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Color Science in Boston

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Abstract

In the 22 years of the Color Imaging Conference, this is the first time we meet in Boston. The history research on color by Bostonians begins with Benjamin Thompson's (Count Rumford's) study of complementary colors in 1793. The history includes the experiments of Oliver Wendell Homes, William James, Leonard Troland, Alfred Munsell, Smittie Stevens, George Wald, Paul Brown, John Dowling, Edwin Land, David Hubel, Torsten Wiesel, Bevil Conway and many more. The talk will trace the many connections between physics, psychology, photography, and color that have roots in Boston.

Color

There is a rich history of Bostonians who studied color vision. It covers more than 200 years. This paper is a review of the people from Boston that were fascinated by human color vision, their experiments, their transitional papers, their scientific instruments, their inventions, and the industries they founded. There is an accompanying website that provides a copy of the illustrations of this talk. [1]

Count Rumford

The story begins with Benjamin Thompson, born in 1753 in Woburn MA, a nearby Boston suburb. He was loyal to the English Crown in the early days of the American Revolutionary War, so he left Boston at the same time as the British General Gage after the battle of Bunker Hill.

In 1793, while staying at an inn in Florence, Thompson recorded observations on Color Shadows created by mixtures of daylight and candlelight.[2] He coined the term "complementary colors" to describe the colors he observed. He also reported that these shadow colors disappeared when the rest of the scene was occluded by a black tube.

Later, in London, he raised money for the Royal Institution and hired Humphrey Davy and Thomas Young as staff members to do research, teach, and edit the Institution's Journal. While working there, Thomas Young delivered his famous Bakerian Lecture at the Royal Society, introducing his speculation of human Trichromacy. It is interesting that Trichromacy alone cannot explain Thompson's "Colored Shadows".

The Nineteenth Century

In 1860, Oliver Wendell Homes Sr. invented the hand-held stereoscope. He is remembered more as a physician, poet, teacher, and father of the Supreme Court Justice. Although he invented the stereoscope, he was not involved in the industry he created. His stereoscope became the basis of a massive photographic travelogue industry. Many examples are found in almost every antique store.

William James came to Harvard in 1861. He studied physics, medicine, and the natural history of the Amazon River. He taught his first "experimental psychology" course at Harvard in the 1875. These lectures brought to the United States the experiments of Helmholtz and Janet.

Milton Bradley, draftsman, color lithographer, game designer, colorist and educator, used his game company to support his interests in research and the education of young children. His books include: "Color in the Schoolroom", 1890; "Color in the Kindergarten", 1893; "Elementary Color", 1895; "Water Colors in the Schoolroom", 1900. Although his company's products for teaching children were not a commercial success, the fact that our children and grandchildren learn, and talk about color in kindergarten demonstrates Bradley's success as an educator.

Alfred Munsell, painter, educator and colorist, attended and taught at the Massachusetts Normal School of Art in Boston, for more than 40 years. Over the last two decades of his life he developed the Munsell Color System (1905). This work led to a company managed by his son, and its products are still widely used by our color research community. Munsell's family foundation helped establish the Munsell Lab at RIT. Munsell Color System and the Munsell Color Products are essential tools in research today.

The Twentieth Century

Leonard Troland (MIT BS Biochemistry 1912; Harvard PhD. Psychology 1915) served on the National Research Council for vision and aviation psychology; taught advanced psychophysics at Harvard; was president of the Optical Society of America in 1922; authored the 1926 book "The Mystery of Mind"; and was a major technologist in the development of Technicolor films. He died at 44 in a tragic hiking accident on Mount Wilson. At the time he was director of Research at Technicolor in California. In his memory, the photometric unit that corrects retinal luminance values for the eye's pupil size is the "troland" (symbol Td).

In 1934 Stanley Smith Stevens received his Ph.D. from the newly independent Psychology department at Harvard. He stayed for his entire career, chairing the departments of Psychoacoustics and Psychophysics. Smitty advocated the power law to describe the fundament transformation of physical energy to psychophysical response. His famous paper " To Honor Fechner and Repeal His Law" [3] described the psychometric links between different sensory modalities.

