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From eye to machine: Shifting authority in color measurement

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Introduction

Given a subject so imbued with contention and conflicting theoretical stances, it is remarkable that automated instruments ever came to replace the human eye as sensitive arbiters of color specification. Yet, dramatic shifts in assumptions and practice did occur in the first half of the twentieth century. How and why was confidence transferred from careful observers to mechanized devices when the property being measured – color – had become so closely identified with human physiology and psychology? A fertile perspective on the problem is via the history of science and technology, paying particular attention to social groups and disciplinary identity to determine how those factors affected their communities' cognitive territory. There were both common and discordant threads motivating the various technical groups that took on the problems of measuring light and color from the late nineteenth century onwards, and leading them towards the development of appropriate instruments for themselves.[1]

The transition from visual to photoelectric methods *could* be portrayed as a natural evolution, replacing the eye by an alternative providing more sensitivity and convenience – indeed, this is the conventional positivist view propounded by technical histories.[2] However, as other case studies have demonstrated, the adoption of new measurement technologies seldom is simple, and frequently has a significant cultural component.[3] Beneath this slide towards automation lay a raft of implicit assumptions about objectivity, the nature of the observer, the role of instruments, and the trade-offs between standardization and descriptive power. While espousing rational arguments for a physical detector of color, its proponents weighted their views with tacit considerations.

The reassignment of trust from the eye to automated instruments was influenced as much by the historical context as by intellectual factors. I will argue that several distinct aspects were involved, which include the reductive view of color provided by the trichromatic theory; the impetus provided by its association with photometry; the expanding mood for a quantitative and objective approach to scientific observation; and, the pressures for commercial standardization.

As suggested by these factors, there was another shift of authority at play: from one technical specialism to another. The regularization of color involved appropriation of the subject by a particular set of social interests: communities of physicists and engineers espousing a 'physicalist' interpretation, rather than psychologists and physiologists for whom color was conceived as a more complex phenomenon. Moreover, the sources for automated color measurement, and instrumentation for measuring color, were primarily from the industrial sphere rather than from academic science.

To understand these shifts, then, it is necessary to explore differing views of the importance of observers, machines and automation.

The nineteenth-century context: the questionable centrality of the observer

The judgement and description of color was based traditionally on visual observation. A dyed fabric, painted wall, glazed ceramic or brewed potion would be compared by its producer to memory or to an available example of the desired color. For such applications, color was seen as unproblematic; the observer merely confirmed what evidently was there.

This understanding of color as being a property of objects, and external to the human senses, was promoted by another implicit assumption: that the only 'proper' light was daylight. The candle, gas and kerosene lighting of the mid nineteenth century were commonly considered to be imperfect substitutes for the rich, balanced tones of sunlight.[4] Hence, variations in perceived color were attributed to improper viewing conditions rather than to complexities of the visual process. Color, and its potential variability, were externalized. Stabilize the viewing conditions, it was argued, and one rendered color judgement reliable. Such assumptions supported straightforward color descriptions and routine evaluation. In short, standardization avoided problems.

Scientific investigations supported this utilitarian view of color by promoting a 'physicalist' interpretation of color perception, linking the perceived color to the wavelengths of the light source and to the spectral characteristics of the illuminated object. According to the trichromatic theory elaborated successively by Thomas Young, Hermann von Helmholtz and James Clerk Maxwell, the eye itself could be understood as a three-component sensor responding to red, green and blue components of light.[5]

There was, however, discordance in this straightforward acceptance of visual observations. The very notion of measuring color attracted criticism, focused initially on criticisms of *photometry*, and centered on undesirable human factors in the evaluation of brightness. Color description, in the physicalist interpretation, was a simple generalization of the unambiguous technique of determining brightness. The measurement of any color could be reduced to three *photometric* measurements: a measurement of intensity through a red, a green and a blue filter.

