The Young-(Helmholtz)-Maxwell Theory of Color Vision*

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Abstract

In the second volume of the *Handbuch der physiologischen Optik*, published in 1860, Helmholtz sets out a three-receptor theory of color vision using coterminal response curves, and shows that this theory can unify most phenomena of color mixing known at the time. Maxwell had publicized the same theory five years earlier, but Helmholtz barely acknowledges this fact in the *Handbuch*. Some historians have argued that this is because Helmholtz independently discovered the theory around the same time as Maxwell. This paper argues that this hypothesis is implausible. By writing what he did in the *Handbuch*, Helmholtz (purposefully or not) influenced the field's perception of its own history. As a result, Helmholtz has received more recognition for his contributions to the field of color mixing than was his due, and Maxwell less.

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1 Introduction

The 1850s saw a revolution in the theory of color vision. In 1850 what was available was a jumble of observations and theories, not all of which were compatible, and a lack of direction for the field (surveyed in section 2). In 1860, with the appearance of the second volume of Hermann von Helmholtz's *Handbuch der physiologischen Optik*, the old observations (as well as new ones obtained through experiments in the 1850s) have been unified and explained by a single theory. This theory has come to be known as the Young-Helmholtz theory of color vision.

The progress made in the 1850s was due largely to two men: Helmholtz and James Clerk Maxwell (sections 3 and 4). But in the *Handbuch*, Helmholtz gives Maxwell surprisingly little credit (section 5). In particular, Helmholtz ascribes the crucial idea ("coterminal response curves") to both Maxwell and himself even though Maxwell appears to have clear priority. Historians of science have wondered why this might be. Some of these historians have argued that Helmholtz independently discovered the crucial idea.

In this paper I consider the case for Helmholtz's independent discovery of the idea of coterminal response curves (in section 6). I argue that several implausible assumptions have to be made to support this case (in section 7). Moreover, I argue that the opposite view—no independent discovery—is not as implausible as it has been made out to be (in section 8). It appears that Maxwell's work on color vision has become the victim of some revisionistic writing of the history by Helmholtz.

2 Scientific Background

In 1850, the field of color mixing was in disarray. Since Newton, a number of different experimental traditions had sprung up, which produced apparently incompatible results (this section follows Kremer 1993, section 4, which contains further references).

Newton had done various experiments with prisms and lenses, separating and recombining light. He had found that white light could be produced by mixing light of different colors, although at least four different colors seemed to be needed to do this. Newton also mixed pigments. He and his contemporaries assumed that mixing colored pigments would yield the same results as mixing light of the same colors. He explained away the observation that mixing pigments that would yield white when mixed as light appeared gray rather than white.

Kremer (1993) distinguishes five traditions of color mixing before 1850, all based to some degree in Newton's work. The first was very practical, addressing itself to painters. This tradition was concerned with pigments only. It identified three primary colors, usually red, yellow, and blue, from which all other colors could be mixed (with white and black pigments added to vary saturation).

A second tradition used so-called color wheels to mix colored light. The color wheel is a disc with different sectors painted in different colors. By spinning the wheel and shining light on it, mixed colors are obtained ("successive intermixture"). In this tradition it was commonly observed that white light could not be produced in this way.

The third tradition, led by Christian Ernst Wünsch, mixed colored light using prisms and lenses ("simultaneous intermixture"). Wünsch claimed, contrary to Newton, that mixing pigments and mixing lights do not yield the same results. Moreover, he was able to produce white light using fewer "ingredients": combinations of four, three, or sometimes only two colored lights, such as violet and "greenish yellow", or red and blue. Wünsch proposed that the solar spectrum consisted of three colors in partially overlapping beams, but differed from the painters' tradition in naming red, green, and violet as the primary colors.

The fourth tradition had a more physiological focus: rather than the nature of light, it was interested in the way the eye and the brain contribute to color sensation. Thus, it experimented with light of different colors entering different eyes (e.g., by looking at a white field through colored glass, but using different colors for the left and the right eye). The results were unstable: often the observer would see the two colors separately, with now one color dominating and then the other. Only some observers saw mixed colors, and only under some circumstances. This tradition thus appeared to be unproductive.

The fifth and final tradition was also focused on physiology, but it was less experimental and more theoretical. Descartes, Newton, and others had suggested that the eye works via vibrations in the retina caused by light. The frequencies of the vibrations were supposed to correspond to light of different colors. The combination of the different vibrations caused by a light beam containing multiple colors was supposed to happen in the brain.

Building on this, Karl Scherffer proposed that different retinal elements might be associated with these different vibrations. However, this would mean that there would have to be infinitely many retinal elements, if Newton's claim that (sun)light consisted of infinitely many homogeneous rays was maintained. Then George Palmer suggested, as Wünsch would, that light consisted of only three homogeneous rays (red, yellow, and blue for Palmer). But he added to this the hypothesis that there are three retinal elements, each of which is set in motion by only one type of ray. Mixed light stimulates more than one of these elements, thus producing the sensation of a mixed color, with equal stimulation of the three elements corresponding to white.

Thomas Young, although unaware of Scherffer and Palmer, proposed a theory that combined features of both. He allowed light to come in a continuum of frequencies, thus maintaining infinitely many homogeneous rays, but postulated only three types of receptors in the eye. Like Palmer, Young (1802a, p. 21) associated the three receptors with red, yellow, and blue; but Young (1802b, p. 395) changes this to red, green, and violet, like Wünsch (a point which Kremer 1993 fails to mention). Homogeneous light stimulates one receptor or two (with the ratio between the stimulations of the two receptors determining the color perceived). Stimulation of all three receptors in roughly equal proportions is perceived as white. However, and this will be crucial, Young excludes the possibility that one homogeneous ray (light of a single frequency) might stimulate all three receptors.

