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The Construction of Colorimetry by Committee[1]

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The Argument

This paper explores the confrontation of physical and contextual factors involved in the emergence of the subject of color measurement, which stabilized in essentially its present form during the interwar period. The contentions surrounding the specialty had both a national and a disciplinary dimension. German dominance was curtailed by American and British contributions after World War I. Particularly in America, communities of physicists and psychologists had different commitments to divergent views of nature and human perception. They therefore had to negotiate a compromise between their desire for a quantitative system of description and the perceived complexity and human-centeredness of color judgement. These debates were played out not in the laboratory but rather in institutionalized encounters on standards committees. Groups such as this constitute a relatively unexplored historiographic and social site of investigation. The heterogeneity of such committees, and their products, highlight the problems of identifying and following such ephemeral historical 'actors'.

Introduction

Today, the colors produced by computer screens, printing inks and other products are described by an international convention known as the CIE color system. In this system, a color is described by three numbers, relating indirectly to three ‘primary’ color components of blue, green and red. Color itself is classified as a ‘psychophysical’ phenomenon, a product of physical stimuli, physiology and mental response. This seemingly straightforward scheme of expressing color characteristics was adopted and elaborated before the Second World War, and widely applied after it. The modern consensus regarding this standard, however, masks deep national and disciplinary divisions that surrounded its introduction, and that questioned its implicit foundations and adequacy. The parties to the debate were aware of the cultural bases of the agreements needed for its resolution.

This paper concerns the question of how groups of practitioners during the past century came to assign specific names, labels, and eventually numbers to colors. It is not primarily a story about new technology or experimental methods, but rather about how a scientific subject came to be created, and how its development was reliant on the social context as much as any inherent natural structure. The historical locus, including interwar politics and the differing goals of national physics and psychology communities, played a significant part. So, too, did the goal of mathematizing and rendering physical a phenomenon whose very nature was contested. In this respect, colorimetry appeared comparatively late in the pantheon of quantitative science (Swijtink 1987). This case supports Simon Schaffer's contention that 'quantification is not a self-evident nor inevitable process in a science's history, but possesses a remarkable cultural history of its own' (Schaffer 1988, 115).

The subject also is closely connected with the ongoing work on the history and stabilization of metrological standards (Schaffer 1992; O'Connell 1993; Olesko 1993; Hunt 1994). Particular systems of color measurement have repeatedly been justified by their 'natural' structures, or by their apparent connection with physiological attributes. The 'taint' of anthropomorphism in this case is central to the work of Phillip Mirowski, who notes: 'measurement conventions – the assignment of fixed numbers to phenomenal attributes – themselves are radically underdetermined and require active and persistent intervention in order to stabilize and enforce standards of practice' (Mirowski 1992, 166). This is perhaps unsurprising for a subject which, at heart, relies upon the relationship between the practitioner and human sources of data, a feature shared with the related subject of psychology (Danziger 1994, 9). The question of 'appropriate' and 'meaningful' definitions of measurement has thus been one of the contentious issues in colorimetry.

But this case study augments such analyses by highlighting the importance of a distinct, and hitherto little explored, type of historical actor – the committee and commission – in generating and resolving disputes. At the same time, this case problematizes the notion of what an 'actor' is. The committees had a fleeting existence; their identities, viewpoints and power could alter dramatically with each meeting. Moreover, their members actively and collectively fashioned these 'composite actors'. Colorimetry offers a particularly explicit example of a scientific subject <u>self-consciously</u> constructed to match its cultural context.[2] Twentieth century color science was shaped by the way in which the committees were structured, by their pragmatic mandates, through their links with government and industry, and as a consequence of the prevailing political climate.

During the interwar period, technical delegations mathematized the subject by simplifying and standardizing some of the many characteristics of human color perception. Some constituencies (notably German researchers) were disenfranchised; other previously separate scientific groups, especially American physicists and psychologists, were brought together for the first time. The melding of physical and physiological factors embroiled these selected communities of practitioners in a debate about the nature of color itself. These constituencies differed both in their perceptions of nature and their professional aims. Consensus proved elusive. As the sociologists Englehardt and Caplan have observed, ‘one must establish by negotiation formal procedures to bring closure to a scientific dispute when more than one community of scientists exists . . . or when a conclusion has not yet been reached by sound argument and one intends to engage in common activities or undertakings’ (Englehardt & Caplan 1987, 17). The establishment of this negotiated consensus can be explored profitably in the context of Collins’ Empirical Program of Relativism (Collins 1981, 3-10). He proposes three stages of analysis, namely (1) showing the interpretative flexibility of experimental data; (2) showing the mechanisms which constrain the potentially endless interpretations; and (3) relating the eventual consensus to wider social and political factors. The present study, unlike several considered by Collins and others, concentrates particularly on this third stage (Collins 1982, 1985).

The case of color measurement also differs qualitatively from these other cases in the Science Studies literature in terms of scale: the primary point of contention for colorimetry was not the production of facts, but the production of a coherent subject. In contrast to the pointed conclusions of Bruno Latour, for example, the laboratory (that is, the locus of experimental data) played a relatively minor role in stabilizing and ‘black-boxing’ colorimetric knowledge (Latour 1979). Rather than disputing the reliability and meaning of experimental evidence – the products of laboratory work – the historical actors differed in their opinions regarding the range of evidence to incorporate in their subject, i.e. in defining the scope and borders of colorimetry. Physicists frequently judged psychologists’ ‘facts’ and organising principles to be irrelevant to constructing the subject, and vice versa. To a considerable extent, the foundations, aims and methodology of these two camps were incommensurable in a Kuhnian sense (Kuhn 1970).[3]

Colorimetry illustrates another weakness in the Latourian analysis of historical change for subjects at the science/technology interface. In discussing how technoscience is shared between large and small actors, Latour suggests that the trend is inevitably towards agglomeration and the eventual control of a subject by the players that can marshal the greatest resources; small countries, for example, lack autonomy (Latour 1987, 167). Replacing the word 'country' by 'color measurement communities', however, it is clear that this trend is not universal. Communities need not merge or even grow into internally sufficient entities to control a subject. They may merely fashion their version of the subject to suit their own ends; ends such as the pragmatic and particular color charts adopted by bird fanciers or automobile manufacturers. These communities experienced no pressure to converge as long as their goals of quantification were expressed in particular and local terms.

Both the technological emphasis and peripheral status of colorimetry thus distinguish it from recent empirical studies. The utilitarian dimensions of the subject are amenable to analysis based on the social construction of technology (Hughes 1986; Bijker, Hughes & Pinch 1989; Pinch 1988) although, here again, its shaping by formal groups provides a distinguishing characteristic.

The paper is divided into two parts. A brief introduction is first given to the measurement of color as it developed in the late nineteenth century. It is important to recognize why practitioners felt a need to specify colors, who was doing the specifying, and how they went about it. The second part is a more detailed narrative and analysis of the period from about 1920 to 1940, during which color measurement was successfully 'institutionalized'. Two significant episodes will illustrate this latter period: first, how Britain and America came to define the international system of color adopted in 1931, and second, how American scientists debated the nature of color through the 1930s.

Emerging Colorimetry, c.1850 – 1900

The subject of color has raised questions since classical times, but widely accepted rules concerning the combination and description of colors have a relatively recent history. Newton, for example, studied the nature of 'white' light and postulated relationships between complementary colors (which combine to yield white), but the subject attracted widespread scientific interest only from the mid nineteenth century.[4]

From its origins, the subject has been of peripheral interest to disparate technical communities.[5] I will argue that the course followed by the subject, particularly its eventual reliance on committees as principal actors, was a consequence of its 'shared' status. Two lines of development are relevant: empirical investigations applied to art and industry, and research into the nature of human vision. Employed by chemists by the 1860s, for example, the term colorimetry originally referred to utilizing the color of liquids to determine the concentration of chemical substances they contained.[6] Researchers of color perception also appropriated the term at about the same time to describe the direct quantification of color – that is, the precise description of a perceived tint. This dual meaning, with color serving as both technique and subject of observation, was central to the evolution of colorimetry through the mid twentieth century.