Yet some practitioners of the photometric art questioned the reliability of their measurements. Photometry itself appeared intrinsically to be an imprecize demi-science, owing to the vagaries of the human eye. They concluded that they could be misled by inadvertent prejudice, and that the matching of two lights by eye was prone to psychological bias. One of the first to voice this concern was Benjamin Thompson, who in 1794 had employed a double-blind method to avoid the problem of being 'led into temptation'.[6] Helmholtz later wrote of visual measurement that

> the whole region is closely entangled with physiological problems of the utmost difficulty, and moreover the investigators who can make advances are necessarily limited, because they must have long practice in the observation of subjective phenomena before they are qualified to do more than see what others have seen before them.[7]

Even careful attention to technique by meticulous observers resulted in measurements that were of doubtful accuracy. Measurements were affected by several subtle considerations that could be easily missed by a novice investigator. 'Bare directions will not suffice', wrote the author of another guide,

> but the practitioner must bring to the task a judgement trained for instrumental manipulation and an appreciation for the many modifying influences that the measurements which he obtains may possess in value.[8]

When differently colored lights were to be compared, even this care was not enough. Because of the differences in the color responses of different observers, no amount of repetition or control of viewing conditions could remove the inherent personal bias.

The industrialization of color

Despite these unsettled and unsettling foundations, practitioners of colorimetry continued to rely implicitly on visual photometry. Most practitioners by the late nineteenth century saw themselves as engineers rather than as scientists. Gas inspectors, in fact, a common feature of towns in the second half of the century, became the principal users and developers of photometry during that period.

Indeed, most research on the subject became associated with the lighting industry: the rise of electric lighting from the 1880s led to immediate competition with gas illumination. The measurement of color was inextricably part of a growing system of standardization and testing. Gas and electric lighting were of distinctly different colors (as were different gas mantle and electric filament technologies). Inter-comparison therefore required the resolution of what was termed the 'heterochromatic photometry' problem: how to determine a quantity called 'brightness' for such different light sources, when their colors complicated matters? Like the measurement of illumination, interest in the measurement of color had strong utilitarian motivations. Dye production had expanded dramatically after the development of synthetic dyes in the second half of the nineteenth century, and by the turn of the twentieth century dye chemistry was a major industry, accompanied by the growth of research laboratories.[9] 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, lamp characteristics and surface finish. These applications also promoted a simple reductionist description of color: colors were to be evaluated in isolation, or by comparison only with a reference standard; they were interpreted as *static* properties that did not change with time; and, they were seen as *intrinsic* characteristics of the products being manufactured.

Proponents of gas and electric lighting both appropriated photometry as a tool to support their claims about the stability and cost efficiency of their products. This, in turn, drove further refinement of color measurement to make it better able to detect subtle differences between light sources.

From a handful of consulting engineers, such research moved to industrial laboratories from the turn of the century. Important research on color was undertaken, for example, at the United Gas Improvement Company in London; the National Electric Light Association (NELA) Research Laboratory in Cleveland, Ohio; at the Westinghouse laboratory in Pittsburgh, Pennsylvania; the Eastman Kodak lab in Rochester, New York; and the British General Electric Company in London.

Governments, too, were developing an interest in more precise measurement of light and color. Photometric and colorimetric standards became a responsibility of the new national labs at the same time: the Physicalisch Technische Reichsanstalt (PTR) in Germany, the National Physical Laboratory (NPL) in England and the National Bureau of Standards (NBS) in America.

