve transmission and other features connected with nerve action and muscle contraction. Telegraphy was not simply a useful model for representing and thinking about vision and hearing. Experiments involving those devices were also crucial in advancing his own program of sensory physiology. This role of telegraphic devices and a variety of imaging devices became particularly important between 1855 and 1860, when, reacting to a critique of his theory of spectral color mixing by Hermann Grassmann, Helmholtz retracted his earlier (1852) rejection of the Young trichromacy theory of physiological color mixtures. Helmholtz suggests that he arrived at this view via a comparative analysis with hearing, and I pursue this suggestion in depth in the third section of this article. Helmholtz pursued a similar research strategy of representing tone production and reception in terms of a variety of components of electrical telegraphic circuitry combined with several techniques for graphic display of wave motion, particularly sound waves. These devices were crucial in his investigation of combination tones, the analogue to forming color mixtures from primary colors. Helmholtz postulated retinal structures—three receptors sensitive primarily to wavelengths in the red, green, and violet ranges respectively—analogous to the arches of Corti in the ear. The analogy provided the path to accepting the Young trichromatic theory, previously rejected. Once again, new media

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technologies associated with communication and representation were crucial in this transition; for Helmholtz drew upon processes of photonegative production in providing a physiological explanation of positive and negative afterimages, crucial to refining the three-receptor hypothesis.

1. THE BERLIN PHYSICAL SOCIETY AND THE NEW MEDIA TECHNOLOGIES

Helmholtz’s researches, including his treatment of color, were situated within a context of interest in telegraphy and technologies of representation. Several of Helmholtz’s closest associates during the late 1840s and early 1850s were deeply involved in electrotelegraphy and photography. These individuals had founded and sustained the Berlin Physical Society; its journal, Die Fortschritte der Physik, a review of the literature on measurement technologies and physics applied to various fields, was intended as a program statement of their so-called physicalist school. The proceedings of the Berlin Physical Society provide an overview of the members’ interests in measurement and technologies of representation. The first volume of the Fortschritte der Physik (1845), for instance, devoted a seventy-two-page review by Gustav Karsten to literature on photography and daguerreotypy, and a twenty-two-page review by Werner Siemens to telegraphy.

Methods for measuring small intervals of time and for graphically representing processes taking place in times too brief to experiment with directly were high on the list of the society members’ interests—Helmholtz referred to these graphic methods as “Mikroskopie der Zeit” (time microscopy) in his paper of 1850 summarizing these different developments. In the meeting of 25 July 1845 Siemens presented a paper on measurement of the velocity of mortar shells using marks on graph paper made by sparks triggered by the projectile moving through the cannon bore; in the same meeting Karsten discussed employing daguerreotypes to measure solar spectra. Emil du Bois-Reymond discussed methods for measuring the speed of nerve transmission and muscle contraction in the meeting of 7 March 1845; and in that same meeting Ernst Brücke gave the first of several papers he would deliver in 1845 on the subjects of retinal cones and on the inability of infrared light to penetrate the optical media of the eye to the retina. Brücke’s experiments were assisted by Karsten, who prepared extrasensitive photographic paper to use as light detectors. Brücke concluded his discussion of the sensitivity of the retina to light in the range of wavelengths between red and violet as “the most sensitive of all known Actinometers.”

Among the topics discussed in the meeting of 31 October 1845 was H. L. d’Arrest’s treatment of various methods for determining the isochrony of pendula. On 20 February 1846 a certain Leonhardt, an instrument maker in Berlin, discussed his new electrical telegraph.

Helmholtz delivered his first paper in the Physical Society on 23 July 1847, on the conservation of force. In the previous meeting, of 9 July, Brücke had discussed afterimages and physiological-contrast colors. He followed this paper with another on 15 October on methods for making the motion of a vibrating string visible. In 1848 Brücke discussed further aspects of color theory, namely, the origins of

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1 Helmholtz, “Über die Methode, kleinste Zeittheile zu messen” (cit. n. 3), p. 870.
2 See Ernst Brücke’s review of the recent progress in physiological optics in Fortschritte der Physik, 1846, 2:227.
3 Ibid., pp. xv-xviii.
"brown" and the order of colors in Newton's rings. Du Bois-Reymond presented work on his "multiplicator," a galvanometer capable of registering bioelectric currents; and he and Johannes Halske presented their related work on the magnetoelectric motor. In the first meeting of 1850 Siemens presented his new work on telegraph apparatus. At the next meeting Helmholtz presented work on the speed of nerve transmission, to which three sessions of 1850 were devoted. One session, 18 July, was devoted to explaining and demonstrating the operation of Helmholtz's myograph in graphically recording nerve transmission and muscle contraction. In addition to telegraphs and recording devices for nerve and muscle action, several sessions in 1850 were devoted to Wilhelm Beetz's work in acoustics, in particular tones produced by rotating tuning forks and work on combination tones. The three years 1854-1857 were probably the most active years in the Berlin Physical Society for presentations on telegraphy. Siemens presented nine lectures on several different topics, including the design and operation of the electromagnetic telegraph, his system for sending multiple messages or messages in opposite directions over the same cable, and the problems of laying underwater cables. Halske presented papers on improvements he and Siemens had made to the Morse telegraph. Halske also discussed his new polarization kaleidoscope and work on moving stereoscopic images. Helmholtz contributed refinements on his earlier work on the speed of nerve transmission. Telegraphy, imaging devices, electromagnetic devices for time measurement, and graphic display of temporal processes connected with light, sound, or neurophysiological phenomena were the most enduring interests of the active members of the Berlin Physical Society.

II. HELMHOLTZ'S REACTION TO GRASSMANN

Helmholtz's decision to reconsider his earlier rejection of Young's three-color hypothesis came not as a result of the technologies explored at the Physical Society, but in response to the extremely abstract criticism of Hermann Grassmann. Helmholtz first encountered Grassmann's work in 1852. As part of the procedure connected with his appointment at Königsberg, Helmholtz chose as the subject for his Habilitationschrift a critique of David Brewster's theory of color, which was based on the view that the spectral colors are mixtures of three elementary colors, red, yellow, and blue. Grassmann found Helmholtz's paper wanting in certain respects, but his primary interest lay in using it to illustrate once again the general applicability of the methods of his Ausdehnungslehre. For Helmholtz, the interest lay in Grassmann's geometrical theory of color-space as a sensory manifold, but he insisted, as Grassmann had not, that the color-space be demonstrated by experiment as well as by logic. The exchange through papers in Poggendorf's Annalen der Physik und Chemie between 1852 and 1855 led Helmholtz to revise his own early ideas.