The measurement of color was supported by a combination of converging pragmatic and epistemological interests. The artisanal tradition of paint mixing and the Newtonian example of light mixing both promoted the idea of combining a small number of 'pure', primary colors. From the second half of the nineteenth century, considerable empirical interest in color measurement centered on ways of describing or mapping out the full range of color. Artists, having more practical experience with the subject than most men of science, were the instigators of several systems. Thus David Ramsay Hay wrote on 'the numerical powers and proportions of colors and hues' (Hay 1846). Hay's numerical descriptions intermingled with the evocative language of the artist: of the three primary colors, he wrote, 'blue . . . belongs more to the principle of darkness or shade . . . and is consequently the most retiring of the three. It is also of these elements the most cool and pleasing to the eye.' In contrast to the later dissociation between physical properties and emotional connotations of colors, Hay's use of such terms as 'retiring', 'cool' and 'pleasing' reflected a common – indeed, almost universal – form of discourse found in nineteenth-century books on color. Moreover, books on the subject of color frequently conflated the idea of color measurement with rules of desirable color combination. However, the subject was to be repeatedly narrowed to recast it into an increasingly mathematical and, according to its practitioners, more manageable form.

Another tactic in stabilizing color description towards the last quarter of the century was in the direction of philology – by assigning more precise color names such as ‘brightish confused yellowish green’ (Lovibond 1897; Walsh 1926, 81). But language proved inadequate to describe the thousands of gradations readily distinguishable by the eye. By 1900, most practitioners referred to colors by numerical designations which usually related to the position of a color on a chart. The creation of ordered charts thus assumed importance and attracted attention.

Most attempts to map out color in some regular way relied upon qualities that the human eye could detect and which could be quantified. Besides ‘brightness’, commonly identified as a fundamental characteristic in the measurement of light, late nineteenth century colorimetry usually included the characteristics of ‘hue’ (or tint) and ‘saturation’ (or color purity) (Luckiesh 1915). By treating these characteristics as co-ordinates, colors could be ‘mapped’ onto ‘spaces’ of three or more dimensions.

A variety of systems were devised, specific to particular uses and to particular countries. In 1858, Michel Eugène Chevreul, the director of a French dye works, developed one of the first such systems to characterize his colors and thus to forestall arguments with customers (Chevreul 1858). By the opening years of the twentieth century there was a proliferation of color systems. In America, the Nomenclature of Colors for Naturalists, published in 1886 by Robert Ridgway to describe bird plumage, found widespread use. La Societé Française des Chrysanthémistes published a Repertoire des Couleurs in 1905 to describe flowers, but the catalogue was quickly applied in other domains. A Boston artist, Albert Munsell, devised a color ‘tree’ to express all possible colors, intending it as a tool for industry and teaching (Munsell 1907, Nickerson 1940). Munsell’s system, spanning a wide gamut in convenient increments, proved the most enduring. Such systems were characterized by a certain rigidity of definition coupled with a mass of empirical detail. The details were far from absolute. The number of hues might be 10 (Munsell), 25 or 36 (Ridgway) values; the number of brightness levels, 6, 9 or 15; and the number of colors thereby defined, anything from a few hundred to several thousand.

Despite such diversity, all these empirical systems aimed at expressing colors quantitatively. It is important to recognize that color charts and color trees were not merely illustrations of the system; they were the system; they embodied it. They acted simultaneously as standard, documentation and example. The color chart as material embodiment of color science echoes Gaston Bachelard's idea of instruments are ‘reified theories’ (Bachelard 1933, 140, Gaukroger 1976).[7] The justification for such color charts rested on their ability to reproduce colors encountered in practice and thus on their illustration of the key attributes of perception.

Apart from defining numerical descriptions of color, more pragmatic investigators concentrated on devising ways simply to match them. One of the most successful of these was the ‘Tintometer’ marketed from 1887 by Joseph Lovibond, a former English brewer (Lovibond 1897). The

Tintometer allowed an observer to match the color of a sample with a combination of glass filters from graduated sets of three primary tints. The key was in designing the graduations to yield an arithmetic relationship between the tint grade and the sample concentration or thickness. But material technology alone was not sufficient: the qualities of the observer and light source proved crucial in obtaining a reliable result. To obviate fatigue due to eyestrain, and the irregularities of color and brightness caused by artificial light sources, Lovibond recommended using north daylight, ideally diffused by mist or an overcast sky, as the standard.

Such devices found applications in fields as diverse as steel production, water quality measurement and medical analysis. The economics of colorimetry were also significant: Lovibond demonstrated, for example, that his method could accurately correlate the color of flour to its market price. Such early applications had a strongly empirical basis. Although Lovibond spent several years investigating schemes of color matching, he was averse to theorising, confining himself to empirical experiment, which 'enabled the author to devote much of his time and energy to actual work, which would otherwise have been employed in profitless controversy' (Lovibond 1915). Colorimetrists such as Lovibond thus made little attempt to measure color; instead, they matched samples to color standards prepared from known constituents or itemized in catalogues. Such an activity was scarcely quantitative. According to the philosopher of science Norman Campbell, who had himself become engaged in colorimetric and photometric research between the wars, 'the assignment of numerals to represent telephones or the articles of a salesman's catalogue is not measurement; nor – and here is a more definite representation of properties – the assignment of numerals to colors in a dyer's list' (Campbell 1928, 1). Centrally important to these developments in colorimetry, then, were practical concerns. The inventors of such systems were artists, brewers, bird fanciers, dye makers and horticulturists – not men of science.

Besides these empirical systems of color measurement, theories of color had a long history by the turn of the twentieth century. In particular, the three-color theory of color combination developed successively by Thomas Young, James Clerk Maxwell and Hermann von Helmholtz was being experimentally verified by other independent researchers, and increasingly applied in empirical systems (Abney 1891; 1913). In 1855, Maxwell demonstrated by experiment that most colors could be expressed as a combination of three 'primary' components. Helmholtz, in the same decade, explained additive and subtractive colors, and synthesized a successful theory of color mixing in his influential Handbuch der Physiologischen Optik. Despite the competing and qualitatively different theory of physiologist Ewald Hering, the three-color theory of perception was widely accepted by scientists and practical men, particularly outside Germany.[8] The important trend of nineteenth century color research was in psychophysics, which linked physical stimuli with perceived response. This line of research was stimulated by Gustav Fechner, who, in his 1860 book Elemente der Psychophysik, discussed the relationship between physical stimuli and human responses such as sound and light (Boring 1950). Experimental study of color perception thus attracted scientists from the psychics, physiology and psychology communities (Ladd-Franklin 1893).

By the 1890s, the complicated question of color measurement was being investigated on both sides of the science/industry interface. As the scale of commercial color measurement escalated, there were more opportunities for pragmatic descriptive systems to combine with perceptual research. Dye production had expanded dramatically after the development of synthetic dyes in the second half of the nineteenth century. By the turn of the twentieth century dye chemistry was a major industry, accompanied by the growth of research laboratories (Homberg 1992). In the printing industry, color printing processes had been much developed and were commonplace by the 1890s. Both of these applications demanded high-quality matching of colors and routine, rapid measurements. The demands from industry for color standards for dyes and inks required research into the perception of color, the effects of lighting, surface finish and so on. The two motivations for colorimetric studies – research into human vision, and utilitarian applications of color specification – began to merge by the turn of the century.

Institutionalization of colorimetry in the early 20th century

The growing scientific interest in color between 1900 and the First World War became focused not in universities, but in new government and industrial laboratories. The national laboratories organized around the turn of the century (notably the German Physikalisch-Technische Reichsanstalt (PTR) in 1889, the British National Physical Laboratory (NPL) in 1900, and the American National Bureau of Standards (NBS) in 1901) undertook the tasks of precision measurement, maintenance of standards, and the application of science to the needs of government and industry (Cahan 1989, Cochrane 1966). None of the institutions had any initial mandate to become involved with color research. However, they did get involved, and played an influential role. I will concentrate on the two institutions that had the greatest influence on international color standards, the NBS and the NPL.

Industries increasingly demanded standards of color from their new national laboratories. As an historian of the NBS has written, 'the field of research at the Bureau in which undoubtedly the greatest variety of industries and interests had a vital concern was the standardization of color' (Cochrane 1966, 170). At first, the NBS simply responded to enquiries. In 1912, for example, representatives of the butter, oleomargarine and cottonseed oil industries requested help in grading the color of their products. Other queries dealt with the color of paints, cement, porcelain, tobacco and foods. The war, too, provided an incentive. During World War I, color research centered on the design of camouflage. In 1916, the director of the NBS requested government funding for special work on color standards, noting that:

> There never was a time in the history of the country when we should be looking at such matters as critically as at present. The items submitted – I think I can say all of them – are as fundamentally concerned with both industrial and military preparedness as any that will come before you. (J. W. Stratton, Congressional Hearings Feb 2, 1916, 991-992 in Cochrane 1966, 171).

For the most part, however, the war was a temporary diversion for the colorimetry and photometry work at the national laboratories. No crucial military applications of the subjects were identified as being worthy of post-war research.[9]

The industrial need for color metrics nevertheless continued to increase dramatically after the war. In the British dyestuffs industry, for example, the production of colors rose four-fold between 1913 and 1927 (Brightman 1934). In America, the idea of 'standardization' was touted as a means of reducing commercial complexity and improving the country's competitiveness in products.[10] The regulation of light and color were key components of this scheme. The Bureau instigated programs for setting standards for electric lamps, gas purity for lighting systems and the color of railway signal lamps.