Such institutions sought to refine measurement techniques based on human observers. By the First World War, it was not unusual to repeat visual photometric observations several hundred times to obtain adequate precision.[10] But even careful attention to time-consuming technique by meticulous observers resulted in measurements that were often of doubtful accuracy because of the differences in the color responses of different observers' eyes. This proved to be a serious problem in evaluating standard lamps, which varied in yellowness of tint. The comparison of the pentane standard – the late-Victorian national intensity standard adopted in Britain – with a carbon filament electric lamp, necessitated the drafting of all available technical staff at the National Physical Laboratory as observers to obtain an unbiased mean.[11]

These energetic and costly programmes to normalize the observer were only possible in large institutions. For industrial applications, a biased visual judgement appeared unavoidable. The reputed imprecision of photometry and colorimetry restricted the usages to which they were applied; in turn, the undemanding usages placed little pressure on practitioners to improve their technique. This circle of low expectations – imprecise results – poor reputation – low expectations thus relegated the measurement of light and color to the depths of the scientific toolbox. By the opening decade of the new century, then, the measurement of color was commonly seen as fundamentally limited, owing to the treacherous human eye.

What could machines do?

Assumptions – often implicit, and not necessarily shared by all practitioners – that color was a property external to human perception, that color judgement demanded a standardization of observing conditions, and that the eye itself was problematic – paved the way for the acceptance of automated methods.

Several communities were concerned with the 'control' of color at the turn of the twentieth century: engineers and industrialists tasked with judging the color of products, physicists responsible for national standards, and astronomers characterising stars. Each drew its expertise from the physical sciences; each implicitly accepted the physicalist view of color.

These groups sporadically considered the replacement of the human observer by a more reliable alternative. Three attributes, only weakly coupled, were behind this: the desires for (i) quantification, (ii) objectivity and (iii) automation.

Quantification

The rise of a quantitative perspective in science, peaking in the late nineteenth century, has been well documented.[12] Lord Kelvin's view, that only 'when you can measure what you are speaking about, and express it in numbers' can you 'know something about it' and 'advance to the stage of science', soon attained the status of unquestioned truth. The dictum also related quantification to occupational status. Scientific and engineering professions were emerging with increasing frequency at the turn of the twentieth century, in parallel with a rise of technical employment in industry. Measurement served both a disciplinary and social function, providing a cachet of scientific respectability and progress for subjects that did not yet have a disciplinary focus.

Objectivity

From the turn of the century, there was an increasingly pervasive mood in the physics community for ‘objective’ measurements (as opposed to the ‘subjectivity’ of the human eye as an observational tool). Visual observations, it was argued, even when stabilized by elaborate experimental protocols, were too reliant on indefinable factors – psychological bias, personal variation and fatigue – to allow precision adequate for commercial purposes. ‘Observer-independent’ methods were claimed by many engineers and physicists to be objective because they would be free from the distortions and complications of human vision, influences that were suspected even if not entirely elucidated. By removing the difficult-to-control human contribution, the quantification would be rendered simpler and intrinsically more trustworthy.[13] And having recently tamed inanimate standards such as resistance, technologists were confident that the measurement of brightness and color could be controlled equally satisfactorily by concerted effort.[14]

But scientific fashion played an important role in promoting this view. Indeed, photodetectors based on physical effects were imbued with very different characteristics (if mostly unconfirmed at this time). Yet, physical detectors had no shortage of ‘distortions’ and ‘complications’ of their own. Indeed, the very definition of a ‘distortion’ hides an underlying definition of normality. The changing fashion was aided by the appropriation of the subject by influential technical communities. There was a two-fold claim to objectivity: first, that color itself is objective, a property of objects rather than a perception constructed by the human visual system; and second, that *measurement*, too, should be objective, by using physical apparatus. The eye, it was argued, was objective only in principle.[15] And the properties of instruments could themselves be measured and regularized in a way that human observations never could be.

