Visibility of Radiant Energy

This classic paper [1] from 1923 reports the results of one of the most enduring projects ever undertaken at NBS, research into the physical description of human vision. The principal result of this work was the "visibility curve," a quantified model of how well a typical person can see the different wavelengths (colors) of light. Today this model function, essentially unchanged, underlies all physical measurements of photometric quantities and their interpretation in photometric units of measure.

It has been understood since the time of Isaac Newton that white light is a combination of a spectrum of different wavelengths, each seen as a pure color. Light is a form of radiant energy, with a power that can be measured in watts, but the connection between this physical description (or the "mechanical" description as it was then known) and the visual result in the human eye was not well established. This was the challenge undertaken by K. S. Gibson and E. P. T. Tyndall: to carry out a study of the visibility of radiant energy or, in quantitative terms, the ratio of the luminous (perceived) power to the radiant (physical) power at the different wavelengths in the spectrum.

Gibson and Tyndall were neither the first nor the last to study the visibility of light, but their work is perhaps the most notable for its thoroughness, timeliness, and impact. The first experiments on this subject were undertaken by Fraunhofer in 1817, and the first energy measurements were made by Langley in 1883 [2]. By 1905, Goldhammer had crystallized the idea of a definite relationship between visibility and power at each wavelength, and at the young NBS, Nutting introduced the term "visibility curve" in 1908 [3]. The Bureau's forefront research continued through the subsequent decade, leading to the major study of the sensitivity of the eye across the spectrum by Coblentz and Emerson in 1918 [4].

However, these and other data accumulated around the world were not consistent. Different experimental methods were a chief cause. In the equality-of-brightness matching method, two lights were projected onto a split-screen viewer, while with the flicker method, two lights were alternately projected on a simple viewing screen in rapid succession. In each case, the lights were adjusted in a known way until an observer declared a brightness match. The equality-of-brightness method was the more precise of the two, but only so long as the color quality of both lights was similar. When the colors were very different, different observers would make different matches. The flicker method did not give as sharp results for similar lights, but the data quality was not much affected by color differences.

Seeing the need to bring closure to the question, Edward P. Hyde (who had left the NBS staff in 1908 to go to the General Electric Nela Research Laboratories), as president of the U. S. National Committee of the International Commission on Illumination (the CIE), requested the Bureau of Standards to make an additional investigation using the so-called step-by-step method. This form of equality-of-brightness matching, where comparisons were made between a series of only slightly different colors, held promise as a means of obtaining more reliable data.

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NBS undertook the challenge under the sponsorship of General Electric. Director Burgess appointed a special committee of experts to oversee the work, which was conducted by Gibson and Tyndall. The University of Nebraska loaned a Brace spectrometer to the Bureau, to be incorporated into an elaborate apparatus that made the best use of the Bureau's primary standard lamps. Special care was taken in all aspects of the experiment; issues that were believed to affect the consistency between previous experiments—such as the size and brightness of the viewing fields—received particular attention.

The results included the brightness-matching data from 52 observers, some of them in common with previous studies. As hoped, the new equality-of-brightness data were within the range of data obtained with flicker methods (except in the outer regions of the spectrum).

However, the strength of the paper was not so much in the new experimental results as it was in its extensive analysis and critical review of all existing data. Gibson and Tyndall carefully compared their own results with those of their predecessors and proposed a mean visibility curve based upon the accumulated data from more than 200 different observers. They were guided in this task by the prevailing theories of the day, which were believed to dictate certain balance in the curve [5].

The result was a smash success, quickly winning wide acclaim. In 1924, the 6th Session of the CIE adopted the Gibson-Tyndall curve as a world standard. In 1933, the Comité International des Poids et Mesures (the supervisory body of the world's metric system) followed suit.

The achievement of Gibson and Tyndall might have remained an academic one were it not for the changing needs in metrology and the advances of technology. As surprising as it might seem today, until 1948 there was no universal standard for the brightness of light. The "standard candle," once made from whale oil, is a part of popular lore, but in reality, different laboratories each had their own favorite "standard." Some used gas lamps, some used liquid-fueled lamps, and following the trend towards electric lighting at the turn of the century, some (including NBS) used electric lamps. It was difficult to compare lighting devices to the standards, and the standards to each other, because different fuels and different lamp constructions would produce lights of different color. The only available instruments that could reliably report how bright a light appeared, or how lights compared to standards, were humans, and as we already know, equality-of-brightness matching was unreliable when the colors were significantly different.

Research in the 1930s, interrupted by World War II, led to international agreement in 1948 to use a platinum-point blackbody as the sole international standard of the luminous intensity of light. When objects are hot, they give off light. By "blackbody," we mean that the object does not reflect ambient light—all the light we see from it is thermally generated, an intrinsic function of the object's temperature. The trick was to operate a blackbody at a temperature that anyone could reproduce—in this case, the temperature of molten platinum as it begins to freeze while cooling. Many felt that this would provide the necessary world-wide stability and uniformity. A unit of measure of luminous intensity was then defined, now known as the candela, to relate the new blackbody standard to a typical standard candle of times past.