From the beginning, the NBS made use of existing empirical systems of color description. The artist Albert Munsell contacted the director of the Bureau soon after its formation in 1901, 'asking questions about color' (Cochrane 1966, 253). Munsell formed a company to market his color charts, educational materials and books in 1917. Over the following decades, the Munsell Color Company under the direction of his son funded seven research associates at the NBS, who were paid by the company but worked and published their results through the NBS (Cochrane 1966, 224-225). The NBS also engaged in considerable collaborative work with the Munsell Research Laboratory in Baltimore, founded in 1922, where several individuals were assigned to mainly scientific work in the late 1920s. The result was some forty collaborative papers before the Second World War (Nickerson 1940).

The Munsell Company was not the only American business having a commercial interest in color measurement. By about 1910, several industrial laboratories were becoming involved. These, along with the NBS, employed most of the workers who were to be important in American colorimetry for the next thirty years. The first of these labs was the National Electric Lamp Association (Nela) laboratory, set up by a consortium of lamp manufacturers.[11] One of the earliest projects of the Nela lab was the study of human color perception in order to design more efficient electric lamps. Gas lighting manufacturers such as the United Gas Improvement Company also supported color research for similar reasons. The Eastman Kodak company, concerned with the recording of light and color on photographic film, engaged in basic research on the visual characteristics of the human eye.

In England, color research was similarly divorced from academic institutions, and instead was focused at the National Physical Laboratory and Industrial Research Associations. Several of these RAs, set up collaboratively by the Department of Scientific and Industrial Research and groups of companies from 1918, pursued research into color measurement as a direct means of improving business competitiveness.[12] Unlike the American situation, color measurement in Britain was sponsored mainly by government-supported institutions rather than directly by companies.

Work at the National Physical Laboratory was on a smaller scale than at its American counterpart, and was a rather schizophrenic affair, as two NPL divisions became engaged in color research: the Optics Division and the Electrotechnical Photometry Division.[13]

The Optics Division, which had begun to specialize in lens design by 1908, received donations of incomplete spectrophotometers from British manufacturers during the First World War. Following the war, the Division decided to begin low-priority work on color vision 'as occasion permits' (NPL 1920, 54). By 1921, however, interest grew because 'considerable attention has been devoted to it in America' (NPL 1921, 73). The Division would do research on color standardization by measuring 'a representative number of colors on various types of colorimeter, both scientific and commercial' (NPL 1921, 71-72). Despite a slow start and limited resources, the research by 1922 had a clearly defined programme involving the development of a standard method of measuring color and inter-relating different commercial instruments and practices. The NPL sought a consensus in British industry by aiming at 'a general co-ordination of the various color systems. . . and their relationships to the fundamental facts of vision with a view to the evolution of a generally acceptable scientific basis for color specification and standardisation' (NPL 1922, 75). The first commercial system to be investigated was the thirty-year old scheme of Joseph Lovibond. Owing to the availability of a single full-time investigator, progress was slow. The year 1923 was devoted to choosing a third color between the standard green and red for railroad signal lamps, and 1924 to measurements of standard filters and instruments. By the end of the decade, the work led to a set of paint colors for the British Engineering Standards Association, and standard colors for testing cod liver oil and coal ash (NPL 1927, 78-80; 1928, 93; 1929, 96; 1930, 88).

Thus, during and after the First World War the national laboratories in America and Britain were being drawn into color measurement in piecemeal fashion to satisfy their industrial and governmental clients. The war itself triggered the formation of technical societies. No longer able to obtain optical instruments from Germany, and to promote national capabilities, practitioners in the United States organized the Optical Society of America in 1916. The launching of this organization had two important consequences. Firstly, it brought together constituencies of workers that previously had been separate: academic scientists, optical craftsmen, physiologists and psychologists interested in vision, industrial engineers and others.[14] Secondly, the OSA proved to be very active in promoting organized research through committees. The Society set up a committee on colorimetry in 1919 to standardize terminology, and published a report three years later (Troland 1922).[15] This committee signalled a new phase in color research that was to dominate the following twenty years.

The OSA committee served as a focus of American interest in colorimetry. An indication of this was the translation into English of the third edition of Helmholtz's <u>Handbuch</u> as the <u>Treatise on Physiological Optics</u> for the first time (Helmholtz 1925). A reviewer noted 'color vision at the present time is probably attracting a greater degree of attention both from the theoretical and practical points of view than ever before in its long history'. Describing its current status, he also observed, 'great difficulty has been experienced in completely harmonizing on any simple basis the extraordinary diversity of facts that must be explained consistently with each other' (Anon. 1925).

This national acceleration of color research carried through to the international stage by the early 1920s. As with the earlier work in individual countries, this was initially an ad hoc affair that took place almost entirely outside the influence of academic institutions. The pivot of this international cooperation was the Commission Internationale de L'Éclairage (CIE). Its main function was to coordinate the light measurement work of national laboratories and committees in order to set international standards. The CIE had been organized in 1913 as a successor to an international commission on photometry (Walsh & Marsden 1989). Consisting initially of a half-dozen member countries, its mandate was to study and try to set uniform standards of lighting among all its members. To do so, it had to instigate a good deal of research into the measurement of light and color.

A failed consensus: colorimetry as photometry

The involvement of the Optical Division of the British NPL has already been mentioned. A handful of staff at another group there, the Electrotechnical Photometry Division, defined colorimetry in quite different terms, having first encountered problems of color measurement while developing standards of light intensity to evaluate lamps. The first national standards of intensity were based on flames – initially wax candle flames, replaced by 1900 with pentane in Britain, amyl acetate in Germany and oil in France. The German standard, known as the Hefner lamp, appeared distinctly redder than the other two. The NPL introduced incandescent lamps in 1903 as more stable standards, but these were hotter and whiter in appearance than the flame standards. The problem was exacerbated in 1907, when carbon-filament bulbs were joined on the market by newer and more reliable tungsten filament types, which were whiter again.

This problem of matching colored lamps was first faced by the CIE in 1924. There was no question of adopting a single international illumination standard. In a close parallel with the case of resistance standards (O'Connell 1993, Hunt 1994), the German national laboratory promoted the Hefner lamp as the most practical standard because it could be manufactured and used in any laboratory, and argued that electric lamps could not be manufactured reproducibly; French, British and American laboratories rejected the Hefner standard because of the flame's dependence on humidity, air composition and temperature.

The problem of photometric standards revolved around how the human eye perceived different colors. Using the human eye to compare the brightnesses of differently colored lights for what was termed 'heterochromatic photometry' proved problematic.[16] And, since the eyes of different individuals in different viewing conditions varied in color sensitivity, how could 'the human observer' be defined? The physical scientists and engineers on standards committees were faced with problems of physiology. Yet the difficulty of relating human response to physical standards was hardly new. As early as 1894, a review of photometry discussed the relationship between the brightness of light and the visual response:

> What we really want is a quantitative measure of the intensity of brain effect. And how can we do this with the brain itself? We are beset with physiological or, rather psychological, effects, and as yet there is no psychological unit which we can represent by

> anything concrete to give to the Board of Trade. (Barr & Phillips 1894, 525).

Thus three constituencies converged on the problem: physics, physiology-psychology, and industry.

The chairman of the 1924 CIE heterochromatic colorimetry committee, the French optical physicist Charles Fabry, deplored the lack of information and admitted himself 'a little frightened at the size and difficulty of colorimetric questions'. He saw the choices in classifying color as a simple dichotomy:

> The problem posed by colorimetry is, in some respects, the inverse of that of heterochromatic photometry, since in [the latter] case, it is proposed to characterize intensity by a number with no allusion to color, whereas in the [former], one seeks to define color without concern for intensity.[17] (Fabry, CIE 1924, 190).

The members debated whether to consider colorimetry to be a particular case of photometry, but eventually decided to set up another committee to study color on its own. Fabry recommended that the commission concern itself with the physical side and ignore the psychology of color. A Swiss delegate concurred, observing that colorimetry was too premature for international discussion. Instead, he suggested, the heterochromatic photometry group should first complete its study, then physicists at the physical laboratories should 'precisely treat the questions which must constitute the bridge between colorimetrists and physicists' (Joye, CIE 1924, 31). American and British delegates, on the contrary, argued that color was a 'question of high importance, ripe for international investigation at present' (Hyde, CIE 1924, 32). Nevertheless, only one British and one American delegate were nominated to take on the work.[18]

Thus, as played out on the CIE committee, two aspects of color measurement became important from the early 1920s: first, a dramatic shift of research impetus from Germany to America and Britain and, second, a growing schism between physical and psychological viewpoints of color.