Helmholtz's papers on color mixtures featured the adaptation and refinement of existing instruments and experimental practice that characterized all his early papers and aroused the admiration of his contemporaries. In his first paper of 1852 the arrangement for mixing pure spectral colors consisted of two slits forming a V in a

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black blind (see Figure 2). The slits were inclined by 45 degrees to the horizontal and were at right angles to one another. Different spectral colors passed through each slit were combined at the point of intersection. To generate the possible combinations of these two colors, a flint-glass prism was placed vertically in front of the objective lens of a telescope, which was focused on the intersection of the slits, both prism and telescope at a distance of twelve feet from the V-slit blind. Helmholtz noted that a similar arrangement with a single vertical slit instead of a V slit produces a rectangular spectrum in which the different color bands and Fraunhofer lines run vertically parallel to one another. The spectrum of an inclined slit is a parallelogram with two parallel horizontal sides and two sides parallel to the slit. In this inclined situation, the color bands and Fraunhofer lines run parallel in the direction of the slit. In the case of Helmholtz’s V slit the two spectra overlapped, with the two sets of color bands and Fraunhofer lines running in the directions of the slits. When viewed through the telescope, the area of overlap of the two spectra was a triangle, and within the triangle all the combination colors resulting from the mixture were visible. Beyond the edges of the triangle, in the remaining portion of each parallelogram, the spectral color admitted through each slit was visible. In this first approach to the problem Helmholtz did not attempt to provide a quantitative determination of the wavelengths of his color mixtures. He fixed crosshair lines in his telescope which he oriented at 45 degrees so that they ran parallel to the Fraunhofer lines. This enabled him to provide a qualitative estimate of the proximity of a color mixture to the dark lines in the spectra of the color bands entering the specific mixture. To compare the relative intensities of the two colors entering a particular mixture, Helmholtz noted that if the prism was rotated about the axis of the telescope, the surface area of the illuminated parallelogram changed, being greatest when the slit and prism were parallel. In that position the illuminated area was a rectangle. As the prism was rotated relative to the slit, therefore, the same quantity of light would illuminate a larger or smaller surface area, and appear correspondingly less or more intense. In the original position of the V slit the intensities of the two spectral colors were equal. By rotating the prism one could achieve all combinations of relative intensities of the two spectra.

Using this experimental design Helmholtz arrived at several remarkable conclusions. The first was that color mixtures formed from pigments or powders differ markedly from color mixtures formed from pure spectral colors. In contrast to the

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experience of painters for a thousand years, Helmholtz wrote, the mixture of blue and yellow spectra, for example, does not yield green but rather a greenish shade of white. The explanation, according to Helmholtz, is that a portion of the light falling upon a colored body is reflected back as white light, while of the portion that penetrates the body, one portion is irregularly absorbed while the remaining light is reflected from the back surface and taken by the observer as the color of the body. Similarly, in the case of powders most of the reflected light comes not from the surface but from deep within the body. If a blue and a yellow powder are mixed, the surface particles will reflect blue and yellow light, which will combine to form a greenish white (as in the case of the mixture of the pure spectral colors). This will be a small portion of the total reflected light, however. Only light that is not absorbed by the blue and yellow particles will be reflected back from within the body. Blue bodies allow green, blue, and violet light to be transmitted; yellow, on the other hand, only red, yellow, and green. Hence, the mixture of blue and yellow particles will allow only green light to be transmitted, and only green light will be reflected to the eye. Green light will predominate in the total mixture of reflected light and not greenish white as the mixture of the pure spectra. What happens when pigments are mixed, Helmholtz concluded, is that different rays of colored light are lost, rather than that colors combine. This is why when two pigments of apparent equal intensity are mixed, the mixture is darker. Only mixtures of pigments standing close to one another in the spectral series will yield colors close in intensity and hue to the mixture of the same spectral colors. The combination of spectral colors and the mixing of pigments rest on two different physical processes.\(^{10}\)

One aspect of the paper that attracted Grassmann's attention was the range of results achieved from mixing pairs of spectral colors. "The most striking of these results," Helmholtz wrote, "departs widely from the heretofore accepted facts; namely, that among the colors of the spectrum only two combine to produce white, being therefore complementary colors. These are yellow and indigo blue, two colors which were previously almost always thought of as producing green." It was because previous investigators had based their theories on mixtures of pigments rather than on the mixture of pure spectral colors that this incredible error had been propagated and reinforced. In his investigation of combinations of three colors (done by replacing the V slit with a lazy-Z slit) Helmholtz observed that it was possible to produce white from red, violet, and green, which in turn could be represented as three pairs of complementary colors: namely, red and a mixture of dim blue-green; green and a mixture of purple-red; violet and dim yellow. He noted that these results agreed with those Newton had reported in his *Opticks*.\(^{11}\)

Helmholtz also concluded that the least number of colors out of which the entire spectrum could be generated was five. He arrived at this result by trying to construct a color circle. As the best method of construction he favored Newton's procedure of producing each simple color by combining it from the neighboring colors on either side, but he restricted Newton's approach even further by adding that the distance between the two combining colors should not be too great. Otherwise, he said, the resulting intermediate shades would not match those of the spectrum. Proceeding in this manner, Helmholtz concluded that the minimal list of colors required to imitate


the spectrum was red, yellow, green, blue, and violet. "We must therefore drop the
theory of the three primary colors as primary qualities of sensation proposed by
Thomas Young."