Although Young merely hints at it, his theory is of particular interest in explaining color blindness (as is Palmer's). The theory readily suggests that color blindness can be explained as a defect in one of the three types of receptors. From this perspective there was some discussion of Young's theory before the 1850s, but not much progress was made.

3 1852: Helmholtz Rejects Young

In his first paper on color mixing, Helmholtz (1852a,b, the latter being the English translation) attempts to create some order in the chaotic field of color mixing. As the central question he considers the nature of "primary colors".

He contrasts three views. First, a physical view, in which the primary colors refer to the way light is constituted, which he attributes to Mayer and Brewster, but was also held by Wünsch and Palmer as I noted above. Second, a physiological view, in which the primary colors refer to "modes of sensation" that are features of the eye rather than light (Young's view). And third, a neutral view on which primary colors allow "the formation of all others from their combination" (Helmholtz 1852b, p. 522).

After reporting some experiments, Helmholtz draws three conclusions, although he would only maintain the first one in later work. The first conclusion distinguishes mixing light ("additive mixing") from mixing pigments ("subtractive mixing"). Pigments act as filters that only reflect light of certain colors, while other light is absorbed. Mixing pigments leads to less color being reflected, and the eye perceives only the remainder, hence the mixing has subtracted some color from the light.

The second conclusion is that at least five colors are needed to combine light of all colors seen in the spectrum. If one attempted to use three primaries to do this, they would have to be red, green, and violet (not red, yellow, and blue) because green could not be obtained as a mixture. But the yellow and blue produced by mixing these three is less saturated than that observed in the spectrum. Hence all five are needed.

The third conclusion is that Young's physiological theory of the primary colors needs to be rejected. Helmholtz's argument is this. If the sensation of yellow obtained by looking at a yellow ray of light from the spectrum is due to its simultaneous stimulation of the red and green receptors in the eye, this sensation should be the same as would be obtained by mixing a red and a green ray of light from the spectrum. But this is empirically false: "by the latter we can never obtain so bright and vivid a yellow as that produced by the yellow rays" (Helmholtz 1852b, p. 533). Thus we are led to "abandon the theory of three primitive colours, which, according to Thomas Young, are three fundamental qualities of sensation" (Helmholtz 1852b, p. 533).

4 1855: Maxwell Adapts Young

In a paper first read in 1855, James Clerk Maxwell uses Helmholtz's experimental results as well as his own to come to the opposite conclusion (Maxwell 1857, Sherman 1981, chapter 8).

In his own experiments, Maxwell asked observers to compare (successive) mixtures of three types of colored light ("vermillion", "emerald green", and "ultramarine") to shades of gray. In this way he is able to quantify the ratios of the various colors needed to obtain other colors. This shows that colors can be decomposed into three variables. Maxwell (1857, p. 283) reaffirms Newton's claim of infinitely many homogeneous rays, and concludes that the decomposition must be a feature of the human eye rather than of physical light.

Thus Maxwell is led to Young's theory of three "modes of sensation". But Maxwell changes the theory in a small but crucial way by assuming *coterminal response curves*. That is, light of any color affects each of the three modes of sensation, albeit in different strengths: “the nerves corresponding to the red sensation are affected chiefly by the red rays, but in some degree also by those of every other part of the spectrum; just as red glass transmits red rays freely, but also suffers those of other colours to pass in smaller quantity” (Maxwell 1857, p. 283). Recalling that Young explicitly ruled out simultaneous stimulation of all three receptors by one homogeneous ray, it is clear that Maxwell changed the theory, although he does not say this himself.

Maxwell is keenly aware of the consequences of Young’s theory for color blindness, and devotes a significant portion of the paper to it. By asking people with color blindness to judge similarity of color in experiments much like those described above, Maxwell obtains quantitative data perfectly consistent with the assumption that in color blind people “the nerves corresponding to the red sensation” are missing or not working.

Moreover, he is able to extrapolate the exact sensation that is missing for the color blind. “The addition of this sensation to any others cannot alter it in their estimation. It is for them equivalent to black” (Maxwell 1857, p. 286). If the theory is correct, this “pure sensation” corresponds to what we would see if only the “the nerves corresponding to the red sensation” are stimulated. This pure sensation turns out to lie outside the solar spectrum; it is “more red” than the red of the spectrum. But this is further confirmation for the theory of coterminal response curves: by this theory the red of the spectrum stimulates all three modes of sensation, and thus appears less red than the (theoretical) pure sensation.

If this were not the case—that is, if the red and green of the spectrum were the purest possible forms of these colors—then we should expect a mixture of spectral red and spectral green to look identical to spectral yellow. But, Maxwell points out, Helmholtz (1852a) has observed that the mixture is less bright than spectral yellow, just as Young’s theory (amended with coterminal response curves) predicts. Thus the same evidence that led Helmholtz to reject Young’s theory is perfectly explained by it in Maxwell’s version.