National divisions

Why did America and Britain get chosen by the CIE to carry out the research into colorimetry? One reason is that both the American and British delegates were vocal in making known their recent history of active work in the subject.[19] The Optical Society of America committee had published its 1922 report attempting to formalize the measurement of color. In Britain, the NPL had been undertaking research since 1922, eventually presenting a one-man equivalent of the OSA Committee report at the 1926 Optical Convention in London (Guild 1926).

American investigators had made determinations of the 'standard observer' in 1912, 1917, and 1923 on progressively larger samples of people. The last NBS results, on 52 individuals aged under 30, measured in 'good lighting conditions', were proposed to the CIE as the response of a 'standard observer'. The committee members recognized that this adoption was rather tentative, since different data would have been obtained with other observers, or the same observers measured under different conditions. Even so, the standard observer allowed colorimetric quantities to be established by definition.

The British and American national laboratories did this colorimetric work as part of the work of their Optics sections, and also benefited from various government grants and support from private industry. Activity in colorimetric research was considerably lower in Germany and France, where physical photometry and physiological aspects of color retained most attention.[20]

There was also a strong political perspective to this post-war division of color science. In 1919, the International Research Council (IRC), sponsored by the Allies, had advocated policies of ostracism for German scholars. This exclusion was in effect during the formative years of the CIE. German attendance at conferences and commissions such as the CIE was almost nil early in the 1920s, and only increased in 1926 when the IRC lifted its bar against the Central Powers (Kevles 1971; Forman 1980; Crawford 1992).

The First World War thus isolated German-speaking countries from participating in this new color research, and from sharing their results on an international stage. Moreover, German research was faltering: the war had interrupted work, and two of the chief German research schools were moribund following the deaths of Helmholtz in 1896 and Hering in 1918 (Turner 1994). By the time German delegates returned to the CIE in 1928, the ‘standard observer’ had been accepted, and further color research had been assigned to American and British workers.

This national monopoly of research was also fostered by the committee structure of the CIE. Most of the Commission’s work was shoe-horned into a week of meetings once every three years, and international travel between laboratories was time-consuming and expensive. To obtain faster results, the Commission assigned particular research projects to national committees for periods of three years. The national committee would then submit a report to the assembled member countries, who would comment and usually accept the recommendations without major change. Thus quite major proposals for international standards were often written by single countries or even a single individual in one lab. As a Dutch illuminating engineer active in the CIE recalled,

> Experience had shown that these committees of specialists from different countries had a low efficiency because the members could not meet regularly and had to rely upon correspondence. Therefore an important change for the work between the session was decided upon. . . Each of the sections (or subjects) was assigned to the National Committee for that subject. It got the full responsibility for fostering on an international scale the study in that field and to maintain for that purpose contact with the other National Committees. (Halbertsma 1963, 25).

The formation of National Committees was modelled on the organization and practice of photometry in each member country. Membership on the Commission was open to those selected by their National Committees. Such committees generally chose a combination of individuals from those most active in the field, typically the presidents of national associations, academic scientists active in photometry, or representatives from national laboratories. The British and American representatives were drawn primarily from the national laboratories and industry.[21]

Thus, the fact that American and British decisions dominated the CIE work on color for twenty years was a combination of international politics, timely research work and organizational details of the Commission. As a result, the particular compromises chosen in these countries were quickly promulgated on the international stage.

The proposed CIE system of color

The American and British collaboration was a rather hasty and, for several CIE delegates, an unsatisfactory affair. In 1931, when the next CIE meeting was held in Britain, the two American and British researchers were able to collaborate particularly closely. Irwin Priest, the American representative, received the report of John Guild, the British member, only a couple of months before the meeting, and they settled upon a system of color in the week before the meeting. The experimental data used in the 1931 color system were based on the observations of only 17 British subjects.[22]

This system, an elaboration of the Maxwell-Helmholtz description of color, combined experimental data, agreed standards, and a mathematical framework for manipulating defined quantities. It proposed to specify color by agreeing on standard light sources, three standard primary color filters, and the already-accepted standard observer. The experimental data included: the spectral distribution of optical radiation from the light sources; the construction and spectral transmittance of standard red, green and blue optical filters; and, the relative spectral response of the standard human eye. Key technical points included the reliability of the experimental data obtained from spectrophotometers and human observers; the practicalities of specifying a 'standard' for variable light sources such as the sun shining through the atmosphere; and various 'internal' mathematical consistencies in the combination of the primary colors. The system defined, among other things, pure colors by three color coordinates ('tristimulus values') and permitted color properties to be illustrated and derived from a 'chromaticity diagram' which plotted ratios of those coordinates. This combined algebraic and graphical system provided considerable analytical power, enabling, for example, the accurate matching of colors viewed under different lighting conditions, or produced by different sets of 'primary' colors.

The decision to accept the modified British system of color was taken solely by Priest, and the CIE delegates did not get revised versions of their agendas. The American representative decided to accept these data in preference to American measurements for one simple reason: they agreed well with each other, although they had been done at two locations, on small groups of people, using different types of apparatus. Guild at the NPL had hesitated so long to present the experimental data because he had not expected Wright's data to agree with his. The good agreement convinced Priest and Guild that the postulated human 'averages' actually worked (Wright 1981).

The British and American compromise on the data and mathematics behind a system of color was accepted unanimously at the

CIE meeting in 1931, but in the 'cooling off' period afterwards, the French and German national committees reversed their votes. Nevertheless, enough countries had voted in favor for the system to become the international standard. One participant later questioned 'why it was so much an Anglo-American concern', and decided that 'in the aftermath of the Great War . . . colorimetry cannot have had a very high priority in the European countries, and perhaps this helps to explain why France and Germany reversed their votes. They may well have felt they were being rushed into making decisions in a subject in which they were only just beginning to gain any practical experience of their own. They needed more time to think' (Wright 1981, 17).

There was thus an impression of being railroaded into accepting an ill-considered compromise. Hints of this discord are apparent in the minutes of the next meeting in 1935. The subject of colorimetry had been passed to Germany, and further work on color specification and measurement were assigned to Japan. The American and British contributions were restricted to the lighting of factories and schools, and to the lighting of mines, respectively (CIE 1931). The lack of effective cooperation with Britain and America limited the range of the work performed. Moreover, neither the German nor Japanese researchers benefited from the combination of industrial and national laboratory support for color research that had sustained the American and British efforts. Progress flagged. At the next session in 1935, Japan presented no report, and Germany gave a relatively brief contribution that filled in omissions from the earlier American and British work (CIE 1935).[23] The colorimetry committee was not reassigned at the session, and no program of work was requested for the following four years. Nevertheless, at the next session in 1939, the German representative proposed that the standards be augmented by a new 'standard light source' representing a particular condition of sunlight. These were rejected by America and Britain because they would have required changes to the rapidly developing colorimetric practice.[24]

The CIE at that time reassigned the colorimetry committee to Germany, but no work was carried out before the outbreak of war. Because of this mainly political and administrative wrangling, active research in colorimetry returned by default to the ongoing national programs in America and Britain.

So, what did it matter that a particular country or research group decided questions about color measurement? It mattered because the subject was so contentious that the only way 'forward' (i.e., toward commercial application) was to negotiate a compromise based on limited goals and definitions. And the choices made about the way to simplify the subject were made by committees harboring particular national outlooks.

Disciplinary divisions

Besides exacerbating the national distinctions in colorimetry, the CIE committees highlighted the crucial cognitive differences between scientific communities. The limited debates between proponents of 'color as a subfield of photometry' and 'color as an independent subject' masked a deep, and worsening, conceptual rift. To discuss the two extreme perspectives, it is necessary to examine the membership of these two social groups. The training, allegiances and experience of these 'core sets' determined the form of certified knowledge that they produced.[25]

Physicists' color

Physicists, such as those at the national and industrial laboratories, wanted to quantify color in terms of light itself. This was a reasonable consequence of their training in optics and applied science, and their answerability to industrial supporters.