Also in 1934, George Wald came to Harvard to continue his life-long study of visual pigments leading to a Nobel Prize in 1967. Paul Brown in Wald's Lab painstakingly measured the difference in absorption spectra of bleached and unbleached intact human cone cells to measure the actual color spectral sensitivity of the eye in 1964.

Edwin Land, was a physicist, inventor, photographer, industrialist, and government advisor.[4,5] He published his first scientific paper on the binocular fusion of colors in 1936. The experiment used his newly invented synthetic sheet polarizers along with depolarizing and non-depolarizing projection screens. Observers simultaneously viewed two spots of light. One spot was the mixture of red and green lights on both eyes, the other was the binocular fusion of red on one eye and green on the other. Observers compared retinal and cortical fused colors. [6]

In 1955 Land was working on the development of Polaroid Color film. He repeated Maxwell's 1861 Royal Institution color photography experiment using R, G, B projectors. At the end of the day, around midnight, Land and colleagues were shutting down the equipment. A colleague brought to Land's attention that after shutting off the B projector, and removing the G filter there remained a wide range of colors on the projection screen. Land recalls he said; "Yes. That is adaptation." Later, at 3 o'clock in the morning, he sat up in bed and said: Adaptation. What adaptation?." He immediately returned to the lab to get a better look at the wide variety of color sensations from Red and White projections.[7] That was the start of Land's lifelong study of color in the natural image. Retinex Theory, Black and White Mondrians, Color Mondrians, Computational Models of Spatial Vision, analog and digital image processing, and Steve Benton's Rainbow Holograms were developed in Polaroid's Vision Research Laboratory.

Land's study of Red and White projections provides a rich set of background information on spatial vision.[7] The quanta catch of the cone's visual pigments does not correlate with color appearances. In 1964 Land proposed the Retinex Theory to explain color sensations.[8-11] He used color displays with hundreds of colored papers. He controlled the spectral properties of the light falling on these papers and arranged illumination so that the identical cone quanta catches appeared to be markedly different colors – in the same scene - at the same time.

Further, Land made a simple observation that explained how vision generates color sensations. In these Color Mondrian experiments he used independent R, G and B broadband illuminants. Each had on/off switches and knobs that controlled the radiance of each spectral band. As an example, Land measured that a red paper on the left sent identical R, G, B radiances to the eye as a green paper on the right of the display. Despite identical stimuli leading to identical cone-quanta catches, the red paper looked red and the green paper looked green. Land made his simplifying observation by studying the appearances of the display separately in the three R, G, B; illuminants. When he shut off the G and B illuminants, he observed that the red paper in red light looked light. It looked the same as a white paper in red light. Further, he observed that green paper looked dark, similar to a black paper in red light. The same amount of red light could appear light and dark in the same scene at the same time. Additionally, in G-only illumination, he made a complementary observation. Namely, the green paper looked light while the red paper looked dark.

Land's insight was that in red light visual spatial processing generated light sensations for a red paper, along with dark sensations for a green paper. Whereas, in G light the lightnesses were different; the green paper was light and the red paper was dark. Color appearances correlate with the apparent lightness generated by spatial image processing. Retinex Theory proposed that independent long-, middle-, and short-wave lightnesses always correlated with color appearances. [12]

Research in Retinexes led to experiments showing that rods are a perfectly good color receptor, when the light strong enough to stimulate the middle- and short-wave cones is removed. [13]

Computational models of lightness began with Land's Ives Medal Address to the Optical Society of America in 1967.[14] This is a large and unwieldy topic, far to big to discuss here. Models of calculated appearance have been studied by: Frankle, Wray, Kiesel, Richards, Lettvin, Stockham, Horn, Marr, Hurlbert, Poggio, Grossberg, Adelson and Sinha. That is just the list of some of the senior Boston people. Additionally, familiar CIC names such as Moore, Rizzi, Marini, Gatta, Gilchrist, Funt, Jobson, Kotera, Pattanik, Fairchild, and Johnson have studied the problem.. The accompanying website provides more information. [1]