By the First World War, for example, American investigators claimed to have developed a physical alternative to the eye. Consisting of the combination of a thermopile and a filter to screen out invisible radiation, they touted it as an ‘artificial eye’.[16] The central problem was to transform the spectral response of the radiometer (which responded almost equally to wavelengths over a very broad range) into a close approximation of the very uneven color response of the human eye. Practical problems, however, centered on the feeble response of such a system to visible light. ‘The degree of sensibility required is very high’, wrote the inventor, suggesting that the refinement of thermopile design and galvanometer sensitivity was severely limited.[17] He was to write sixteen years later that 'the possibility of using some form of radiometer as a substitute for the eye has been a long-standing dream', but evidently one not yet realized satisfactorily.[18]

Automation

As with quantification and objective measurement, the argument for automating color measurements was part of a general trend in engineering and industry.[19] This was supported by economic factors: the de-skilling of measurement, for example, enabled mass production of standardized products, and automated measurement promised greater speed and lower labour cost.

For practitioners trained in the physical sciences, then, machine measurement of color promised distinct advantages such as better precision, objectivity or speed than the eye could provide. Along with these practical promises, however, physical methods required a shift of epistemology. The physical scientists who took it up saw colorimetry no longer as a common-sense procedure intimately tied to human vision, but as a branch of energy measurement closely linked with spectrophotometry. By re-interpreting it in this way, they reclassified the eye, making it merely one of the more unreliable detectors of radiant energy, rather than as the central element in a perception-oriented technique.

Thus, instruments had the capacity to do things human observers could not. They could regularize the measurement of color, and regulate it both numerically and legally. They could, in fact, validate human observations, serving as a standard that normalized visual experience. In so doing, instruments de-privileged visual observation, reclassifying it as individualistic and second-best. This tailoring of colorimetry to the conceptions of physical scientists proved irresistible in the commercial world.

The trajectory of automation

While the intellectual environment was favourable for the advance of automation at the turn of the century, there were deep practical roots for this technological inclination.

Early measurement technologies

The human observer of color had long been assisted by various aids, intended to enhance discrimination or to bolster memory. The earliest of these could be termed 'paper-based' technologies. In the first half of the nineteenth century, several systems had been proposed for describing or mapping colors. These were usually based on color charts that divided color into a few distinct dimensions, constructions pursued earlier by Newton and Goethe. But these systems were devized for, and of interest to, distinctly separate groups: artists, bird fanciers, flower enthusiasts and industrialists – all having distinct ideas of color measurement.[20]

Color-measuring instruments appearing through the late nineteenth century, such as those devized by Hermann von Helmholtz, James Clerk Maxwell, William de Wiveleslie Abney, could be described as *adjustable* or *interactive* color charts, because they permitted mixing two or three colors to create the perception of another.[21] These devices had two effects. First, they promoted the trichromatic theory, demonstrating that the colors perceived by humans could be synthesized from three primaries. This had a stronger intellectual basis than many of the *ad hoc* divisions of color space earlier in the century, and attracted physical scientists particularly. Second, these instruments argued persuasively that color could be usefully expressed by the measurement of a few numbers.[22]

Such devices gave credence to colorimetry as a quantitative study. This was a limited and highly reductive sort of analysis, to be sure, but still one that allowed practical applications and great scope for research.[23]

Attractive alternatives

New varieties of so-called 'photocells' and 'photoelectric tubes' proliferated between the 1870s and 1920s and were proposed periodically as solutions for routine photometry and colorimetry.[24] The photosensitivity of selenium had been discovered in 1872 and was repeatedly proposed as a close electrical analogue of the eye, notably by the industrialist Werner Siemens.[25] A turn-of-the-century practitioner was optimistic but not entirely accurate, reporting that 'light of all refrangibilities from red to violet is effective' and that 'a mere pin point of sensitive surface is as effective as a square centimètre'.[26]

Samuel Langley invented the *bolometer* in 1880, a detector consisting of a thin metal strip that changed resistance with temperature. This joined the thermocouple and thermopile as a sensitive detector of heat, and light radiation. The quantitative use of such electrical devices was made more practicable by the development in 1882 of the D'Arsonval galvanometer.