Two research associates of the Munsell Company came to dominate color research at the American National Bureau of Standards and, later, played key roles in setting the international standards. Irwin Priest headed the Colorimetry Section of the NBS from 1913 until his death in 1932, and was president of the Optical Society of America in the late 1920s. The second was Deane Judd, who took over when Priest died. Links with the Munsell Company determined the direction taken during the early history of the NBS. Priest responded to both research and industrial pressures, working in the NBS laboratories while providing considerable support in the planning and operation of the Munsell company. Much of his research centered on putting Munsell's original empirical system on a more regular 'scientific' footing. For example, spectrophotometers were used to measure the reflectance of the Munsell color standards as a function of wavelength, and then the color steps of the Munsell scale were adjusted to follow a more regular mathematical sequence. In other words, these researchers sought to mathematize or regularize an existing color scale. Priest, a physicist, had been hired to conduct the Bureau's work in spectroscopy and applied optics, and not surprisingly tried to develop a physical definition of color that standardized or minimized the importance of the human observer.

At the British NPL, John Guild of the Optics Division began his program of colorimetry research in 1922 (Guild 1928). He had been hired originally to design lenses and optical systems, and his early involvement with color was devoted to designing a spectrophotometer, or instrument to measure the relative intensity of wavelengths contributing to colors. By 1925, he was developing a trichromatic measurement system based on three standard color filters, and collaborating with Hilger & Watts Ltd in the manufacture of a standardized trichromatic colorimeter. For Guild, like Priest, colorimetry was an elaboration of the Young-Maxwell-Helmholtz model of color combination. Color itself could be meaningfully defined by the relative intensities of three color components, and colorimetry consisted of specifying the spectral transmission characteristics of standard filters, the spectral distribution of a standard light source and (most contentiously for psychologists) the spectral response of the standard human eye.

The original 1919-22 Colorimetry Committee of the Optical Society of America was similarly dominated by this physicalist view of color. Of its five members, four were physicists. Like Priest, one of the members, three of the others combined backgrounds in physics with industrial liaisons. Thus Harold Ives, at the United Gas Improvement Company, had invented the trichromatic colorimeter and initiated the program of characterizing 'standard' filters-light source-observer before world war I. Another, Loyd

Jones, was later chief physicist at Kodak Research Laboratories and longtime associate editor of the Journal of the Optical Society of America, and specialized in the physics of photography and colorimetry (Anon. 1944). The sole non-physicist, committee chairman Leonard Troland, had gained a PhD in psychology in 1915 and worked for two years at the Nela laboratory (Southall 1932). He was elected president of the OSA in 1922-3 and later held an academic post in psychology at Harvard while Research Director of the Technicolor Motion Picture Corporation.

An assumption of a fixed relationship between spectral wavelength and perceived color was implicit in the program followed by these researchers and committee members. In the original 1922 report of the OSA Colorimetry Committee, for example, color had been defined as:

> all sensations arising from the activity of the retina of the eye and its attached nervous mechanisms, this activity being, in nearly every case in the normal individual, a specific response to radiant energy of certain wavelengths and intensities (Troland 1922, 565).

Color was thus defined as a specific and replicable response to a physical phenomenon. Implicit in this was the assumption that, neglecting physiological differences between the eyes of individuals, color was an invariant sensation common to all observers.

The promotion of this physicalist interpretation of color can be attributed to more than merely physical consistency and analytical convenience. The physicists dominating the OSA, and indeed all the committees discussed here, sought to ratify the prevailing view of the contributing communities, i.e. to cause 'minimal disturbance to the network' (Collins 1985, 135).[26] The NBS, OSA and NPL consensus which produced the 1931 CIE system of color was a physicists' consensus.

Psychologists' color

The physicists' prevailing orthodoxy in colorimetry was increasingly threatened through the 1920s. Experimental psychologists developed a distinct perspective, seeing color intrinsically as a perception related not only to light itself but, even more importantly, to physiological and mental processes. The physicists, they claimed, had failed to model human perception, making a wide class of color measurement impossible and ill-defined.

The standards of measurement adopted by the NBS and NPL were based on very particular and, to psychologists, almost meaninglessly restrictive, viewing conditions. There, experimenters combined the data from a few participants observing a two- to three-degree bright, featureless patch of color against a black background into a presumed 'human average'. This proved successful for simple color measurements, such as determining the appearance of the light transmitted by color filters. But, argued psychologists, the apparent color of an object could depend on many additional factors.

To the physicists' definition in terms of the three physical attributes of hue, saturation and brilliance the German psychologist David Katz (1884-1953) added 'modes of appearance' such as lustre, glow, gloss, transparency and body color (Katz 1935).[27] Katz's work from the first decade of the twentieth century paralleled the rising Gestalt school of psychology. Widely influential from the early 1920s, this group of German researchers expanded their initial interest in the perception of movement to a longer list of visual attributes, including time-dependent color effects such as glitter, sparkle and flicker, the importance of memory effects, light and dark adaptation, the effect of after-images, and the difference in perceived color at the periphery of the visual field. Katz elaborated these perceptual aspects in his 'totality theory of the perception of illumination', stressing a holistic analysis and the importance of complex spatial relationships in perceived color (Katz 1935, xiii). Indeed, it has been argued that such 'holism' amounted to a German cultural style in the interwar period which seriously impeded international scientific connections (Harrington 1991). Whether or not they can be categorised as a cultural style, German psychological concepts proved attractive to some American workers, including the influential Leonard Troland.[28]

The very language and cognitive entities differed for the two communities. The idea of sensation adopted by physicists and psychophysicists such as Gustav Fechner was being criticized in the literature of psychology. As early as 1893, William James, professor of psychology at Harvard University, had argued that a sensation – a standard and repeatable conscious response to a physical stimulus – could not be realized except in the earliest days of life, because memories and stores of associations clouded the response (James 1892, 12). Instead, psychologists by the twenties were expunging discussion of sensation and replacing it with perception, i.e. a stimulus dynamically interpreted by the brain in combination with other physical attributes (Troland 1929a). Thus a sensation was increasingly seen as the constant 'core' response that an observer's perceptions might ideally approach. This linguistic substitution represented more than a mere terminological nuance, but rather a conceptual shift away from attempts at measurement. Yet psychologists were not as coherent a group as were optical physicists. Experimental psychology was itself divided by the diffidence many of its practitioners felt for the ability to measure 'social averages' (Danziger 1992). Indeed, some psychologists sought to stem the tide by demonstrating that perceptions could be quantified:

> Psychology will never be an exact science unless psychic intensities can be measured. Some authorities [e.g. James] say that such measurement is impossible. (Richardson 1929, 27).

This is not to say that psychologists neglected the feasibility of quantification, but rather saw color as an inherently complex mental construct rather than as a straightforward and obviously quantifiable response to physical conditions.

Differentiating the issues

The disciplinary disputes can be summarised by observing that physicists tended to 'cordon off' or exclude the importance of viewing conditions on color perception, while psychologists focused and elaborated upon them.

The disputes between psychologists and physicists did not originate after the First World War, even if they escalated then. The issues being reopened had been raised earlier in a more localized and intra-disciplinary context. As discussed by R. Steven Turner, the physicists' approach had been championed a half-century earlier by Helmholtz, who, despite his close associations with physiology, found his ideas criticized as too 'physicalist' and simplistic by the proposer of an alternate system, Ewald Hering. Helmholtz's theory found stronger support among physicists, while Hering's was defended chiefly by physiologists and ophthalmologists. Turner notes resentment of non-physicists to the 'veneer of mathematics' in German colorimetry of the 1890s (Turner 1994, 238, 251). Indeed, the debates concerning the relation of color to physical reality hearken to Goethe's criticism of the Newtonians in the first decade of the nineteenth century (Jackson 1994). Such metaphysical overtones do not appear to have been a consideration in the American debate.

Psychologists were thus seeking to deconstruct physicists' color to incorporate new and important phenomena. For them, 'decisions about the existence of phenomena [were] coextensive with the 'discovery' of their properties' (Collins 1985, 129). The interpretation of colorimetry divided these cognitive communities; the move to restrict color attributes was seen as progressive by physicists, but ad hoc by psychologists. The elucidation of 'modes of appearance' was seen as disruptive to standardization by physicists and industrialists but cognitively essential by psychologists. On another level, the technical divisions mirrored social organization; the desire to standardize units of commerce was favoured by physical scientists employed in intercommunicating national laboratories and industrial posts; psychologists, more frequently with academic affiliations, sought to bring new concepts and specialties into both their study of color and their broadening profession.[29]

The interpretative flexibility in colorimetry existed at three levels. Most fundamentally, color could be described either as a physical or mental entity. Secondly, the number of attributes required for a meaningful description of color was open. Physicists generally opted for three, along with stringent viewing conditions. Psychologists either postulated more perceptual attributes, or sought a deeper understanding for the dependence of color perception on environmental context. Thirdly, the precise definition of attributes – even when only three were invoked – was debatable. Thus color systems could be based alternately on a partitioning of color space into three additive (red, green and blue) or subtractive (cyan, magenta and yellow) components; or on less directly measurable quantities such as hue, saturation and brilliance; or on even more abstract entities such as chromaticity coordinates. The disputes between early color systems, including the contentions surrounding the adoption of the 1931 CIE standard, operated at the last of these levels. The OSA committee discussions centered on restraining the interpretations at the first two levels.