Grassmann took issue with Helmholtz's claim that there is only one pair of com-
plementary colors. Contrary to this assertion, Grassmann set out to show that New-
ton's view was indeed correct: Every color has a complement with which it combines
to produce white light. Grassmann's mathematical demonstration of this claim was
remarkable for being built directly upon certain structural features of the perception
of color. He thus examined the purely phenomenal, mental side of color relations;
here was exactly the analogue of the problem of generating the spatial components of
visual experience from the phenomena. I cannot follow the tortuous details of
Grassmann's argument here. It suffices to observe that the "proof" must have seemed
strange to an experimentally oriented empiricist such as Helmholtz, for it proceeded
as a reductio ad absurdum. Instead of experimentally demonstrating that every color
has its complement, Grassmann proceeded in an abstract mathematical fashion by
attempting to show that if this were not the case, our concept of continuity and our
experience of the closure in the continuous transition of colors would be violated.13

Grassmann concluded the paper with a discussion of the rule for combining col-
ors. His purpose in this discussion—indeed, the primary objective of his entire cri-
tique of Helmholtz's work on color—was to show that the rule for combining colors
was not a straightforward application of an operation he called geometrical addition (for
all practical purposes equivalent to our vector addition), which was one of the central
operations of the new mathematical calculi developed in his Ausdehnungslehre
(see Figure 3). Grassmann went on to show that the method of geometrical addition
was fully equivalent to the method for mixing colors employed by Newton in his
Opticks, where the procedure is analogized to the problem in statics of finding the
center of gravity of two arbitrary weights. In Newton's method hue is represented as
a radius directed to the outside of a circular band of pure spectral colors, while the
intensity of the color entering a mixture producing white light is represented by the
weight hanging from the radius.

Grassmann's discussion of color mixtures led Helmholtz to rethink his own ap-
proach to the subject. Helmholtz believed that Grassmann scored several crucial
objections. Yet he still felt that Grassmann's paper contained a number of loose ends.
For one thing, he would have to reexamine his own treatment of complementary
colors. Inadequate instrumentation seemed to be the primary weak point. Indeed, in
his own paper Helmholtz had noted that a more refined instrumental arrangement
for projecting the color mixtures onto a larger surface area and an improved method
for measuring the distance of the color mixture from the nearest Fraunhofer line
might lead to different results concerning the composition of the whitish hues.14 But
Grassmann's argument was totally inadequate. Among the community of measure-
ment physicists Helmholtz respected, it was insufficient to establish a claim based

12 Ibid., p. 21.
repr. in Gesammelte mathematische und physikalische Werke, ed. F. Engel, 3 vols. (Leipzig: Teubner:
the Nineteenth Century: The Young-Helmholtz-Maxwell Theory (Bristol: Adam Hilger, 1981), for the
details of Grassmann's argument.
14 Helmholtz, "Über die Theorie der zusammengesetzten Farben" (cit. n. 9), pp. 13–14.
on an abstract mathematical argument without also demonstrating the result empirically. The production of white light from complementary spectral colors had to be demonstrated by an experiment. Furthermore, Grassmann's *reductio* argument depended upon assumptions about the discriminating power of the eye as a measuring device. These were extremely interesting physiological assumptions. But having made them, Grassmann left the plane of physiological argumentation altogether. A particularly glaring problem from Helmholtz's point of view was that Grassmann's mathematical technology began to drive his physiological argument: his mathematical methods led him to assume that *four* colors would be required to perform the parallelogram construction. Yet even in Grassmann's ingenious construction one of the colors, purple, was itself a mixture of red and violet. Perhaps *three* colors would indeed suffice. By wedding himself to a circle as the method for representing color spaces instead of a triangle, Grassmann had introduced some unnecessary, perhaps even unwarranted, assumptions. Furthermore, casting the argument in terms of a triangle might correspond more adequately to the physiology of the color perception. This too needed to be checked empirically. In any case, the entire issue of Young's theory was reopened and the theory of color mixtures given a decisively physiological dimension as a result of the encounter with Grassmann.

### III. HELMHOLTZ'S RECONSIDERATION OF COLOR MIXTURES

Helmholtz took up these issues in a paper entitled "Über die Zusammensetzung von Spectralfarben," published in *Poggendorff's Annalen der Physik und Chemie* in 1855, and in much expanded form in the *Physiologische Optik* in 1860. While experimental in character, the 1852 paper criticizing Brewster was qualitative in its approach. In his renewed attack on the problem Helmholtz sought to produce a fully quantitative theory of color mixtures by refining each component of his apparatus.
for viewing and mixing spectral colors. With his new instrument, in place of the qualitative mixtures of hues in the earlier experimental arrangement, Helmholtz could now measure the wavelengths of the complementary colors entering a mixture of white light.\textsuperscript{15} He could also experimentally control and quantitatively measure the intensities of the light entering a mixture. With this improved capability Helmholtz determined anew the series of complementary spectral colors. Consistent with Grassmann’s prediction he now was able to produce white from violet and greenish yellow, indigo blue and yellow, cyan blue and orange, greenish blue and red. He was, however, not able to produce white from mixing green with any other simple color, but only from mixing it with purple, “that is with at least two other colors, red and violet.”\textsuperscript{16}

Helmholtz represented these results in a graph relating complementary colors to one another as a function of their wavelengths (see Figure 4). From the graph it was immediately obvious why his V-slit arrangement could not have been expected to reveal colors complementary to red and violet: the transitions between the blue and green color bands proceed extremely rapidly, being represented as a nearly vertical line in the graph: thus these colors form extremely narrow bands difficult to detect in Helmholtz’s experimental arrangement. Indigo blue and yellow, on the other hand, had the advantage of being relatively wide bands of color.

These results also had certain consequences for the geometrical representation of the color table. Helmholtz now praised Newton’s use of the center-of-gravity method to represent the colors in a plane as one of the most ingenious of all his creative ideas.\textsuperscript{17} But Newton himself had proposed the rule as a mere aid for summarizing the phenomena in a qualitative manner and had not defended its correctness as a quantitative explanation. Grassmann’s contribution had been primarily to call attention to the mathematical assumptions underlying the center-of-gravity method, and his treatment had convinced Helmholtz that this was indeed the appropriate quantitative method to use. But he was not convinced that the color table should be represented as a circle. Grassmann’s analysis simply duplicated Newton’s assumptions. But in fact, the center-of-gravity method for mixing colors was compatible with many geometrical representations.\textsuperscript{18} To determine which of those representations fit the causal picture most closely, it was necessary to interpret the parameters in Grassmann’s model in terms of empirical measurements. Subjected to this requirement, the choice of a circle would no longer adequately fit the refined data Helmholtz had derived. In fact, the result was a completely different shape for the color space. Instead of a circle or a circular lumen, a representation consistent with the experimental measurements turned out to be a hyperbola-like curve with violet, green, and red at the vertices (see Figure 5).