The selenium cell was joined, in the second decade of the twentieth century, by the phototube. This thermionic valve having a photosensitive cathode was developed into a variety of sizes, materials and constructions. Physicists, in particular, were strongly drawn to phototubes for the same reasons that they rejected the human eye: such tubes could be understood. While contemporary theory was inadequate to explain the behavior of selenium, phototubes were based on the photoelectric effect, a phenomenon amenable to concerted research. Phototubes were part of the new physics, elevating photoelectric devices from mere components for inventors to the subjects of research in their own right. These new devices were both a fascinating technical challenge and means to advancement for physicists in industry.

Making machines work

The shift towards objective measurements was consolidated by technological change between the world wars. The inter-war period was a turning point, characterized by active development of non-visual, quantitative and automated instruments for color measurement.

Engineering practice, centring on visual methods, had remained little changed from the 1870s until the 1920s for the vast majority of colorimetric work. By the Great War, however, there was an independent trend by astronomers towards physical methods of stellar measurement that were based principally on photography. Laboratory spectroscopists also took up these photographic methods after the war.[27] Physicists, on the other hand, increasingly investigated photoelectric measurement techniques. As they gradually resolved many of the technical limitations of these detectors, other scientists began to adopt them for light and color measurement by the late 1920s.

This merging of method saw the newly categorized 'subjectivity' of visual photometry decisively rejected for the 'objectivity' of physical techniques. This gradual process, repeated in each technical community, involved the recasting of colorimetry into a less problematic form. In the process, the human component of the measurement chain was minimized, and the observer was made ever more remote. Nevertheless, the limited successes of the first decade of photoelectric instrumentation highlighted an earlier concern: how reliable were the measurements, and how did they relate to human perception? The new technologies proved, in their own ways, to be as troublesome as visual methods had been. The superiority of physical detectors over the eye was a matter of scientific *faith* rather than reality; photodetectors of the 1920s were fickle and highly fallible.

The mapping of what were, at the time, largely illusory properties onto these physical detectors was begun by the astronomers, for whom visual observation of star magnitudes and color were particularly difficult. Most astronomers designed their own. In England, A. F. and F. A. Lindemann published the first account of the details of photoelectric apparatus and methods for astronomical photometry in 1919.[28] The potassium phototube responded most strongly to blue-violet light, while the response of the caesium type peaked in the yellow portion of the spectrum. That the photocells responded differently to light than did the eye did not deter them; indeed, the Lindemanns marshalled it as a demonstration of the *success* for the new technology. They described the fabrication of photocells having potassium and caesium sensitive surfaces, noting that the two types could be used to measure a 'color index' for stars. Thus the astronomers recast the stumbling block that had dissuaded lighting engineers into a pedestal to extend their own observational grasp.

Physical detectors had other disadvantages besides responding to colors differently than did the eye. They tended to produce erratic or drifting signals because of temperature and chemical change, ageing and instability, and nonlinearity of the early electronic circuitry. By the mid 1920s systems of compensating for the (very different) intrinsic defects of such devices had been devized, making them roughly the equal of the human eye for some photometric applications.[29]

Enthusiastic proselytising by early proponents was also important, as illustrated by the American physicist Arthur Hardy. Hardy had begun to study problems in the field of color printing when he joined MIT in the early 1920s. Realizing that 'a great mass of spectrophotometric data would be required', he sought an alternative to visual color analysers, which typically were used to make measurements at thirty discrete wavelengths in the visible spectrum. The available 'Thalofide' cells, a compound of thallium sulphide that changed resistance when illuminated, gave erratic results. Like the Lindemanns before him, Hardy did not judge this extreme variability to be a disadvantage. He noted that 'this erratic behavior was not altogether unexpected. Neither was it a great disappointment because of the almost certain necessity of employing vacuum tube amplifiers, which at that time were almost as erratic.'