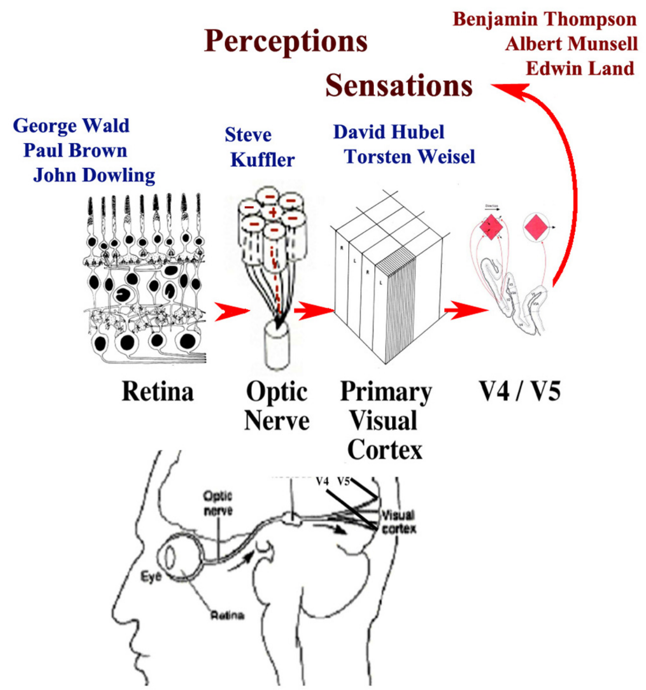

Figure 1. *A side view of the human visual pathway from the lens, retina, optic nerve, to the primary visual cortex at the back of the head. From there the pathway radiates from posterior to anterior. Above the pathway are diagrams of the organization of neurons. Wald, Brown and Dowling taught us about the photochemistry, cone sensitivities, and spatial organization of the retina. Kuffler discovered that ganglion cells are spatial image processors. Hubel and Wiesel mapped the binocular, spatial, and orientation mechanism of the primary visual cortex. While the absorption of light is the first step in the neurobiology of vision, color appearance is the end of the process. Thompson, Munsell and Land studied the sensations generated by the entire visual system.*

Stephen Kuffler came to Harvard Medical School until 1964 where he founded, and worked in the Department of Neurobiology until 1980. His earlier work published in 1953 showed that the mammalian ganglion cell was a spatial processor. These cells combined the excitatory response from the center of the ganglion cell's receptive field with the inhibitory responses from the surrounding peripheral receptive field inputs. The optic nerve did not just provide a phone line to the cortex; rather it was involved in active spatial image processing of the image on the retina.

In 1959 David Hubel and Torsten Wiesel moved to Harvard Medical School. They mapped the spatial processing architecture of the visual cortex. They showed the organization of different size receptive fields, different spatial orientations, and different ocular disparities brought together to analyze the spatial content of the retina's receptors. Hubel and Wiesel received a Nobel prize in 1981. Their work along with colleagues Nigel Daw, Margaret Livingstone, Bevil Conway, and many others described the presence of large spatial blobs, and double-opponent spatial processors.

Figure 1 shows a side view of the visual pathway, starting with the lens, then retina, optic nerves, visual cortex and further projections. It also identifies the location of the research by Bostonians along that pathway, as well as recalling the work of those who studied sensations and perceptions generated by the entire visual system.

What did we learned from Boston Scientists?

David Wright, who measured human color matching functions, wrote:

"Where does colorimetry end and appearance science begin? An interesting question. My short answer would be that colorimetry ends once the light has been absorbed by the colour receptors in the retina and that appearance science begins as the signals from the receptors start their journey to the visual cortex. To elaborate a little, tristimulus colour matching is governed solely by the spectral sensitivity curves of the red-, green-, and blue-cone receptors (if we may be allowed to call them that), whereas the appearance of colours is influenced by all the coding of the signals that takes place along the visual pathway, not to mention the interpretation of the signals once they arrive in the visual cortex." [15]

Virtually all imaging capture and reproduction technologies work on the local chemistry, or electronics, in response to local quanta catch. In silver-halide films each local image region is processed to the final image densities independent of the light falling on the rest of the image. Unlike film, every stage of the post-receptor visual pathway makes spatial comparisons. Dowling extended the study of the complex retinal pathway begun by Cajal and Polyak, but at much greater resolution. Dowling's retina, Kuffler's ganglion cells, Hubel and Wiesel's, Daw's, and Conway's cortical cells are spatial image processors.