Yet certain issues were closed for both physicists and psychologists. Observations themselves were generally accepted (although the scope of observing conditions differed for the two communities). Thus by agreeing at least on the results of experiments in artificially restricted conditions, the debate was constrained to a manageable number of issues and color could be portrayed as a meaningful and replicable entity.

Voting on color

The use of a committee structure at the Optical Society of America and the CIE to study color was a consequence of their constitutions. It also indicated, however, an essentially confrontational standpoint and aura of compromise for the subject. Upon the formation of the first OSA Committee on Colorimetry in 1919, discord had soon become apparent between the four physicists and one psychologist of its membership. The difficulties centered upon the adoption of a physicalist versus a psychological view of color, and the consequences for the timing and content of a commercial standard for color description.

The early 1930s saw an acceleration of colorimetric activity in America owing to a combination of planning and contingency. The 1931 CIE meeting was a clear incentive for further organization, because the new international system was seen by (physicist) colorimetrists as being capable of further refinement and applicable to industrial problems. An Inter-Society Color Council was set up that year to define color designations of drugs and chemicals (Judd & Kelly 1939).[30] The Committee on Colorimetry of the Optical Society of America was reactivated in 1932 to extend the work undertaken at the CIE meeting on the Guild-Priest system of color measurement (Colorimetry Committee 1953), but Priest himself died the same year.[31] The original chairman of the OSA committee, psychologist Leonard Troland, also died in 1932, and was replaced by physicist Loyd Jones, the only member from the original committee. Despite the change of leadership, psychologists had a greater influence in the re-formed OSA committee than they had had a decade earlier.[32]

The even balance and differing philosophies of psychologists and physicists on the committee caused the meetings to be confrontational and stalemated. In a series of encounters through the 1930s, the committee members were split by their incompatible philosophies about the nature of color.

The original OSA committee report in 1922 had opted for a definition of color as a purely physical phenomenon – a definition that had carried through to the 1931 CIE standards. But when the question was reevaluated in 1932, the majority on the new committee proposed considering the perception-based psychological concept to gain a more wide-ranging, and potentially applicable, system of color description.. When they heard the first discussion paper detailing this concept, however, the members were split down the middle. The majority of committee members rejected the addition of spatial or temporal color characteristics, because the 'extra' attributes would be difficult to quantify or standardize.[33] Instead, they attempted a return to the limited 'physical' definition of color of the 1922 report, suggesting that it could be revised to make it acceptable to all members. Such a revision hinged on restricting the number of color attributes to the original three – hue, saturation, and brilliance – and in returning to the notion of color as a 'sensation', or replicable and determinate physiological response to a physical phenomenon (Colorimetry Committee 1953, 8-9). This move simultaneously left the existing CIE system unmarred while disturbing the philosophical foundations of colorimetry itself, because ‘sensations’ were implicit and uncontentious in the physicalist version.

Such a definition was still unacceptable both to psychologists, who increasingly subscribed to Gestalt precepts, maintaining that perceptions of color were highly dependent on the viewing conditions. It was unacceptable for opposite reasons to instrument scientists, who saw color as a physical phenomenon reducible to observer-independent data. The committee as a whole agreed that neither perspective could be sustained; color measurement, they decided, involved physical measurement and psychological factors which could, in the appropriate viewing conditions, be made adequately repeatable for standards to be practicable.

The stalemate between “physicists' color” and “psychologists' color” continued ‘for more years than the chairman likes to remember’ through 1937, when a proposal was published for nomenclature (Jones 1937). On this limited question, nearly unanimous agreement was obtained. Besides technical terms, though, the report attempted to relate the concept and measurement of color to that of light. Color was relegated to the psychological category, while light fell in the psychophysical category and radiometry in the physical category. Thus, for example, ‘radiance’ described a physical attribute (the amount of electromagnetic energy radiated per unit time into a unit solid angle), ‘luminance’ was the corresponding psychophysical unit and ‘brightness’ was the associated psychological unit. ‘Slightly more than half’ the committee accepted these definitions, with ‘no one. . . particularly pleased with the outcome’ (Colorimetry Committee 1953, 10). This lukewarm agreement led the committee to explore a definition of color as a psychophysical phenomenon.

Configuring compromise: color as 'Psychophysical'

The chairman of the original OSA committee, psychologist Leonard Troland, had earlier tried to marshal both the psychologists and physicists, writing:

> the term, light, is no longer used technically as an equivalent of radiant energy, whether or not the latter is ‘visible’. Light consists in radiant energy evaluated in terms of its capacity for evoking brilliance, when it acts upon an ‘average normal’ psychophysiological organism. Consequently, if we are interested to formulate psychophysical laws which have exclusively physical terms on one side of the equation, we must avoid the photometric concepts and use those of radiant energy, pure and simple. (Troland 1929b, 57).

And later:

> Light can neither be identified with brilliance nor with radiant energy. It has the properties of both, taken together. (Troland 1929b, 71).

Troland, the psychologist among the physicists, had sought to establish a crucial link between perceived color, physical measurement and mind.

According to Loyd Jones, the new committee chairman, the adoption of a psychophysical concept of color was a matter of compromise.

Initial reaction to a psychophysical concept of color in 1934 had been ‘quite unfavorable’. As described earlier, color was associated with different phenomena and practical goals for physicists and psychologists. When a report on the consequences of a psychophysical definition was tabled in 1935 the reaction was ‘not in the least enthusiastic’, because, according to Jones, only ‘a few had reached the point in their thinking where they felt that the psychophysical point of view should be considered. . .’ A second report was prepared to investigate these mixed physical-physiological-psychological definitions of color more fully before they were finally rejected (Colorimetry Committee 1953, 10). This had a more promising reception by the committee, because the debate had moved slightly away from philosophical underpinnings (i.e. the nature of light) to workable schemes for merging physical phenomena (e.g. spectral distributions) with mental responses (e.g. awareness of brightness and hue). Again Loyd Jones appealed to various members to elaborate the psychophysical scheme. David MacAdam, a 28 year old physicist at Eastman Kodak specialising in human color vision, tabled a report based on a psychophysical scheme in 1938.[34] The content of MacAdam’s report attempted to achieve a consensus by straddling both the CIE 1931 conclusions (based on the physicalist interpretation of color) and concessions to the psychological perspective (in which the mental contributions to color perception were acknowledged).[35] This synthesis of two perspectives was not well received. ‘A lengthy discussion indicated considerable dissatisfaction’, but the committee members agreed to give it further consideration (Colorimetry Committee 1953, 13).

A key argument mounted by MacAdam and Jones was that there were only two options available: either (a) to reclassify light itself from a psychophysical to a psychological phenomenon, or (b) to reclassify color from a psychological to a psychophysical phenomenon. Because of the prior work of photometrists (often associated with electrotechnical, rather than optical, specialties), light had since the turn of the century been interpreted as a psychophysical phenomenon, that is, a moderately repeatable mental response to a physical stimulus. The committee members generally agreed that light and color were similar entities, and hence should either both be seen as psychological or both as psychophysical. But prevailing practice militated against redefining the concept of light; photometrists were content with their definition. As Trevor Pinch has persuasively argued for the detection of solar neutrinos, the attainment of consensus is tied up with the degree of 'externality' of debate, that is, by how widely the decision affects other ‘facts’ or cultural groups (Pinch 1985). Applying Pinch’s interpretation, the existing networks of photometry sustaining ‘light as psychophysical’ were too difficult to break, and so the concept of color also defaulted to a psychophysical definition.

The contention surrounding the subject, and the difficulty in achieving consensus, is illustrated by the large swings in committee opinion through the decade. In the end, the committee delegated Deane Judd, the principal spokesman for psychology, and Arthur Hardy, representing the perspective of physics, to give final approval to the report.[36] MacAdam himself described the committee work as comprising ‘long discussions, multilateral deadlock, and finally exhaustion’ (MacAdam 1994). The result of this strained consensus was a definition of color as a carefully delimited aspect of light, which in turn was interpreted as a physiological response to radiant energy:

> Color consists of the characteristics of light other than spatial and temporal inhomogeneities; light being that aspect of radiant energy of which a human observer is aware through the visual sensations which arise from the stimulation of the retina of the eye (Colorimetry Committee 1953, 221).