Grassmann had stimulated Helmholtz to revise fundamentally his approach to the theory of subjective colors. Grassmann’s abstract, structural mathematical approach to these problems was indeed impressive. But while acknowledging that Helmholtz

\textsuperscript{15} For details on this innovative apparatus see Sherman, Colour Vision (cit. n. 13), pp. 81–90, 111–115.


\textsuperscript{17} Ibid., WA, p. 64; PO, p. 288.

\textsuperscript{18} See Helmholtz’s discussion and mathematical treatment ibid., PO, p. 287.
had profited from the interaction, we should also not overlook the object lesson Helmholtz was prepared to give Grassmann in relating abstract mathematical structures to the requirements of physics and physiology. A point Helmholtz would state explicitly in the next stage of his researches in sensory physiology was that to be meaningful in reference to a physical problem, an abstract structure had to be embedded in measurements, and its internal logic adapted to the requirements of that problem. That process of adaptation was achieved through a dialogue with the instruments, and the dialogue would result in a model of the physical system, in this case the physiological apparatus of the eye responsible for the production of color sensations. In his reference to Newton’s approach, Helmholtz made it clear that the proper mathematical or graphical representation of a system was not merely convenient or useful but rather corresponded to the causal properties of the physical system. Helmholtz’s color space was offered as such a representation of the physiological apparatus employed by the eye in measuring color.
IV. MUSIC TO THE EYE: PHYSIOLOGICAL ACOUSTICS, VISUALIZATION DEVICES, AND THE RECEPTOR HYPOTHESIS

It is tempting to assume that Helmholtz reversed his stand on Young's theory of color vision in the course of writing up the new experiments central to the 1855 paper. However, the original paper says nothing about the three-receptor theory. Indeed, Helmholtz stated in a footnote for the version included in his Wissenschaftliche Abhandlungen that his first recorded support of the Young hypothesis appeared in the third part of the Physiologische Optik, published in 1860.\(^{19}\) Nothing about the encounter with Grassmann would have forced him to reverse his position on the physiological bases of colors. That dispute had confirmed Newton's center-of-gravity method for determining color mixtures but led Helmholtz to conclude that the color chart should be represented geometrically as a shape approaching a conic section rather than as a circle, as both Newton and Grassmann had assumed. Nothing concrete had been determined about the physiological causes of color mixtures. Helmholtz had shown that any three colors would suffice to generate the color chart, but those methods did not specify which three colors must be associated with the color receptors in the retina. Helmholtz had established, furthermore, that the center-of-gravity method for representing color combinations was indeed useful, but he wanted to go further and establish that its underlying principles embodied a more general calculating apparatus for the representation of sensations; that is, he wanted

\(^{19}\) Helmholtz, "Über die Zusammensetzung von Spectralfarben," WA (cit. n. 16), p. 70.
to establish it as a psychophysical principle as well. What led Helmholtz to change his mind about the Young hypothesis between 1855 and 1860? How did he arrive at red, green, and violet as the three primary physiological colors?

Neither unpublished materials, nor experimental notebooks, nor correspondence answers these questions unequivocally. I suggest that work in physiological acoustics and a concerted effort to analogize the eye and ear provided the grounds for Helmholtz’s reevaluation of the Young hypothesis. Strong support for this suggestion comes from a series of popular lectures Helmholtz delivered in Cologne in 1868 on the recent progress in the theory of vision, in which he tried to convince his audience that the three-receptor hypothesis was plausible by analogy with the sensations of tone:

I have myself subsequently found a similar hypothesis very convenient and well suited to explain in a most simple manner certain peculiarities which have been observed in the perception of musical tones, peculiarities as enigmatic as those we have been considering in the eye. In the cochlæa of the internal ear, the ends of the nerve fibers, which lie spread out regularly side by side, are provided with minute elastic appendages (the rods of Corti) arranged like the keys and hammers of a piano. My hypothesis is that each of these separate nerve fibers is constructed so as to be sensitive to a definite tone, to which its elastic fiber vibrates in perfect consonance. This is not the place to describe the special characteristics of our sensations of musical tones which led me to frame this hypothesis. Its analogy with Young’s theory of colors is obvious, and it explains the origin of overtones, the perception of the quality of sounds, the difference between consonance and dissonance, the formation of the musical scale, and other acoustic phenomena by as simple a principle as that of Young.20

The passage presents the order of discovery as if the Young three-receptor hypothesis suggested exploring a similar mechanism for hearing, but my claim is that the actual order was just the reverse. The internal evidence of Helmholtz’s papers between 1855 and 1860 argues instead that his work in physiological acoustics supported the receptor hypothesis before he took up the line of investigation that established the receptor theory in physiological optics. In addition, the papers published in this period indicate that the juxtaposition of these two sensory modalities, the back-and-forth comparison of models in one domain with those in the other, guided Helmholtz toward the reversal of his earlier position on Young’s trichromatic receptor hypothesis. Moreover, it was his work in physiological acoustics that drew most directly on the new telegraph technologies, and it was through the sound-light analogy that these technologies influenced Helmholtz’s theory of color vision.