Hardy's first automatic instrument could yield good visible-range spectra in as little as 30 seconds. The prototype was soon being used to record as many as 3000 spectra in a single month.[30] Hardy's enthusiasm was contagious. His recording photoelectric 'color analyser' was widely publicized. The instrument was adapted and commercialized by General Electric in 1935 as the first automated recording spectrophotometer.[31] His later production of the *Handbook of Colorimetry* argued for the superiority of automated devices over the eye by sheer quantity of data. Through such convincing demonstrations, colorimetry became closely allied with, and directed by, the disciplinary and occupational rise of spectrophotometry and physical photometry, themselves the construction of physicists, chemists and astronomers.

So automation symbolically removed the problematic observer from the measurement, making this an attractive and highly visible benefit of physical methods. By relegating the operator to interpreting graphs or numerical lists – an activity seemingly free of physiological and psychological factors – automated instruments appeared to redraw the boundaries to position colorimetry firmly within the realms of physical science. That such a demarcation entailed the adoption of new light detectors having their own complexities, and requiring a definition of how the visual sensation related to their replacements, was not at first an issue. The growing acceptance of the photoelectric detection of light and color were promoted on several fronts. In Britain, for example, members of the NPL photometry department, gradually convinced of the practical superiority of such detectors to the eye, cautiously endorsed the use of physical photometers in 1930; their collaborators at the GEC Research Laboratory were demonstrating prototypes of commercial instruments; and small firms were introducing photoelectric colorimeters. In 1933, the Science Museum recognized this commercial wave by mounting a three-month exhibition of photoelectric equipment.[32]

Such public demonstrations rode on a wave of technological enthusiasm for quantification and objective measurement, driven by commercial forces for high-throughput measurement of color. By the late 1930s, the adjectives 'photoelectric' and 'automatic' had become a short-hand for 'modernity'.

Opposing the machine

As discussed above, the movement towards automated instruments suggests a gradual and largely unopposed transition. However, once detectors other than the eye were proposed seriously, opposition began to be voiced in several quarters. Critics included a handful of physicists and a larger, and growing, community of physiologists and psychologists.

Disciplinary perspectives

As we have seen, the communities developing instrumental practices in color measurement were firmly aligned with physical science. During and after the First World War, the new links between colorimetry, national laboratories and industry were consolidated by the formation of optical societies. The Optical Society of America, for example, was founded in 1916 principally by a group at Eastman Kodak, and brought together researchers and engineers concerned with all aspects of optics, including photometry and colorimetry. Its *Journal of the Optical Society of America and Review of Scientific Instruments* became the principal English-language organ for scientific optics in the 1920s. Unlike continental optical journals, *JOSA* dealt with subjects such as color measurement and the physical principles of light detectors. In Britain, the *Journal of Scientific Instruments* (founded in 1923) covered similar subjects, notably electrical measuring devices. In both countries, societies of 'illuminating engineering', comprizing mainly engineers and scientists, provided another important outlet for research papers.[33] The new technology was being embraced through a broadening and redefinition of optics through such publication channels.

A few physicists argued that the eye was an *essential* component in any measurement purporting to quantify visual attributes. The inventors of the most popular visual photometer, Otto Lummer and Eugen Brodhun of the PTR, noted at the turn of the century:

> The purpose of practical photometry is to compare the total intensities of light sources as they are perceived by our eyes. In such a measurement of the purely *physiological* effect of flames only the eye can therefore be used; all other measuring instruments, such as the radiometer, selenium cell, bolometer and many more of the kind, are to be discarded in so far as these indicate *physical* effects of light sources.[34]

If the one-dimensional measurement of brightness could not be entrusted to physical detectors, so the argument went, how could the more subtle three-dimensional measurement of trichromatic color be done by anything but the human eye?