Closure and senescence

The American committee took the hard-won psychophysical definition of color and its colorimetric units back to the next CIE meeting in June 1939. At the international level, acceptance was considerably easier, with no significant dissension. A few reasons for this can be suggested. A psychophysical definition, originally inspired by German psychologists, was congenial to the German delegates. The British delegates had maintained a close working relationship with their American counterparts and generally supported their mixed units. Other nations were not immediately concerned with the conceptual points tied up in the new metrics and had fewer practical pressures to endorse any particular scheme. The psychophysical definition of colorimetric units was tabled as a discussion paper and quickly ratified. The psychophysical concept of color thus suffused from an American committee into the international realm by way of the CIE.

The debates of the 1930s were never reopened by the formal committees. In America, though, there were open disagreements between the physical and psychological camps into the early 1940s. Physicists and psychologists continued to write about how they 'aimed at reconciliation of opposing points of view'.[37] The cracks were rapidly disappearing, however. An OSA editorial soothed that the 'field of colorimetry will soon supply another example of cooperation among scientists' (JOSA 1940). Collins' discussion of the invisibility of social factors after a consensus appears particularly apt here (Collins 1985, 142-145).

The subject stabilized after the war.[38] When the Optical Society of America finally published its definitive book <u>The Science of Color</u> (Colorimetry Committee 1953), the controversy was vanishing. The book proved to have a role in capping the debate: the completed chapters, written principally by Jones and Macadam, had appeared sporadically in the <u>Journal of the Optical Society of America</u> between 1943 and 1951. The first chapter, in which the debates of the 1930s were sketched, was followed by nine chapters in which color was expressed solely and incontrovertibly in psychophysical terms (Jones 1943; Colorimetry Committee 1953). The committee work of restricting colorimetry to a mathematical model and defining it as a shared property of mind and matter was complete. H. D. Murray summed up the situation in his book of the same period:

> Simplification of complex situations is a feature of all physical measurement and it has been nowhere more extensively applied than in subduing color to the requirements of measurement. (Murray 1952, 264).

Subdued and yoked to its intended applications, color measurement became less contentious (Kelly 1974). That is, the philosophical basis of colorimetry no longer triggered controversy once the committees were disbanded and practical issues came to the fore. Key historical actors, ceasing to exist, no longer focused the issues. By emphasizing the utilitarian goals (standardization) over theoretical foundations (i.e. the physical, psychological or physico-psychological basis of color), a mundane consensus was achieved for a broad technical community (delegates to the CIE). For Deane Judd, editing a collection of papers on the Munsell color system, it proved difficult even to explain to a non-specialist readership the nature of the controversy. Psychological vs. psychophysical concepts of color had, he emphasized, either been seen as 'unproblematic' or as 'so utterly different in their concepts that there is no possibility of correspondence'. And, he cautioned, 'there are possible many psychophysical color systems' (Judd 1940, 574). Similarly, the Inter-Society Color Council (ISCC) was careful to stress the limited nature of the agreement: 'These definitions of color, hue, saturation and brightness do not express a unique coordinate system, for they may be related to other sets of coordinates that may be more practically useful. . . . They represent a cultural development upon which there is reasonably general agreement' (Burnham, Hanes & Bartleson 1963, 5).[39] Thus the social contingency of the standard was apparent to some of its key negotiators, but not to all their contemporaries.

Yet the enveloping consensus did not progress to a Latourian autonomy for the 'winning side' controlling the greatest resources. The CIE mathematical system remained highly popular, but more empirical systems such as Munsell, Pantone and even Lovibond continued to be used widely for specific types of color comparison. Nor did the subject retain the high profile it had enjoyed during the 1930s. The decline in institutional interest is illustrated by the case of the National Bureau of Standards, where color research was shunted between departments seven times between 1948 and 1974, finally ending up as part of the Sensory Environment section of Building Research. It had thus been pigeon-holed into a slot far removed from its turn-of-the-century general research.

Conclusions

Different constituencies of color – disciplinary, practical and international – shaped the controversies in the subject and determined how they were eventually resolved. These factors embodied in the present CIE system of color are not all intrinsic in the science but arose from a range of historical situations – both in terms of the different conventions present in physics and psychology, and by interwar politics. Color measurement was a subject fashioned in a particular cultural and political context by heterogeneous committees. The scale of construction was not intrinsically individualistic (through experimentalists and synthesizers such as Irwin Priest, John Guild and Leonard Troland) nor centered in laboratories (such as the NBS and NPL). These particular actors were given prominence by the circumstances pertaining between the wars.

The formal structure and rigidity suggested by the decision-making bodies belied their transient compositions and contingent decisions. The distribution of the committee memberships controlled the dominant philosophical view and the form of standard adopted. Thus an evolved version of the three-color theory of Maxwell and Helmholtz formed the basis of the international system because it was socially accepted as an operational concept by physicists and physiologists and, in restricted circumstances, by psychologists.

Committee-based colorimetry proved an ineffective method of reaching agreement. Disputes were both drawn out in the time between meetings and all too quickly debated in person. The dynamics of consensus were considerably more turgid than were debates between physicists alone, for example.[40] Nor were all constituencies equally satisfied: the CIE system of color proved popular with physicists but less so with psychologists.

The cultural schisms in colorimetry (technological vs. scientific, Anglo-American vs. German, physical vs. psychological) made it peripheral for several communities and determined the method and shape of consensus. In such conditions, committees became the central, if fugitive, historical actors.

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NOTES

[1]An earlier version of this paper was presented at a seminar in the History & Philosophy of Science Division of the Philosophy Dept, University of Leeds in March, 1994. I would like to thank two anonymous referees, Geoffrey Cantor and Graeme Gooday for providing very helpful criticism, and David MacAdam for informative correspondence.

[2]The connotation of the term 'social construction' here is broadly consistent with that employed in the rather divergent literature (Sismondo 1993). The construction in this case, however, is at a different level: in the sense of the formation of a scientific subject by formal collectives of practitioners rather than the synthesis of knowledge or experimental evidence.

[3]Colorimetry sits awkwardly in a Kuhnian analysis for two reasons. First, 'pre-paradigm' and 'revolutionary' periods are difficult to identify in this subject and arguably telescope into the brief period discussed in this paper. Second, the 'incommensurability' is across disciplines rather than time periods.

[4]Simon Schaffer (1989) has explored the controversies surrounding the assumptions underlying, and difficulties of replicating, Newton's colorimetric work.

[5]Colorimetry, and the closely associated subject of photometry, straddled the technology/science divide and attracted the interest of a heterogeneous variety of specialists in institutions, industry and academia (Johnston 1994, 1996).

[6]The use of indicator solutions to infer content from color dates back at least to Gabriel Fallopius in 1564 (Debus 1962).

[7]Color charts arguably are embodiments of particular theories more clearly than are Bachelard's instruments. As summarized by Gooday, subsequent historical studies have tended to erode the presumed linkage between a theory and the status accorded to the corresponding instrument (Gooday 1996). A color chart, however, directly maps a unique theory onto the physical world.

[8]For details of this work, and of the competition between the views on color perception propounded by Hermann von Helmholtz and Ewald Hering, see Turner 1994, esp. 235-280. The present paper is complementary to his historical account, extending its color measurement aspects to the international stage which came to dominate the subject after World War I. See also Cahan 1993. An earlier, positivistic history of color science was given by P. J. Bouma (Bouma 1944, 199-222).

[9]The wartime color perception research was, however, popularized, for example in descriptions of camouflage in a popular illuminating engineering text (Gaster & Dow 1920).

[10]For a description of the American 'crusade for standardization' between the wars, see Cochrane 1966, 253-263.

[11]Not to be confused with the National Electric Light Association, founded in 1885 and dedicated to promoting the interests of power utility companies. This earlier and better known NELA was renamed the Edison Electric Institute in 1933.

[12]These included the British Photographic Research Association (1918), the Scientific Instrument Research Association (1918), the Research Association for the Woolen and Worsted Industries (1918), the Glass Research Association (1919) and the Research Association of British Paint, Color and Varnish

Manufacturers (1926). The findings of the RAs were considered proprietary and for the exclusive use of the member companies; the DSIR could veto their communications to foreign individuals or companies. Such commercial secrecy inhibited dissemination of knowledge in color measurement, and placed British workers at a disadvantage compared to their American counterparts (Varcoe 1970; 1974).

[13]The completely independent but similar research by the two groups continued throughout the 1920s. The overlap of work was considerable: in 1924, the Photometry Division began work on color filters that had been undertaken by the Optics Division two years earlier; in the same year, the Optics Division did preliminary research on instruments intended for color photometry that had already been completed by their counterparts in Photometry. Color standardization work was carried out by the Optics Division for the Physics Co-ordinating Research Board; the Photometry Division was motivated by their responsibilities as delegates to the Commission Internationale de l'Éclairage and as collaborators with the National Bureau of Standards in Washington (NPL 1924, 77).