The analogy between physiological acoustics and color vision presumed that just as in the ear a set of fundamental or primary tones is objectively based in the rods of Corti, so in the eye a set of primary colors is based in specific nerve endings in the rods and cones. Neither assumption could be established in humans, although some evidence from comparative anatomy supported the analogy on the side of physiological acoustics. The analogy between eye and ear was a salient feature of Helmholtz’s work on physiological acoustics. Comparisons between eye and ear are prominent in his first extended acoustical study in 1856, and they abound in the

first edition of his *Tonempfindung*, or *Sensations of Tone*, published in 1863. Such analogies were by no means new, and Helmholtz was certainly familiar with similar comparisons made by other authors. He had followed work on physiological acoustics for several years, writing the reports on advances in the field for the *Fortschritte der Physik* in 1848 and 1849. Central among the works he reported on in those years, and influential for all his later work in acoustics, were the papers of August Seebeck on the siren and on resonance phenomena. Although the comparison was not a main concern of his researches, Seebeck assumed that under certain circumstances transverse (light) and longitudinal (sound) waves behave similarly, and he had proposed an optical analogue to acoustical resonance, suggesting that resonance of spectral colors with vibrating molecules in groups of nerves in the retina was the mechanism for the sensation of brightness.

The specifics of earlier uses of the analogy between vision and hearing and their speculated mechanical and physiological bases do not concern me here. It is striking, however, that Helmholtz took up physiological acoustics in earnest in 1855, precisely at the time he was searching for anatomical and physiological bases for the trichromatic theory. The analogy seems to rely on the discovery in 1851 by Alfonso Corti of the cochlear membrane that bears his name. Helmholtz set forth the central elements of his approach to physiological acoustics in two papers on combination tones published in 1856. His goal was to establish that all musical tones are compounded from a set of fundamental, simple tones. In the report of this research to the Berlin Academy of Sciences Helmholtz explicitly deployed an analogy between spectral colors and primary tones: “In analogy to the primary colors of the spectrum we intend to call such tones simple tones in contrast to the compound tones of musical instruments, which are actually accords with a dominant fundamental tone.”

The objective Helmholtz set for his acoustical investigations turned on issues much like those that had prevented him from further developing the Young three-receptor hypothesis: He wanted to determine that the mathematical form of the physical description of hearing had a material, physical basis in the physiology of the ear. Helmholtz wanted to show not just that Fourier analysis is a useful mathematical tool for representing the phenomena, but rather that the ear itself is a Fourier analyzer; that, like spectral colors, primary tones have an independent objective existence; and furthermore that combination tones as well have an objective existence, that they are not simply a psychological phenomenon.

The theorem of Fourier here adduced shows first that it is mathematically possible to consider a musical tone as a sum of simple tones, in the meaning we have attached to the words, and mathematicians have indeed always found it convenient to base their acoustic investigations on this mode of analysing vibrations. But it by no means follows that we are obliged to consider the matter in this way. We have rather to inquire, do these

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partial constituents of a musical tone, such as the mathematical theory distinguishes and the ear perceives, really exist in the mass of air external to the ear? ... [T]herefore, we shall inquire whether the analysis of compound into simple vibrations has an actually sensible meaning in the external world, independently of the action of the ear, and we shall really be in a condition to show that certain mechanical effects depend upon whether a certain partial tone is or is not contained in a composite mass of musical tones. The existence of partial tones will thus acquire a meaning in nature, and our knowledge of their mechanical effects will in turn shed a new light on their relations to the human ear.\textsuperscript{24}

It was possible to show that theory corresponded to experiment when one examined a vibrating string, such as a piano wire. Helmholtz noted that in most other cases, however, the “mathematical analysis of the motions of sound is not nearly far enough advanced to determine with certainty what upper partials will be present and what intensity they will possess.”\textsuperscript{25}

This inadequacy of theory to analyze a given wave form into its components was particularly evident in the determination of tone quality or timbre, the character that distinguishes a violin from a flute or clarinet. The same tone produced at the same intensity will sound characteristically different depending on which instrument produced it. Helmholtz made the plausible assumption that tone quality was determined by the form of the sound wave,\textsuperscript{26} and devoted much of his subsequent investigations to elucidating the relation between the form of the sound wave and tone quality. Noting that the problem had been solved for only a few isolated cases,\textsuperscript{27} he compensated for the defect in theory by resorting to resonators and a variety of devices for visualizing the form of a sound wave and mechanically analyzing it into its constituent primary tones. He introduced this empirical method of attacking the problem in the first edition of his \textit{Sensations of Tone} in 1863:

No complete mechanical theory can yet be given for the motion of strings excited by the violin-bow, because the mode in which the bow affects the motion of the string is unknown. But by applying a peculiar method of observation proposed in its essential features by the French physicist [Jules] Liassaud, I have found it possible to observe the vibrational form of individual points in a violin string and from this observed form, which is comparatively very simple, to calculate the whole motion of the string and the intensity of the upper partial tones.\textsuperscript{28}

Helmholtz’s investigations in these years were guided by the ever-present analogy of eye and ear. The encounter with Grassmann had netted the important point that the sensation of color is determined by three variables: brightness, hue, and saturation. Tone was analogous in being similarly determined by three variables: loudness, pitch, and tone quality (timbre). Although light and sound were different types of wave phenomena, brightness and loudness were both associated with amplitude, and

\textsuperscript{24} Hermann Helmholtz, \textit{Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik} (Brunswick: Vieweg, 1863), trans. Alexander J. Ellis, as \textit{On the Sensations of Tone as a Physiological Basis for the Theory of Music} (London: Longmans, Green, 1885), 2nd ed., pp. 35–36.

\textsuperscript{25} \textit{Ibid.}, p. 55.

\textsuperscript{26} \textit{Ibid.}, pp. 19, 21.


\textsuperscript{28} Helmholtz, \textit{Sensations of Tone} (cit. n. 24), p. 80.
hue and pitch were dependent on frequency. To pursue the analogy further, tone quality would not depend on wave form. If, as we have seen, saturation was due to the mixture of colors entering the composition, then tone quality might plausibly be expected to result from the combination of primary tones. All tones are combinations of primary tones, and the timbre of musical instruments is characterized by a primary tone and numerous upper partial tones modulating it to produce a specific quality. The difference between these acoustic phenomena and the sensation of colored light is that the eye is incapable of distinguishing the components of any compound color in the sensation. The ear, by contrast, can be trained relatively easily to distinguish the component elements of a compound tone: "The eye has no sense of harmony in the same meaning as the ear. There is no music to the eye." Helmholtz's teacher, Johannes Müller, had argued that each sensory modality owes its particular quality—color in the case of the stimulated retina, sound in the case of the stimulated auditory nerve—to a "specific sense energy." Helmholtz sought to locate this difference in sensibility in the organization and mechanical functioning of the two organs; namely, in the case of the ear in the thousands of different fibers embedded within the membrane of Corti. He conceived of these fibers as each resonating with a different primary tone. Musical tones, then, would be combinations of these primary sensations.