Finally, Maxwell notes that the coterminal response curves make it difficult to investigate the pure sensations. "The determination of the exact nature of the pure sensations, or of their relation to ordinary colours, is therefore impossible, unless we can prevent them from interfering with each other as they do. It may be possible to experience sensations more pure than those directly produced by the spectrum, by first exhausting the sensibility to one colour by protracted gazing, and then suddenly turning to its opposite" (Maxwell 1857, p. 296). Here Maxwell proposes an experiment, which Helmholtz would soon carry out, and which could provide further support for the theory.

5 1860: Helmholtz Accepts Young

In 1860, the second volume of Helmholtz's *Handbuch der physiologischen Optik* appears (Helmholtz 1860 / 1925, the latter being the English translation). In it, he reverses his stand on Young's theory, relative to Helmholtz (1852a). Rejecting, as he did in 1852, the notion that physical light could somehow be reduced to three fundamental colors, he now accepts a physiological theory in which the eye contains "three distinct sets of nerve fibres":

> Objective homogeneous light excites these three kinds of fibres in various degrees, depending on its wave-length. The red-sensitive fibres are stimulated most by light of longest wave-length, and the violet-sensitive fibres by light of shortest wave-length. But this does not mean that each colour of the spectrum does not stimulate all three kinds of fibres, some feebly and others strongly; on the contrary, in order to explain a series of phenomena, it is necessary to assume that that is exactly what does happen. Suppose the colours of the spectrum are plotted horizontally in [figure 1] in their natural sequence, from red to violet, the three curves may be taken to indicate something like the degree of excitation of the three kinds of fibres, No. 1 for the red-sensitive fibres, No. 2 for

the green-sensitive fibres, and No. 3 for the violet-sensitive fibres. (Helmholtz 1860, pp. 291–292 / 1925, p. 143)

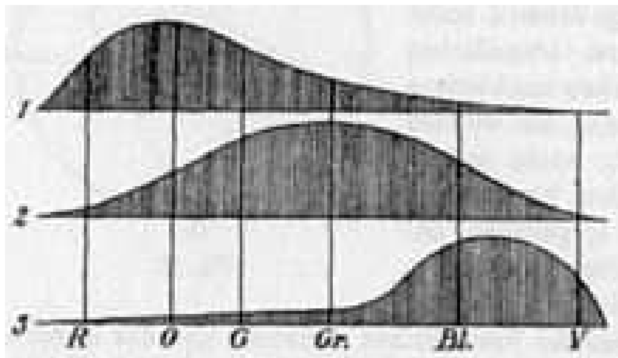

Figure 1: The three hypothesized coterminal response curves for the three "distinct sets of nerve fibres" (Helmholtz 1860, p. 291 / 1925, p. 143).

Clearly, Helmholtz now accepts Young's theory. Also clearly, the form in which he accepts it is identical to the form proposed by Maxwell (1857). It might be thought that Helmholtz adds something to the theory by proposing specific shapes for the response curves, but this would be mistaken. The figure is merely illustrative: Helmholtz made no attempt to measure the actual shapes of the response curves. In fact it was Maxwell who would perform the first experiments to measure these shapes (Maxwell 1860, Sherman 1981, pp. 207–208).

Later on in the *Handbuch*, Helmholtz applies the adapted version of Young's theory to various puzzles in physiological optics. Here he does add something compared to Maxwell's presentation, by showing that Young's theory, in this form, can account for a wide range of disparate color phenomena. Where Maxwell had only mentioned color blindness and the experiments of Helmholtz (1852a), Helmholtz added the Purkyně shift, color harmony, and subjective colors to the range of phenomena the theory could explain.

In a crucial passage, which the rest of this paper will try to explain, Helmholtz characterizes the nature of his and Maxwell's contributions to the theory of compound colors:

> Young's theory of the colour sensations. . . remained unnoticed, until the author himself and Maxwell again directed attention to it. (Helmholtz 1860, p. 307 / 1925, p. 163, notably Helmholtz did not change this phrase for the second edition)

This passage is surprising for two reasons. Firstly, it incorrectly suggests that Young's theory had been ignored between its first appearance in 1802 and Helmholtz and Maxwell's work in the 1850s (Sherman 1981, pp. 217–221). I will return to this point later.

Secondly, and more importantly for this paper, it suggests that Helmholtz and Maxwell are independent co-discoverers of the adapted version of Young's theory. This is very surprising at first glance: Helmholtz first proposes the theory in the *Handbuch*, which appears in 1860, five years after Maxwell has done the same. Moreover, by explicitly mentioning Maxwell—in fact, he includes Maxwell (1857) in the bibliography—he clearly shows awareness of Maxwell's priority. Yet, other than in the quoted line, Helmholtz never credits Maxwell for inventing the theory.

The *Handbuch* went on to become a classic textbook, and as such it had a big influence on how the history of the field of color vision came to be viewed. This is probably one of the main reasons why the adapted version of Young's theory is known as the Young-Helmholtz theory of color vision, where Young-Helmholtz-Maxwell theory (the name used by Sherman 1981) or even just Young-Maxwell theory may be at least as appropriate.

Kremer (1993, p. 207) points to the influence Helmholtz himself had on the history of this field when he writes: "Many earlier studies of Helmholtz's color research have, by following too closely Helmholtz's own accounts of the history of the field, overemphasized his originality. The stories of victors, however, may conceal as much as they illuminate."

In particular, could it be the case that Helmholtz in the *Handbuch* simply took Maxwell's proposal, presenting it and building on it without clearly attributing it to him? This is what Turner (1988, p. 141) suggests when he writes that "Helmholtz probably borrowed this insight [i.e., coterminal response curves] from Maxwell".