[14]This was substantially an American phenomenon. By contrast, in Britain Silvanus Thompson had been trying since about 1903 to organize a similar group, along with institutionalized teaching facilities. This was only partly successful, with the Northampton Institute and Imperial College becoming centers for technical optics in London. In France, the optical society was firmly in the control of academics, and treated primarily instrumental optics. Despite the formation of the Institut d'Optique in 1920, the industrial-scientific-governmental linkages in French optics were weaker than in Germany, although training was better organized than in Britain and America (Paul 1985, 311-312, 340-353; Williams 1994, 139-144). Dominique Pestre has discussed the 'rapports inéxistants' between the physics community and industry during this period (Pestre 1984, 238-241).

[15]This had been preceded by an earlier summary (Colorimetry Committee 1920). Copies of the unpublished 50 page report of 1919 were provided to American parties who had expressed an interest in color measurement, principally at the NBS, two universities and four companies (Kelly 1974).

[16]The difficulties of determining the intensities of differently colored lights had not been obvious to all investigators. One of the earliest, Pierre Bouguer, noted 'a comparison of two lights of different colors in the way that we prescribe is chiefly embarrassing in case it is necessary to do it with more care, that is to say, when the two intensities closely approach equality; but there is a point where one of two lights will certainly appear more feeble. We have then only to take the mean between these two limits' (Bouguer 1760, 73). The early confidence in the ease of color matching was eroded by the experiences at standards laboratories in the first two decades of this century.

[17]My translations. Although Fabry retained his position for an unusually long period in the CIE, the American contributions (from E. C. Crittenden of the NBS, and E. P. Hyde and Taylor of Nela) outnumbered his reports by three to one. The differing views for a new committee cannot be seen, however, as a simple desire of the existing committee to retain control. Rather than wishing to explore all aspects of color in an expanded version of the committee, the members wanted to omit all question of color measurement until they, and other physicists, had cautiously investigated practical techniques for removing its effect from photometric measurement. The two positions amounted to either including or excluding colorimetry from the study of photometry.

[18]Three members had been sought, but only two were proposed. The appointed members were Irwin Priest of the NBS and T. Smith of the NPL. Smith, the

provisional head of the Optics Division, was not present at the CIE session. The proposers were unaware of the work already underway by John Guild of the Division, who performed all colorimetry work at the NPL until Smith collaborated in the early 1930s.

[19]For the American activity during this period see the publications of the Colorimetry Committee (Colorimetry Committee 1929).

[20]Although there was a large body of German work following the physiological optics research of Helmholtz and Hering from the 1860s, this was relatively unknown and made little impact in England and America. American physicists generally preferred American research.

[21]'The National Illumination Committee of Great Britain comprised 18 organizations and government departments in 1927 (Anon 1928).

[22]The data represented the mean measurements of ten observers measured by research student William Wright at Imperial College in 1929, and seven subjects provided by the Research Association for the Woolen and Worsted Industries, measured by Guild at the NPL from 1926 to 1928 (Guild 1934).

[23]The Japanese delegation of seven persons did not table a paper or participate in the discussion periods; no record of their contribution appears in the minutes. The German work was limited to more careful definitions of a standard 'white point' using CIE color coordinates, and the brightness of test surfaces. This 'fine-tuning' did not materially extend the scope of colorimetry.

[24]The German delegate, Dresler, recommended a new standard 'illuminant E' to add to the existing three illuminants. Other delegates criticized its poor approximation to sunlight, the adequacy of the existing 'illuminant C' for this purpose, and the desirability of <u>reducing</u>, rather than increasing, the number of standards (CIE 1939, 40-42).

[25]Collins (1985, 142-145) notes the characteristics of core-sets, and emphasises their private nature, i.e. the 'covering up' of social factors once a 'fact' has been constructed. The 'invisibility' of the social interests here is underlined by the (lack of) importance accorded to them by the historical actors: no records of the pre-war OSA Colorimetry Committees are extant.

[26]Andrew Pickering's history of quarks has illustrated how physicists reached consensus by attempting to maintain alliances regarding social norms of experimental practice and theoretical conceptions (Pickering 1984).

[27]The 1935 English edition was preceded by German editions in 1911 and 1930.

[28]Most American psychologists first became aware of Gestalt principles when English editions by the three principal Gestalt psychologists (Max Wertheimer, Kurt Koffka and Wolfgang Köhler) appeared in 1922, 1922 and 1925, respectively, and when the three immigrated to America following Nazi persecution in the 1930s. Troland publicized the Gestalt approach in his writings, noting, for example, 'the subjective study of color. . . in respect to those nuances which the German psychologists call. . . modes of appearance offers a fascinating field for investigation' (Troland 1929, 233).

[29]Danziger (1994, 136-155) discusses how psychologists embraced quantification as a means of simultaneously grounding, justifying and extending their subject.

[30]The diversity of groups concerned with color is illustrated by the ISCC members, which included the American Association of Textile Chemists and Colorists, American Ceramic Society, American Psychological Association, American Society for Testing Materials, Illuminating Engineering Society, National Formulary, American Pharmaceutical Association, Optical Society of America,

Technical Association of the Pulp and Paper Industry, and the United States Pharmacopoeial Convention.

[31]Contingency repeatedly directed colorimetry: Priest spent 'many years of labor' on 'an exhaustive treatise giving the results of his studies and conclusions' for the specification of white light, which was left unpublished when he died (Ives 1932).

[32]The reformed OSA committee had a five-fold larger membership than the 1919 version. The 23 members of the 1932 committee included 11 from industry, 4 from government, 3 from universities and 5 with unlisted affiliations. Consisting 'almost entirely of industrial and government technologists', according to David Macadam, 'most members of the 1933-1953 committee had little experience with colorimetry' (MacAdam 1994).

[33]'Additions to colorimetry' is a leading description, but the majority of committee members at this point saw a psychological basis for colorimetry as a complication to already-developing colorimetric practice, based on the work proceeding in physical laboratories and the rapidly applied CIE coordinate system.

[34]MacAdam was a research associate at Eastman Kodak from 1936, when he obtained his PhD. His association with the OSA began earlier, becoming a member of committees from the 1930s, Fellow in 1932, a director 1942-45 and President in 1962. He was later to trace the history of color metrics from an unproblematic 'internal' viewpoint (MacAdam 1970).

[35]Its author noted that his devised measuring units and definitions were strongly influenced by physicist Percy Bridgman's philosophy of operationalism, citing passages such as the following: 'Physics, when reduced to concepts [defined in terms of their properties], becomes as purely an abstract science and as far removed from reality as the abstract geometry of the mathematicians, built on postulates. It is the task for the experiment to discover whether concepts so defined correspond to anything in nature.' (Bridgman 1927, 4-5). This was reiterated by the ISCC committee: 'in the science of colorimetry a great many years were spent deriving a precise operational concept of color which would represent a careful specification of operations performed' (Burnham, Hanes & Bartleson 1963, 3).

[36]D. B. Judd, the Munsell research associate at the NBS, had adopted a psychological concept of color in contrast to his predecessor Irwin Priest. A. C. Hardy, professor of Optics and Photography at MIT, had supported a physical basis for color measurement from the early 1920s, when he designed and promoted his recording spectrophotometer (commercialized in 1935 by General Electric). The voluminous data in his MIT Handbook of Colorimetry persuaded practitioners of the reliability and applicability of the new CIE system.

[37]See, for example, a special issue devoted to the Munsell Color System in JOSA 1940. As late as 1944, evidence seemed to show that heterochromatic photometry could not be made to give consistent results (Wright 1944).

[38]The publishing of The Science of Color in 1953 was contemporaneous with the adoption in America of the National Television System Committee (NTSC) standard for color television. The earlier colorimetric research that informed the report was directly applied to the technical decisions taken by the television committee (Carnt & Townsend 1961). On the other hand, earlier color television systems (e.g. J. L. Baird's system of 1928) implicitly drew upon the Maxwell-Helmholtz theory which formed the foundation of the CIE system of color.

[39]This positivistic ISCC catechism classified the definition of color as a 'basic fact', colorimetry as 'applied facts', and color vision theory as 'marginal facts' (Burnham, Hanes & Bartleson 1963, vi). Two of the OSA colorimetry committee members

served on the ISCC committee, and four others, including Deane Judd, reviewed the report.

[40]The case of the discovery of magnetic monopoles was settled in a three-year period primarily, according to Pickering, because the participants agreed to conduct the debate within a static set of socially-accepted concepts (Pickering 1981). For colorimetry, the existence of distinct acting troupes following different scripts and with awkward staging led to a more lengthy resolution.