Physiologists, too – particularly at the National Electric Lamp Association Laboratory in Ohio, which boasted of its research on 'the physics of illumination and its physiological and psychological effects on the human organism' – argued for the indispensability of the human eye in any color-measuring instrument.[35]

But as I have argued elsewhere, the measurement of color provoked strongest criticism in post WWI committees tasked with standardization.[36] Psychologists contended that color is a subjective sensation difficult to quantify and accord between different observers, let alone 'physical' instruments. In 1931, the Commission Internationale de L'Éclairage (CIE), the only international forum for light and color, defined a specification of the 'standard observer' – an 'average' human color response based on fewer than two dozen British males – along with standardized color filters and light sources. The specification was engineered by John Guild and Irwin Priest, physical scientists at the national laboratories in Britain and America, respectively. The instruments embodied the theoretical perspective of a particular intellectual group.[37] The accepted artificiality of this averaged, mathematized human response made the acceptance of a non-human observer that much easier, and promoted the use of physical colorimeters.

While the CIE standard triggered some complaints, these centered on the issue of domination of the research program by certain countries, rather than on the cognitive aspects of color.[38] The CIE membership was top-heavy with physicists and engineers, the Commission itself having developed from a pre-war international photometric commission. For many of the CIE members, color was reduced to the problem of heterochromatic photometry.[39]

A better opportunity for debate was the Committee on Colorimetry formed by the Optical Society of America, and operating during 1919-1922 and 1932-1953. In these committees, psychologists gained first a foothold and then equality of representation. There, they argued that the trichromatic definition was founded on a dearth of experience and had a paucity of descriptive capacity. They emphasized that perceived colors were a combination of physiological mechanisms and psychological constructs, often bearing no simple relationship to the wavelengths of light involved. Nevertheless, by the time the differing theoretical stances of the two academic communities were confronted, commercial colorimetry was well advanced. The combination of standards and new instrumentation promoted the view of color as essentially a physical phenomenon through the early 1930s. The standard made possible the numerical expression of some color attributes, but did not make color *matching* any easier.

Complications in practice

The adoption of physical instruments eventually could assure more repeatable measurements, but at the expense of generality: the machines did not always do an adequate job of mimicking the human eye. To cope with the more awkward visual characteristics such as surface gloss and the angular dependence of color, firms developed specialized photoelectric instruments. These proliferated in variety and number through the 1930s.

But separating the subjective and physical characteristics of color remained a problem faced daily and directly on the factory floor. Writing of his mixed experiences with colorimetric instruments, a representative of the Printing and Allied Trades Research Association (London) observed:

> Unfortunately, the spectrophotometer is a costly instrument and requires skilled operation: as a result, many so-called reflectometers, whiteness- and brightness-meters have made their appearance…It is not generally realized, however, that papers are not necessarily a good match even when the ‘red’, ‘green’ and ‘blue’ readings are the same; conversely, papers may be a good visual match and yet give different readings. . . it is not commonly appreciated in the trade that color is ‘three-dimensional’, and that consequently no single instrument reading can define a color.[40]

Two options were available: either to use human observers and visual colorimeters – i.e. to revert to conventional but tedious color matching – or to employ physical colorimeters. The demand for rapid and reliable testing of products during the 1930s argued for physical methods, just as the testing of incandescent electric lamps had done in the national laboratories a decade earlier. Again, practitioners made the shift from physiological to physical methods. Their pragmatic solution was to continue with the development of specialized instruments to measure more of the awkward visual characteristics, while sharpening the specification of standardization of color comparison.

Conclusion

The seemingly inexorable advance of automated color instruments was, in fact, contentious and fragile. Development was pressed by the three rising fashions of quantification, objectivity and automation by physicists and engineers. Only when machines were presented as a credible alternative was the human eye vaunted as indispensable; the rise of machines came in parallel with a rise of the psychological understanding of color. As the non-physicalist perspective became more vocal, the very serious limitations of physical detectors were tamed quietly by narrowing the scope for their use and claims for their utility.

One color text of 1952 spoke of the 'simplification' and 'subduing' of color to the requirements of measurement.[41] Yoked to its intended applications, color measurement has, today, become a technological workhorse. And while the physicalist theory has lost its luster, the machines that embody it have more authority today than *any* pair of eyes.