But Turner goes on to suggest an alternative: Helmholtz "may also have been led to it in part by a careful study of Fechner's early work" (Turner 1988, p. 141). Kremer (1993) takes up this hypothesis and argues in more detail that it is plausible that Helmholtz came to the adapted version of Young's theory independently of Maxwell (although Kremer thinks a careful study of Müller's work rather than Fechner's provided the impetus).

On this hypothesis, the fact that Helmholtz has received more recognition than Maxwell (as illustrated by the name "Young-Helmholtz theory") is simply a case of the Matthew effect (Merton 1968). According to the Matthew effect, when two scientists make a discovery (either independently or collaboratively), the better-known one will get more applause. In 1860, the 39-year-old Helmholtz, known for discovering the law of the conservation of energy and measuring the speed of the nervous impulse, was certainly better known than the 29-year-old Maxwell, with his famous work in physics still ahead of him.

The only two scholars who have seriously discussed the question (Turner and Kremer) seem to think that this is what happened. In the next section I discuss the evidence they present in favor of Helmholtz's independent discovery of coterminal response curves. In sections 7 and 8 I argue that they are mistaken, i.e., that Helmholtz did not come to the adapted version of Young's theory independently.

6 The Case For Independent Discovery

The fact of "Maxwell's clear priority in revising and accepting Young's hypothesis" (Kremer 1993, p. 241, see also Turner 1988, p. 141, and Turner 1994, p. 105) is undisputed. The question is thus not whether Helmholtz was first, but whether Helmholtz got the idea for the adapted version of Young's theory from Maxwell (1857), or whether he came up with it independently and Maxwell (merely) beat him by publishing it first. Kremer (1993, section 6) and Turner (1988, pp. 140–141) provide some reasons to believe the latter, which I will now examine.

The earliest explicit indication Helmholtz gives of the version of Young's theory with coterminal response curves is in a speech delivered in 1858 (Helmholtz 1858). Here Helmholtz describes experimental results concerning after-images. In particular, he observed that the sensation of a given color can be strengthened by staring at the complementary color first, the experiment suggested by Maxwell (1857, p. 296). The stenographic report of the speech (the only record) fails to mention Maxwell but includes the following relevant remark:

> The speaker already had concluded in his earlier works on color mixing that if Thomas Young's theory were correct, i.e., that there are three types of optic nerve fibers, red-sensing, green-sensing, violet-sensing, then the spectral colors would not be the most saturated colors which appear to the sensation of the eye; the investigations described herein were planned to test exactly this point. (Helmholtz 1858, p. c, the translation appears to be original work of Kremer 1993, pp. 241–242)

This prediction only follows if one uses the adapted version of Young's theory, since, as Helmholtz (1852a) himself had observed, the original version of Young's theory provides no reason to expect color mixing to lead to changes in saturation.

By 1858, Helmholtz must have been aware of Maxwell's work. The latter's essays were abstracted in *Fortschritte der Physik*, a review journal which Helmholtz wrote for (Kremer 1993, p. 241). Moreover, the experiment described matches Maxwell's suggestion so closely that Helmholtz almost certainly got the idea for it from Maxwell (1857).

So the fact that Helmholtz seems to have come to the adapted version of Young's theory by 1858 is not in itself a good reason to believe that he came to it independently of Maxwell. Rather, the interest in the 1858 speech lies in the phrase "The speaker already had concluded in his earlier works". Helmholtz appears to claim not only that he thinks *now* that Young's theory requires coterminal response curves to be workable, but moreover that he had *established* this in previous work.

What previous work could he be referring to? Since Helmholtz (1852a) is the only paper before 1858 in which Helmholtz so much as mentions Young's theory, it appears to be the only candidate. But of course the 1852 paper had rejected Young's theory (in its original form), saying nothing about alternative possible interpretations of that theory (see section 3). If Helmholtz (1858) "reinterpreted his 1852 paper, now claiming that he always had understood Young's theory to require coterminal responses" (Kremer 1993, p. 242), it is an extensive reinterpretation indeed. Helmholtz (1852a) provides no indication whatsoever of such an understanding.

Remarkably, Kremer finds an alternative possibility. When Helmholtz said that he had "already concluded in his earlier works" that coterminal response curves were needed, he may have been referring to his 1855 "Kant speech", which he gave in February, a month before Maxwell first presented his work. Here we find the following surprising claim: "If light of different colors is mixed, it excites an impression of a new color, a mixed color, which is always whiter and less saturated than the simple colors of which it is compounded" (Helmholtz 1855b, pp. 18–19, translated by Kremer 1993, p. 245).

The claim is surprising, because the 1852 paper had found that mixing lights of different colors gave light sometimes equally saturated, sometimes less saturated than the ingredients of the mixture. So, Kremer speculates, perhaps this comment "derived from some 'physiological law' about how the retina mixes colors, a law which Helmholtz now accepted but did not elaborate" (Kremer 1993, p. 245). The "physiological law", of course, being Young's theory amended with coterminal response curves.

If this is right, Helmholtz adapted Young's theory independently of Maxwell sometime between 1852 and 1855. What could have led him to this discovery? Turner (1988, pp. 140–141) suggests that it was through reading the work of G. T. Fechner on contrast and afterimages, while Kremer (1993, pp. 244–247) thinks that Helmholtz came to the view by relating it to his teacher Johannes Müller's law of specific sense energies. It is also possible that some combination of the two was responsible.