To demonstrate that sound waves are composed in the way he hypothesized, Helmholtz resorted to instruments that "artificially" produced and visually displayed primary tones. He then compared the wave forms of, for example, notes bowed on a violin with the wave form of the primary tone. In similar fashion he compared the tones produced by horns or clarinets and the vowels produced by the human voice. The device he employed for producing the primary tones was a modification of the self-regulating current interrupter patented by his friend Werner Siemens as the basis for his improved telegraph. Described in the various patent applications as a kind of oscillating fork, the interrupter was meant to insure the synchronous operation of different parts of the telegraphic apparatus and the constancy of the translation of the message relayed between several telegraph instruments. In place of the spring and oscillating lever by which Siemens's instrument interrupted a continuous direct current, Helmholtz introduced a tuning fork (see Figure 6). Electromagnets near the ends of the fork alternately attracted the ends of the fork, made contact, and transmitted pulses of current at the frequency of the fork. These current pulses were transmitted to a second apparatus in which a tuning-fork was placed between the poles of an electromagnet activated by the incoming pulses (see Figure 7).

29 Ibid., p. 19.
Extremely low prime tones were required, which entailed using forks whose tones were barely audible. These tones were amplified by placing a resonator tuned to the proper frequency near the fork. By connecting these resonator devices, Helmholtz was able to combine numerous partial tones into tones indistinguishable from those produced by musical instruments (see Figure 1, p. 184 above).

Helmholtz described several methods for making auditory vibrations visible. The first he termed the "graphic method," to "render the law of such motions more comprehensible to the eye than is possible by lengthy verbal descriptions." He illustrated the graphic method with the phonautograph, which consisted of a tuning fork with a stylus on one prong of the fork. The vibrating fork produced a curve on paper blackened with lampblack and attached to a rotating drum, the same arrangement as in Carl Ludwig's kymograph or in Helmholtz's own myograph. The most dramatic of these visualization devices was the so-called vibrational microscope, an instrument embodying methods described first by Jules Lissajous for observing com-

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32 Helmholtz, Sensations of Tone (cit. n. 24), p. 20.
pounded vibrational motions. The microscope was constructed so that the objective lens was mounted in one of the prongs of a tuning fork. The eyepiece of the microscope was mounted on a plate so that the tube of the microscope was attached to the backing of the bracket holding the tuning fork. The prongs of the fork were set in vibration by two electromagnets just as in the interrupter and resonator described above. When the tuning fork was set in motion, the object lens would vibrate vertically in a line. When the microscope was focused on a stationary grain of white starch and the forks set in motion, a white vertical line would be seen. If the grain of starch was placed on a vertical string so that the grain was vibrating horizontally while the lens was moving vertically, the image viewed in the field of the microscope would be a line compounded of both motions inclined at 45 degrees (see Figure 8).

The principal use Helmholtz made of these instruments was to demonstrate that phase differences in primary tones making up a compound tone had no effect on the perceived quality of the tone. To make this argument he used the vibration microscope to study the form of waves compounded from primary tones out of phase with one another. Phase changes were produced in two ways: (1) by putting the tuning fork of the resonator out of phase with the interrupter; and (2) by putting the resonator out of phase with the resonator fork. Both the tuning fork of the resonator and the fork of the vibration microscope were set in motion by the same interrupter. Thus the pitch of the two forks was the same, both being determined by the number of interruptions of current per second. To change the phase of the fork in the resonator, Helmholtz placed small clumps of wax on the fork. He placed the fork of the vibration microscope in a horizontal position. The tuning fork of the resonator was placed vertically, with grains of white starch on one prong. Thus the object glass of the microscope vibrated vertically, while the grain of starch on which the microscope was focused vibrated horizontally. As the phase of the resonator fork altered,
the line visible in the field of the microscope shifted from a straight line inclined by 45 degrees (when the two forks were in unison) through various oblique ellipses until the phase difference reached one quarter of the period, and then passed through a series of oblique ellipses to a straight line inclined 45 degrees in the other direction from the vertical when the phase difference reached half a period—the first series of waveforms depicted in Figure 9. If the resonator fork chosen was the upper octave of the interrupter fork, phase alterations generated the second series of wave forms shown.\footnote{Ibid., p. 126.}

Helmholtz’s point in these experiments was that the form of the wave, here visibly evident in the vibration microscope, did not determine the quality of the tone. That quality was determined by the force of the impression on the ear, that is, on the amplitudes and primary tones entering the composition of the tone. As long as the relative intensities of the partial tones compounded into a musical tone remained the same, the tone would sound the same to the ear no matter how the alteration of phases of the partial tones affected the form of the wave. This last point was made evident through phase alterations controlled by shading the aperture of the resonator, the second method of altering phase mentioned above. In the experiments with the vibration microscope described above, for instance, as long as the resonator chambers were fully open, no difference of tone quality could be heard even though the phase differences produced by the wax clumps on the tuning fork would visibly alter the wave form. In a second series of experiments, without the microscope, Helmholtz brought the resonator out of tune with its fork by partially closing the lid on the aperture. He had shown in an 1859 paper that narrowing the aperture of the
chamber altered the phase of the wave. For the ear the effect of closing the lid was to diminish the loudness of the tone, it being loudest with the aperture fully open. The same effect of reducing the loudness of the partial tones could be achieved by leaving the apertures fully open and adjusting the movable resonator platform, $k$ in Figure 6, distanc ing the resonator from the tuning fork. Thus a compound tone could be produced either by combining partial tones and weakening the resonance by closing the aperture, or by weakening the partial tones through moving the chamber further away from the fork. The former approach altered the phase of combining tones, whereas the latter did not:

In this manner every possible difference of phase in the tones of two chambers can be produced. The same process can of course be applied to any required number of forks. I have thus experimented upon numerous combinations of tone with varied differences of phase, and I have never experienced the slightest difference in the quality of tone. So far as the quality of tone was concerned, I found that it was entirely indifferent whether I weakened the separate partial tones by shading the mouths of their resonance chambers, or by moving the chamber itself to a sufficient distance from the fork. Hence the answer to the proposed question is: the quality of the musical portion of a compound tone depends solely on the number and relative strength of its partial simple tones, and in no respect on their differences of phase.\(^{35}\)

These experiments and the crucial role of the vibrating microscope in particular were the basis of a direct comparison between the eye and ear. As the imaging device revealed, the eye is capable of detecting differences, even relatively minute differences, between wave forms. The ear is not. "The ear, on the other hand, does not distinguish every different form of vibration, but only such as when resolved into pendular vibrations, give different constituents."\(^{36}\) This conclusion emphasized several of the differences as well as the fundamental similarities in the mechanism of color vision and hearing. The reason the ear is able to distinguish the partial tones in a compound tone is that among the 4,500 or so different nervous fibers in the arches of Corti specific nerve fibers resonate in sympathetic vibration with the spectrum of primary tones composing musical tones. Simple tones of determinate pitch will be felt only by nerve fibers connected to the elastic bodies within the cochlear membrane whose proper pitch corresponds to the various individual simple tones. The fact that even amateurs paying minimal attention are able to distinguish the partial tones in a compound tone, and that trained musicians can distinguish differences of pitch amounting to half a vibration per second in a doubly accented octave, would thus be explained by the size of interval between the pitches of two fibers. Similarly the fact that changes in pitch can take place continuously rather than in jumps finds its explanation in the sympathetic vibration of arches with proper tones most nearly identical, while the elastic bodies in the membrane with more distantly separated proper tones were incapable of vibrating in resonance.

The physiological organization Helmholtz envisioned as the basis of tone

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35 Helmholtz, Sensations of Tone (cit. n. 24), p. 126 (italics in original).

36 Ibid., p. 128 (italics in original).
sensation was modeled directly by the tuning fork and resonator apparatus. Indeed, the full set of resonators and connected tuning forks was a material model of the ear in reverse. The resonator apparatus was used to produce compound tones artificially out of the simple tones generated by the tuning-fork interrupter. But this transmitting device could also be imagined to run in reverse as a recording device. In this sense it was a material representation of the functioning ear, its resonators being the material analogue of the fibers in the Corti membrane, its tuning fork and acoustical interrupter being the device for translating, encoding, and telegraphing the component primary tones of the incoming sound wave analyzed by the resonators.

Moreover, the representation rendered material by these communication technologies also provided a resource for understanding the differences between the eye and ear as well as a suggestion for further development in the theory of color vision: "The sensation of different pitch would consequently be a sensation in different nerve fibres. The sensation of a quality of tone would depend upon the power of a given compound tone to set in vibration not only those of Corti's arches which correspond to its prime tone, but also a series of other arches, and hence to excite sensation in several different groups of nerve fibres." Thus some groups of nerves would be stimulated through shared resonance, whereas other nerves would remain silent. The analogy to the eye and to Young's hypothesis was obvious:

Just as the ear apprehends vibrations of different periodic time as tones of different pitch, so does the eye perceive luminiferous vibrations of different periodic time as different colors, the quickest giving violet and blue, the mean green and yellow, the slowest red. The laws of the mixture of colors led Thomas Young to the hypothesis that there were three kinds of nerve fibres in the eye, with different powers of sensation, for feeling red, for feeling green, and for feeling violet. In reality this assumption gives a very simple and perfectly consistent explanation of all the optical phenomena depending on color. And by this means the qualitative differences of the sensations of sight are reduced to differences in the nerves which receive the sensations. For the sensations of each individual fibre of the optic nerve there remains only the quantitative differences of greater or lesser irritation.

The same result is obtained for hearing by the hypothesis to which the investigation of quality of tone has led us. The qualitative difference of pitch and quality of tone is reduced to a difference in the fibres of the nerve receptive to the sensation, and for each individual fibre of the nerve there remains only the quantitative difference in the amount of excitement.\(^{37}\)

The analysis of hearing seemed to suggest that just as the myriad of musical tones capable of being distinguished is rooted in an organic Fourier analyzer that yields specific elemental sensations, so the eye in similar fashion could be conceived as generating color from a primary set of sensations rooted in specific nerve fibers. The delicate power of distinction the ear is capable of was explained in the large number of specific nerve fibers and related elastic resonating bodies in the Corti membrane. The inability of the eye to resolve colors into elemental sensations would be explained accordingly as a result of the small number of different types of sensitive nerve fiber, and by the assumption that all three nerve types respond in different degrees to light stimulation. The assumption that fibers predominantly sensitive to red, green, or violet light nonetheless respond weakly to light of other wavelengths

would explain the continuity of transitions in the sensation of color as well as the inability of the attentive mind to analyze compound light into its elements. There is no music to the eye, because the eye has only three rather than the roughly 1,000 "resonator" types of the Corti membrane. Here was a remarkable feature of the Helmholtz-Young hypothesis that could be tested empirically. From the point of view of Grassmann's theory of color mixtures, any three colors that could combine to produce white would be satisfactory choices for producing the color space. From the perspective of the assumed physiological mechanisms of the Helmholtz-Young hypothesis, the most-saturated colors should be those generated by the primary receptors. Experiments aimed at diminishing or eliminating the activity of one or two of the color-sensitive nerve endings in the retina would thus provide support for the distinction between three different nerve types as well as dramatic evidence for the choice of red, green, and violet as the three primary physiological colors.  