Notes

1. Johnston (1996a; 1996b; 2000).
2. See, for example, the implicit technological determinism and positivism in successive editions of Walsh (1926; 1953; 1958; 1965).
3. The case of instruments for the detection of ionising radiation has been discussed in Hughes (1993); for radio astronomy, see Agar (1994).
4. See Schivelbusch (1986).
5. Helmholtz (1924); Maxwell (1857).
6. Thompson (1794, 362).
7. Helmholtz (1924, viii).
8. P. Stiles, *Photometrical Measurements,* quoted in Walsh (1926).
9. Homburg (1992).
10. Walsh (1926, 175-80).
11. NPL (1911, 39).
12. On the changing social value of quantification, see Kruger *et al* (1987) and Kuhn (1962).
13. The importance of 'observation without an observing subject' as a precondition for non-subjective reasoning is discussed in Swijtink (1987). See also Porter (1996).
14. E.g. Hunt (1995). This opinion pervaded the early national laboratories and was actively pursued at the PTR, where an 'absolute' standard of brightness, the so-called Violle standard, was under development at the turn of the century.

15. Via trichromatic perception.

16. E.g. Coblentz (1915) and Ives (1915). The thermopile, a high-sensitivity variant of the thermocouple, had been in use since the middle of the previous century to detect heat.

17. Ives (1915).

18. Ives and Kingsbury (1931).

19. On the attractions of automation, see Bennett (1991). For technical histories, see Bennett (1979; 1993).

20. E.g. Hay (1846); Chevreul (1858); Ridgway (1886); Chrysanthémists, Société des (1905); Munsell (1907).

21. See, for example, Maxwell (1857); Helmholtz (1924); Abney (1913).

22. E.g. Abney (1891) and Lovibond (1897).

23. E.g. Luckiesh (1915).

24. Langley (1881; 14); Hempstead (1977). For the background context, see also Johnston (2001).

25. Siemens (1875a; 1875b).

26. Minchin (1892).

27. E.g. Dobson *et al* (1926); Harrison (1934).

28. Lindemann (1919).

29. Selenium cells, by contrast, produced inadequate voltage to deflect even a sensitive electrometer when illuminated with violet light. This made them unsuitable for colorimetric measurement, because researchers had established the importance of these extreme wavelengths on color perception. Unable to respond to a color to which the eye responded, selenium failed as a viable replacement for colorimetric applications, but found a place in photometry: such cells were at the center of commercial developments from the 1930s, when firms such as Weston marketed selenium-based instruments as light meters.

30. Hardy (1929; 1935; 1938).

31. Michaelson (1938).

32. This included displays of the major types of photocell and their principles, and industrial examples such as package counters, burglar alarms, street lamp switching and daylight brightness meters.

33. The original membership of the Illuminating Engineering Society of London included only 4% medical doctors; its New York counterpart listed none.

34. Lummer and Brodhun (1899), quoted in Kangro (1976).

35. Fleming and Pearce (1922); Hyde (1909). The NELA lab was established in 1908, and became a wholly-owned part of General Electric in 1911.

36. See Johnston (1996a.) for the confrontation of these views.

37. The instrument as 'reified theory' was first described in Bachelard (1933), and has subsequently been taken up by many commentators.

38. Britain and America had dominated the post-war CIE, when Germany and its former allies were excluded from international scientific conferences.

Germany, through the research lines pioneered by Helmholtz and Ewald Hering, had hitherto dominated color research.

39. The President of the heterochromatic photometry committee, Charles Fabry, admitted himself ‘a little frightened at the size and difficulty of colorimetric questions’, and argued that the Commission should concern itself solely with the physical side of color, ignoring its psychological aspects. See Fabry (1924).

40. Harrison (1941).

41. Murray (1952).