Fechner (1840) had speculated that whenever light of a certain color strikes the eye, this creates a "primary" sensation (of the color of that light) and a "secondary" sensation of the complementary color. He used this hypothesis to explain contrast effects and afterimages. He added that if the eye is fixed on a certain color long enough, fatigue diminishes the intensity of the primary sensation, leading the secondary sensation to become more prominent (relatively speaking), which makes the overall sensation tend to gray.

Turner (1988, p. 140) notes that this only works if "even a monochromatic light evokes a slight complementary response". So Fechner's work may be viewed as an anticipation of Maxwell's and Helmholtz's, in postulating (a) that every sensation of color is in fact a mixture of that color and its complementary color, and thus (b) that colors (at least under normal circumstances) are perceived in a less saturated form than they theoretically might. The latter claim, which Maxwell (1857) and Helmholtz (1860) note follows from their version of Young's theory and Helmholtz (1858) confirms empirically, is not explicit in Fechner. Still, it is implied by his view, and it may have (partially) spurred Helmholtz to accept Young's theory.

Alternatively or additionally, it may have been Müller's law of specific sense energies that led Helmholtz to adapt Young's theory. This law states that stimulation of sensory nerves always leads to the same effect in sensation, regardless of the way the nerve is stimulated (Müller 1826). It is not a peculiar feature of light that it leads to the sensation of color, but rather a peculiar feature of the nerves in the eye. Thus the sensation of color is also produced by physical pressure on the eye. And conversely, light that strikes the skin rather than the eye produces a sensation of heat rather than of color.

A problem for this view is the qualitative difference in color sensations. If light of different colors stimulates the nerves in different ways, this seems to go against the spirit of the "one nerve, one sensation" view. If different nerves exist for different colors, an infinite number of nerves would appear to be needed. Young's theory, with its three different kinds of nerves, can solve this problem, and Kremer (1993, pp. 245–246) notes that Müller anticipated a solution of this form.

Thus Young's theory appears as "only a more special application of the law of specific sense energies" (Helmholtz 1925, p. 145). Helmholtz would, in this version of the story, have missed this fact in 1852. But when he was preparing the Kant speech early in 1855, which discussed Müller's law extensively, he would have come to this realization. Moreover, he would then have noticed that an adapted version of Young's theory could account for the experimental results of Helmholtz (1852a), and seen as one of its consequences that light mixtures are "always whiter and less saturated", a comment which he included in the Kant speech immediately after discussing Müller's law (Helmholtz 1855b, p. 18).

7 Problems With the Case For Independent Discovery

The claim from the 1858 speech, that Helmholtz had "already concluded in his earlier works" that coterminal response curves were needed to make Young's theory work, in itself proves very little. If Helmholtz made the discovery independently, that explains the comment. But if he did not, it merely shows that Helmholtz was already in 1858 committed to his cause of understating Maxwell's contribution and overstating his own, as he would do in the *Handbuch*.

The crucial question is thus whether these "earlier works" in fact exist. Although Helmholtz (1852a) is the only paper before 1858 that explicitly discusses Young, it is not a viable candidate, as it explicitly rejects Young's theory in its original form and gives no indication whatsoever that an alternative form might save the phenomena observed. If the "earlier works" claim is to be vindicated, then it must be in the Kant speech (Helmholtz 1855b).

Five months before the Kant speech, in September 1854, Helmholtz presented a paper focusing on complementary colors (Helmholtz 1855a). Responding to criticism by Grassmann (1853) of Helmholtz (1852a), he refined his experimental methodology and was able to find seven pairs of complementary spectral colors (such that mixing homogeneous rays of the two colors yields white light), where in 1852 he had found only one. By comparing the relative intensities needed to create white light out of the complementary colors, Helmholtz was able to quantify the way color is mixed in the eye (see figure 2).

Recall the two conclusions from the 1852 paper that Helmholtz would reverse when he published the *Handbuch* in 1860: first, that at least five spectral colors are needed to mix the other colors in the spectrum out of, and second, that Young's theory must be rejected. Helmholtz (1855a) does not mention either of these. If Helmholtz had adopted the theory of coterminal response curves by September of 1854, surely he would have mentioned that in this paper, either by explicitly reversing his 1852 position on Young's theory, or at least by indicating that he no longer held that five colors were needed to mix the others, a consequence that would have been very relevant to mention in the context of this paper. Kremer (1993, p. 237) concludes, correctly I think, that "Helmholtz in late 1854 still viewed Young's three-receptor hypothesis with skepticism".

The reconstruction Kremer gives is thus the following. Until September 1854, Helmholtz rejects Young's theory. At some point between September and February, primarily inspired by thinking about Müller's law of specific sense energies (but perhaps helped by his own recent experiments on color mixing, and by the work of Fechner), he changes his mind. He notes that positing coterminal response curves turns Young's theory into a powerful explanatory tool.

He may or may not have seen immediately all the consequences of this view which he describes in the *Handbuch*. However, he must at least have noticed that his own experimental results from 1852 can be explained by it, and that it predicts that color mixtures are "always whiter and less saturated" than the original colors, a prediction which he incorporates in his speech (Helmholtz 1855b, p. 18).