VI. CONCLUSION

I have argued that the new media technologies that captivated the interest of Helmholtz and his young friends in the Berlin Physical Society, particularly the telegraph and a variety of new audio and visual inscription devices, were crucial in establishing the boundaries for his experiments in physiological optics and physiological acoustics. These new devices provided the means for delimiting the domain of scientific objects in a form in which they could be differentiated (and hence characterized), manipulated, and recombined. We miss the significance of these devices for producing traces, however, if we regard them simply as instruments for testing theoretical claims and resolving disputed issues, such as the dispute over Young's hypothesis, or the debate on whether musical tones have an objective existence independent of the ear. I have attempted to show that the new technologies were a resource for representing the scientific object, and that in their material form they were not just "representatives" of an object described by theory; rather they created the space within which the scientific objects, "eye and ear," existed in a material form. These technologies of representation exceeded the power of theory. By this I do not intend that theory carried Helmholtz only so far and that the technologies of representation then provided a mere supplement enabling the extension of research into areas where theory was insufficient to tread. Rather, I have been suggesting that we need to pay closer attention to the materiality of the inscription devices themselves and to the manner in which they are actually constitutive of the signifying scene in technoscience.

We are used to speaking about the relation of theory to its object as if the scientific instrument and experimental system were somehow a passive and transparent medium through which the presence of the object is to be achieved. The instrument, in our traditional manner of speaking, is simply an extension of theory, a mere supplement, useful for exteriorizing an ideal meaning contained within theory. When we treat the experimental system as a model of the theory, we tend to regard it simply as an expression, an unproblematic translation of the ideal relations and entities of the theory into the representative hardware-language of the experimental system. But this manner of proceeding neglects the empirical, material character of the

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experimental system as a graphic trace, a *grapheme*, in Jacques Derrida's sense. This exterior materiality is not molded to the demands of theory; it resists and imposes its own constraints on the production of meaning. As Derrida notes, "the outside of indication/indexicality does not come to affect in a merely accidental manner the inside of expression. Their interlacing (Verflechtung) is originary." 39 In Derrida's view, there is never a "mere" supplement; the supplement, in this case, the materiality of the experimental system, is a necessary constituent of the representation.

The Derridean perception is useful in understanding Helmholtz's experimental strategies. In the quoted passage and elsewhere Derrida refers to the material character of the signifier, the set of marks on the page of written text. In order to extend this line of thinking to Helmholtz's scientific theorizing, I suggest that we consider the centrality to Helmholtz's work of the graphic method and of the products of technologies for visualization such as spectral collimators (the V- and Z-slit experiments) and the Lissajous figures in the vibrational microscope; particularly important is the manipulability of elements of physical models such as the system of tuning-fork resonators, which both physically and graphically (via the vibrational microscope) represent the sensation of tone. In Derrida's terms, the materiality of these signifiers was nonaccidental in structuring the content of Helmholtz's sensory physiology. As Helmholtz noted, mechanical theory was insufficient for depicting in detail how the ear functions when sensing tone quality. The mathematization of the theory of resonance in terms of Green's function and Fourier analysis did not indicate whether phase difference and wave form should affect tone quality. By using the tuning fork and resonator device coupled with the interrupter and vibrational microscope, however, one can depict visually the relationships central to the production of timbre. The device did not merely enable Helmholtz to provide a more detailed graphic representation of the elements involved in producing tones of different timbre; more important, the representation of the ear as tuning-fork resonator linked to a telegraphic device became the object upon which he experimented to correct an assumption about wave form held by most physicists, enabling him to arrive at a deeper understanding of the sensations of tone. The representation thus fundamentally affected the articulation of theory.

I have also suggested that the selection of telegraphic apparatus and its modification in various ways to achieve the ends of experiment had a significance beyond the fact that these devices were readily available and familiar objects of investigation for Helmholtz. Telegraphic devices were not only important as means for representa-

tion and experiment; telegraphy embodied a system of signification that was central to Helmholtz's views about mental representations and their relationship to the world. I have suggested that apart from the challenge to his own early work and the adaptation of Grassmann's approach needed to make it relevant to physiological modeling, Grassmann's proposal of a formalism that operated in terms of three quantifiable measures was of interest because it was a system, based on the notion of n-dimensional manifolds, for constructing spatial representations that operated similarly to the way messages were encoded in the telegraph. Viewed in this light, the telegraphic system with which Helmholtz was familiar in his daily experience and upon which he and his friends frequently reflected was a materiality conditioning the choice and development of his own ideas about representation:

Nerves have been often and not unsuitably compared to telegraph wires. Such a wire conducts one kind of electric current and no other; it may be stronger, it may be weaker, it may move in either direction; it has no other qualitative differences. Nevertheless, according to the different kinds of apparatus with which we provide its terminations, we can send telegraphic dispatches, ring bells, explode mines, decompose water, move magnets, magnetise iron, develop light, and so on. So with the nerves. The condition of excitement which can be produced in them, and is conducted by them, is, so far as it can be recognised in isolated fibres of a nerve, everywhere the same, but when it is brought to various parts of the brain, or the body, it produces motion, secretions of glands, increase and decrease of the quantity of blood, of redness and of warmth of individual organs, and also sensations of light, of hearing, and so forth. Supposing that every qualitatively different action is produced in an organ of a different kind, to which also separate fibres of nerve must proceed, then the actual process of irritation in individual nerves may always be precisely the same, just as the electrical current in the telegraph wires remains one and the same notwithstanding the various kinds of effects which it produces at its extremities. On the other hand, if we assume that the same fibre of a nerve is capable of conducting different kinds of sensation, we should have to assume that it admits of various kinds of processes of irritation, and this we have been hitherto unable to establish.

In this respect then the view here proposed, like Young's hypothesis for the difference of colors, has still a wider signification for the physiology of the nerves in general.40

Helmholtz's work in physiological acoustics relied on the materiality of the representation of the ear as tuning-fork resonator. The juxtaposition and comparison of differences between media, between hearing and vision, was a positive resource for revisiting Young's hypothesis. Indeed, as the above passage implies, the analogy between the Young hypothesis for color vision and Helmholtz's model for hearing and the assimilability of both to the telegraph as apparently generalizable for sensory physiology provided convincing support for the analogical approach. For Helmholtz the construction of the color chart as a graphical representation embodied the very principles used by the eye in encoding signals perceived as color in the brain. In his studies on tone sensation Helmholtz had constructed a mechanical simulacrum for advancing his theory. In the final stages of his work on color vision the graphic trace itself became both the material embodiment of theory and the source of its improvement.

40 Helmholtz, Sensations of Tone (cit. a. 24), p. 149.