This development had an unintended consequence. Unlike the previous lamp and flame standards, the behavior of blackbodies are calculable from first principles, using Planck's radiation law. We had a light source that we understood in detail. The other piece of the puzzle was an understanding of how the eye responded to this light, and this is where the work of Gibson and Tyndall fit in. Suddenly, it became feasible to design and build electrical devices to measure brightness just as a human would, or at least the ideal human modeled by the Gibson-Tyndall curve 25 years earlier. The definition of the candela in 1948 had the effect of eliminating the need to have someone actually looking through a visual comparator, a process today called "visual photometry." It began an era of "physical photometry" in which luminous intensity could be evaluated through more objective measurements, yielding better precision and accuracy.

As time went on, the platinum-point standard fell into disfavor. The devices were difficult to maintain, their temperature was much lower than that of common electric lamps, and the melting-point temperature itself was too uncertain. This limited how well their emission spectra could be calculated. Finally, in 1974, Bill Blevin from the National Measurement Laboratory in Australia and Bruce Steiner at NBS published the seminal paper that said 'enough is enough.' They formally proposed that the SI base unit for photometry, the candela, be redefined so as to provide an exact numerical relationship between it and the SI unit of power, the watt [6]. They stated the case so well that, in 1979, the world metrology community effected a redefinition of the candela.

The 1979 redefinition puts even more reliance upon the work of Gibson and Tyndall. It says, "the candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of (1/683) watt per steradian." That specific frequency corresponds to a wavelength of 555 nm, which is where the peak of the Gibson-Tyndall curve lies. In order to determine the luminous intensity of light at other wavelengths, one uses the Gibson-Tyndall curve (more precisely, its modern, smoothed form, denoted as $V(\lambda)$) to find the corresponding number of watts. The era of visual photometry is truly over. Today, essentially all photometry is physical photometry, relying upon this definition and the $V(\lambda)$ curve to characterize any real light source or the performance of any tangible light detector.

This success of the Bureau in the early 1920s led to another important success towards the end of the decade. Having solved the problem of modeling brightness, Bureau staff next turned their attention to modeling color. This was a field that remained active well into the 1960s, but in those early days, a young staff member named Deanne Judd made his mark through another compelling analysis of existing data, resulting again in establishing the principles and methods that led to international consensus [7]. In 1931, the CIE adopted the system for quantitative color nomenclature that has continued to be used for 70 years. Judd, serving as the U.S. Joint Representative to the CIE, was one of the principal architects of that standard. His paper laid out technical recommendations that were accepted a year later, together with additional data developed by John Guild of the National Physical Laboratory (NPL) in the UK [8].

The system of colorimetry that Judd envisioned in 1930 has been a foundation for technologies not even dreamed of then—color photography (Kodachrome was invented in 1935), color television, modern color printing, and digital imaging. The tools of today's electronic commerce—color scanners, color-calibrated computer monitors, and all manner of color printers—all still rely on the 1931 CIE color system for "device independent" color specifications.

As beautiful as the Gibson and Tyndall work was, it was not without warts. The most famous occurs in the blue-violet portion of the spectrum, where they were forced to choose between conflicting data. They wrote, "The I. E. S. [Illuminating Engineering Society] data in the violet have been accepted by the authors for lack of any good reason for changing them, but the relative as well as absolute values are very uncertain and must be considered as tentative only." Their guess was wrong, but it so quickly earned acceptance that it did not remain "tentative" for very long. Years later, Judd attempted to institute an "improved" version of the visibility curve [9], but the Gibson and Tyndall version had been so thoroughly adopted that the revision never gained wide usage.

The second problem is more subtle and beguiling. The world of Gibson and Tyndall did not include the narrow-band light sources so common today: the phosphors in fluorescent lamps and CRT displays, lasers and LEDs, and the high-efficiency outdoor lighting that turns nighttime into a murky orange. The modern system of physical photometry based upon a simple visibility curve is no longer enough, not because of flaws in the curve, but because the human visual system is much more complex than this simple model suggests. Our vision responds nonlinearly to combinations of narrow-band lights, and perceived brightnesses can differ markedly from the predictions of their model. In a sense, it is the same problem that was recognized in the 1920s as the limitation of equality-of-brightness matching. The data told a story which was not understood then, nor of much technological importance. Today, vision researchers are revisiting the issue in an attempt to improve upon the standard model.

Nonetheless, to the extent that we continue to use electronic instruments to observe our surroundings, and to the extent that physical photometry remains the gold standard around the world for the metrology of lighting, the Gibson and Tyndall curve continues to play an essential role in estimating our perception of light more than 75 years after its introduction.

Kasson S. Gibson received his education at Cornell and joined NBS in 1916. In addition to the work described here, he made important contributions to the design of optical filters for transforming radiation from incandescent lamps to simulate natural daylight. He headed the work on photometry and colorimetry at NBS from 1933 to his retirement in 1955, publishing over 100 papers in spite of his administrative responsibilities. Gibson served as president of the Optical Society of America from 1939 to 1941 and was a Fellow of the American Physical Society, Illuminating Engineering Society, and American Association for the Advancement of Science. He died in 1979 at the age of 89.

Edward P. T. Tyndall worked at NBS in 1917-1919 and later returned for shorter stays as a visiting researcher. He spent most of his career as Professor of Physics at the University of Iowa, where he did important research on the optical and electrical properties of metals. He distinguished himself as a teacher and supervised 74 masters and doctorate students. He also died in 1979 at age 86.

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