Sooner rather than later, he must have heard about or read Maxwell (1857), which was first presented only a month later, in March of 1855. If Helmholtz had any plans to publish a paper on his adapted version of Young's theory, he now abandons these plans. Instead, he focuses on testing its predictions, such as color sensations more saturated than spectral colors (Helmholtz 1858), and on writing up a full-blown version of the theory and its consequences (Helmholtz 1860). On both occasions, he alludes to his independent discovery ("the speaker had concluded in his earlier works" and "the author himself and Maxwell directed attention") but does not insist on it.

Kremer's reconstruction is consistent and, I think, impossible to refute conclusively. However, the following features strike me as implausible.

First, on this reconstruction the time window for Helmholtz to make the independent discovery is extremely small (five months).

Second, as a result Helmholtz's independent discovery is almost simultaneous with Maxwell's discovery. While multiple discoveries are quite common in science (Merton 1961), this case is noteworthy because there was no recent experimental work that could have put them on the path toward the discovery (the most recent relevant work being Helmholtz 1852a and Grassmann 1853). It would thus be a complete coincidence that the idea of coterminal response curves occurs to Helmholtz as a result of studying Müller's law, just as Maxwell comes to the idea via his own independent investigations.

Third, in the Kant speech he states his newfound belief that color mixtures are "always whiter and less saturated" but feels no need to defend this claim, despite the fact that on this reconstruction it follows from a radical new theory he has recently discovered (such that even he himself would not have held this belief mere months ago).

Fourth, on this reconstruction the claim that Helmholtz (1858, p. c) "had already concluded in his earlier works on color mixing that if Thomas Young's theory were correct... then the spectral colors would not be the most saturated colors which appear to the sensation of the eye" would still come out as false. While Helmholtz would have indeed come to this conclusion, he never actually stated it in published work. If Kremer is right, this remark is an extremely oblique reference to his Kant speech, in which he stated a *different* consequence of the adapted version of Young's theory, without mentioning that he accepted it *because* it followed from Young's theory. Also, the work referred to is not actually "on color mixing": the Kant speech mentions color mixing only in that one sentence.

Fifth, even if it turned out to be technically true in some sense, the claim about conclusions drawn in earlier works is still unfair to Maxwell, who had explicitly (and in print) drawn the exact conclusion Helmholtz ascribes to himself (Maxwell 1857, p. 296).

Sixth and similarly, the *Handbuch* is unfair to Maxwell: even if Helmholtz independently discovered the same theory, Maxwell deserves full credit as an independent co-discoverer and the first one to publish. The vague remark that Young's theory "remained unnoticed, until the author himself and Maxwell again directed attention to it" (Helmholtz 1860, p. 307 / 1925, p. 163) belies these facts.

Finally, Helmholtz is also unfair to himself, by never saying explicitly that he had come up with the theory independently. If he really did come up with it independently, it seems much better to say so explicitly in the *Handbuch*, giving full credit to both Maxwell and himself, rather than skirting the issue.

None of these features that I find implausible are perhaps decisive. But they must be taken into account when weighing the plausibility of Kremer's reconstruction against the alternative, which I consider next.

8 The Case Against Independent Discovery

So what is the alternative? It is to apply Kremer's own claim that "earlier studies of Helmholtz's color research have, by following too closely Helmholtz's own accounts of the history of the field, overemphasized his originality" (Kremer 1993, p. 207) to the present case. It is to accept that, while Helmholtz made important contributions by bringing the adapted version of Young's theory to a wider audience and by expanding the range of phenomena to which it can be applied, it is Maxwell (1857) who deserves sole recognition for the discovery of the theory. Helmholtz (1858, 1860), purposefully or not, does not give Maxwell his due.

Here it should be recalled what the stakes and the incentives are for those involved. Credit (recognition, eponymy, etc.) for scientific discoveries is awarded in accordance with the *priority rule*: credit goes to the original discoverer (Merton 1957). There are no second prizes, except, perhaps, when the discoveries can be established to have been independent.

The priority rule is important to science in encouraging the rapid sharing of results and, it has been argued, in establishing an appropriate division of cognitive labor (Kitcher 1990, Strevens 2003). However, the pressure it places on scientists can sometimes lead to extreme behavior. Merton (1969) describes, among other cases, the lengths to which Newton went in his priority dispute with Leibniz over the invention of the calculus. In this case, it is now believed, both men had a genuine claim to independent discovery. But in his eagerness to defend his priority Newton established a committee to investigate the matter, loaded it with proponents of his own priority, and anonymously wrote a preface to their report. Merton (1969, p. 206 / 1973, p. 335) argues that "this was not so much because Newton was weak as because the newly institutionalized value set upon originality in science was so great that he found himself driven to these lengths".

So even well-established scientists, as Helmholtz certainly was in the late 1850s, may go to great lengths to claim priority for important results. In this light, I argue, it is not so hard to see how Helmholtz may have been led, consciously or unconsciously, to understate Maxwell's important contributions. Thus, in the *Handbuch*, when introducing the adapted version of Young's theory, Helmholtz does not attribute the theory to Maxwell, mentioning him only to say in passing that "Young's theory. . . remained unnoticed, until the author himself and Maxwell again directed attention to it" (Helmholtz 1860, p. 307 / 1925, p. 163).

On this alternative reconstruction, then, Helmholtz does not appear as an independent co-discoverer. Does this reconstruction have its own problems or implausible features? I can see three of them, but I will argue that each can to some extent be explained.

First, the comment in the stenographic report of Helmholtz's 1858 speech that "[t]he speaker already had concluded in his earlier works on color mixing that if Thomas Young's theory were correct. . . then the spectral colors would not be the most saturated colors which appear to the sensation of the eye" (Helmholtz 1858, p. c). My reconstruction rejects the notion that this is a reference either to Helmholtz (1852a), which says nothing remotely like this, or a reference to the Kant speech (Helmholtz 1855b), about which more in a moment. On my reconstruction the claim about earlier works is simply false. I offer two possible explanations of it.

First, it is possible that Helmholtz, already working on the *Handbuch*, had at this time decided he wanted to take some of the credit for the discovery of the adapted version of Young's theory. The comment is then explained as a deliberate attempt to establish to his peers the notion that the key ideas of that theory were (at least partially) due to him. While this affords a certain economy of explanation (the lack of recognition of Maxwell in this speech and in the *Handbuch* are both attributed to a consistent plan of Helmholtz's), it paints Helmholtz in a rather malicious light that I am not sure the evidence can support.

Hence the second explanation. Here I call attention to the fact that the comment about earlier works is from a stenographic report of a speech by Helmholtz, rather than from an article written and proofread by Helmholtz.

It is possible that Helmholtz meant to say that *Maxwell* had concluded that "if Thomas Young's theory were correct. . . then the spectral colors would not be the most saturated colors", which he in fact had: Maxwell (1857, p. 296) not only draws this inference but explicitly suggests the experiment that Helmholtz performs "to test exactly this point" (Helmholtz 1858, p. c).

If it is supposed that either Helmholtz misspoke or the stenographer misheard (admittedly a highly speculative supposition) then the comment makes perfect sense: rather than referring in a highly oblique manner to Helmholtz's earlier works, the comment would refer to Maxwell's earlier work, which says exactly what Helmholtz claims.

How does this compare to Kremer's explanation of the "earlier works" comment? Recall that Kremer explains it by relating it to a line in the Kant speech to the effect that a mixed color "is always whiter and less saturated than the simple colors of which it is compounded" (Helmholtz 1855b, pp. 18–19). While I have already indicated some reasons to think this explanation of the "earlier works" comment is implausible, it does present a problem for my reconstruction: how does Helmholtz come to this conclusion, quite different from what he said in Helmholtz (1852a)? This is the second problem I will consider.

I find the answer in Helmholtz's paper on complementary colors, presented in September 1854 (Helmholtz 1855a). By measuring the relative intensities of complementary colored lights needed to produce white, Helmholtz sketches a curve to represent the way color is mixed in the eye, shown in figure 2. The spectral colors appear on the edges, connected by a curved(!) line.

Helmholtz (1855a) is concerned only with complementary pairs, so he does not comment on this fact, but it seems plausible that he would have noticed that any mixture of (non-complementary) spectral colors will, due to the curve, end up somewhere in the interior of the diagram, i.e., closer to white (note that Helmholtz rejects purple as a spectral color for independent reasons, so the straight line from violet to red does not invalidate my

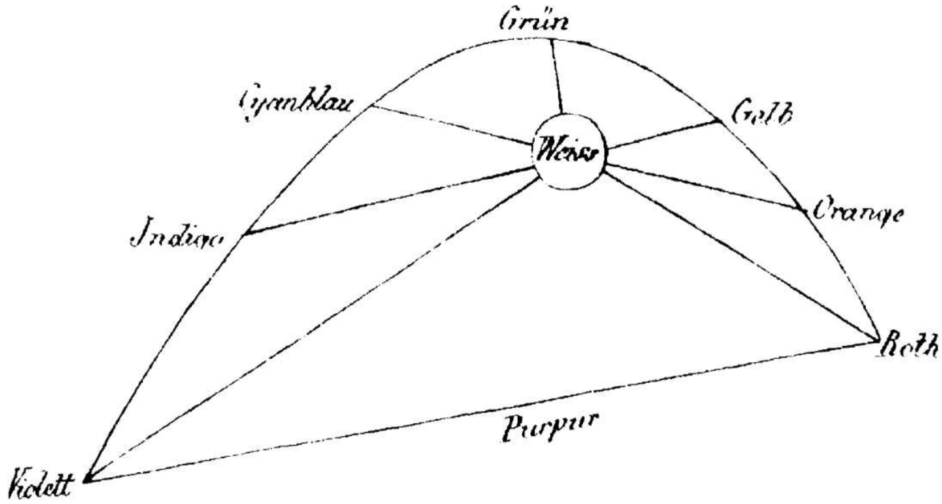

Figure 2: Hypothesized graph of color mixing based on the relative intensities needed to produce white (Helmholtz 1855a, Tafel I, Figure 5).

hypothesis). The curve shown in figure 2 thus directly *implies* that mixtures of spectral colors will appear whiter and less saturated.

With this work fresh in his mind, it does not seem surprising that Helmholtz would mention this fact at an appropriate juncture in the Kant speech. While it would later be marshaled as evidence in favor of the adapted version of Young's theory, it in no way implies that Helmholtz had at this time already inferred that something like Young's theory had to be true (again, if he had, why does he not mention this in either the paper or the Kant speech?).

Kremer (1993, p. 245) rejects this interpretation of the line from the Kant speech, saying that "the 1855 paper reported only mixtures of complementary rays, which are irrelevant to the above claim". I disagree: by using quantitative information (about relative intensities) to draw the curve in figure 2, Helmholtz obtains evidence for the curvature of the spectral colors, which directly implies the relevant statement from the Kant speech, even if it was not the topic of that paper. To me, this interpretation seems much more plausible than explaining this one comment about color mixing by a major shift in Helmholtz's views, a shift which he does not otherwise allude to in the Kant speech.

The third and final way in which my reconstruction may appear implausible is in what is ascribed to Helmholtz, the eminent scholar: either sheer maliciousness in attempting to take credit for Maxwell's discovery (even if he did make some noteworthy additions of his own in the *Handbuch*) or egregious oversight in "forgetting" to give Maxwell credit. By noting that even Newton (as eminent as they come) occasionally stooped to questionable behavior when questions of priority were concerned, I have already indicated that I do not think this as *a priori* implausible as others might.

Yet it is worth spending some time investigating a more specific statement of this objection to my reconstruction. Thus Turner (1994, fn. 4 to chapter 6, p. 291) writes: "Helmholtz never acknowledged Maxwell's priority for the amended version of Young's theory, but rather wrote of himself and Maxwell as co-discoverers... This niggardliness is sufficiently untypical of the mature Helmholtz as to lead some scholars to conclude that he indeed came to the amended Young theory independently of Maxwell."

So is there perhaps reason to believe that while some scientists may be tempted to questionable behavior by the pressure to be original, Helmholtz at age 39 is not one of them? Turner provides no evidence to support this claim, and I think it should be rejected.

Kremer (1993, p. 207) argues that Helmholtz's 1852 and 1855 papers on color theory "show him either uninformed about his predecessors' work or somewhat less than generous in citing that work". In Helmholtz (1852a) he "displayed, at best, a truncated knowledge of his predecessors and overemphasized his own originality" (Kremer 1993, p. 221). For example, in writing that he had not found "among Newton's followers, up to the latest period, experiments on the mixture of the single prismatic colours" (Helmholtz 1852a, p. 49 / 1852b, p. 522), he incorrectly claims to have been the first since Newton to perform this kind of experiment (Kremer 1993, p. 228). The originality of his claim that mixing pigments and mixing lights yield different results was also disputed (Kremer 1993, p. 232).

So at least until a few years before the *Handbuch* Helmholtz was very much the kind of scientist who (again, purposely or not) would occasionally engage in "niggardliness". Perhaps Turner would claim in reply that this does not reflect the "mature" Helmholtz, with maturity then apparently having set in right before the second volume of the *Handbuch* was written. I do not find this argument very convincing. The fact remains that, just a few years before, writing on the exact same topics, Helmholtz had displayed just the kind of "niggardliness" that Turner calls "untypical" of him. Expecting him to continue this trend into the *Handbuch* does not strike me as particularly implausible.

Moreover, the *Handbuch* itself contains other dubious claims of a similar kind. In writing that "Young's hypothesis is only a more special application of the law of specific sense energies", Helmholtz (1925, p. 145) makes a claim that, while perhaps technically true, is also misleading: Helmholtz incorrectly suggests that Young merely applied Müller's law, which did not in fact exist at the time of Young's work.

Similarly, in writing that "Young's theory. . . remained unnoticed, until the author himself and Maxwell again directed attention to it" (Helmholtz 1860, p. 307 / 1925, p. 163), he significantly understates the attention that Young's theory had received between 1802 and 1852 (Sherman 1981, pp. 217–221).

Having considered these three potential problems, I do not think they make my reconstruction particularly implausible. Given the problems with Kremer's reconstruction, it seems to me that a preponderance of the evidence suggests that Helmholtz did not discover the adapted version of Young's theory independently of Maxwell, without, admittedly, establishing it beyond reasonable doubt.

9 Conclusion

I have considered two reconstructions of the history of the theory of color vision from 1852 to 1860. On the former, worked out in the most detail by Kremer (1993), Helmholtz independently discovered in late 1854 or early 1855 that an adapted version of Young's three-receptor theory, using coterminal response curves, could explain a large range of color vision phenomena. The phrasing in Helmholtz (1860), which suggests Helmholtz and Maxwell co-discovered the theory, would thus be vindicated.

The other reconstruction maintains that Helmholtz borrowed the theory from Maxwell. On this view the phrasing in Helmholtz (1860) is even more unfair to Maxwell than Kremer's reconstruction would suggest.

Barring the appearance of significant new evidence, it is impossible to establish with certainty which reconstruction is correct. However, I have argued that the view that Helmholtz independently discovered the theory has a number of implausible features: the time window is really short, Helmholtz says surprisingly little about Young's theory at a time when he must have thought to have made a major innovation, and it only partially mitigates the unfairness of the phrasing in Helmholtz (1860).

The alternative view (no independent discovery) is implausible only insofar as it is viewed as independently implausible that Helmholtz would try to claim credit for work that was not his. I suspect that this must have at least partially motivated Kremer and others to suggest the independent discovery view. But I have argued that such an approach involves an undue tendency to picture eminent scholars as flawless beings, a tendency which has been discredited by the sociological literature. Moreover, Helmholtz in particular is known to have engaged in similar behaviors in earlier works on color vision as well as in the *Handbuch* itself.

I conclude that, most likely, Helmholtz did not independently discover the version of Young's theory with coterminal response curves. This suggests that Maxwell's contributions have been undervalued even more than was previously assumed. As Sherman (1981) has noted, the theory should have been called the Young-Helmholtz-Maxwell theory rather than the Young-Helmholtz theory. But perhaps the Young-Maxwell theory would have been even better.

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