In fact, the observations of Benjamin Thompson and Edwin Land are remarkably similar. Both saw something that did not make sense: color shadows and Red and White color. They both were startled by what they saw. What was so disturbing was that the same light could change its appearance. In both their experiments, they kept the light of the area of interest perfectly constant. Nevertheless, they observed that colors from constant stimuli were markedly different when viewed through a black tube, compared to viewing the entire scene.

Both experiments showed that the content of the scene controlled the appearance of the area of interest. Spatial content matters.

Thompson's and Land's interpretation of their experiments could not be more different. Thompson believed that color should correlate with the properties of the light on the retina. He wrote:

"But as soon as I removed my eye from the tube and contemplated the shadow with all its neighbouring accompaniments the other shadow rendered really yellow by the effect of the yellow glass and the white paper which had likewise from the same cause acquired a yellowish hue the shadow in question appeared to me as it did to my assistant of a beautiful blue colour.

… Reflecting upon the great variety of colours observed in these last experiments many of which did not appear to have the least relation to the apparent colours of the light by which they were produced I began to suspect that the colours of the shadows might in many cases notwithstanding their apparent brilliancy be merely an optical deception owing to contrast or to some effect of the other real and neighbouring colours upon the eye.

…The result of the experiment was very striking and fully confirmed my suspicions with respect to the fallacy of many of the appearances in the foregoing experiments.

… In the mean time I believe it is a new discovery at least it is undoubtedly a very extraordinary fact that our eyes are not always to be believed even with respect to the presence or absence of colours."

When Thompson looked at the entire scene, he described what he saw as "merely an optical deception" and "the fallacy of many of the appearances".

Land, 158 years later, was an expert on the interactions of light and matter. He had invented synthetic sheet polarizers, 3-D color images using the dye transfer of dichroic dyes, instant sepia silver halide films. Further, he reinvented the fundamental chemistry of the Polaroid sepia process to make black-and-white instant film. He did this by changing the size and electromagnetic properties of the transferred silver particles. He was in the process of producing instant color film. He had, by then, hundreds of patents on how to make images. All of these processes depended on the interaction of light with photosensitive matter in a small local region.

When Land observed the variety of colors in Red and White projections, he knew that human vision was fundamentally different from all other chemical image making processes. The content of the entire image influenced the appearance of each color in the scene. Human color was the result of spatial image processing. What Thompson call "optical deception", Land realized was the signature of the spatial interaction in human color vision.

Bostonians have made many contributions to our understanding of color. They have studied the actual light patterns reaching the retina, the spectral sensitivity, and chemistry, of the visual pigments. They have identified the spatial interactions of the visual pathway. As well, they have studied the problem from the sensation and perception end of the system. They found the 3-D shape of human color space of color sensations and the need to incorporate the entire scene in any analysis of the color appearance of each object in the scene.

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Author Biography

John McCann received a B.A. degree in Biology from Harvard University in 1964. He worked in, and later managed, the Vision Research Laboratory at Polaroid from 1961 to 1996. He currently consults and continues to do research on color. He has studied human color vision, digital image processing, large format instant photography and the reproduction of fine art. His 130 publications have studied Retinex theory, color from rod/Lcone interactions at low light levels, appearance and intraocular scatter, and HDR imaging. He is a Fellow of the Society of Imaging Science and Technology (IS&T) and the Optical Society of America (OSA). He received the SID Certificate of Commendation, and is the IS&T/OSA 2002 Edwin H. Land Medalist, and IS&T 2005 Honorary Member. He is past President of IS&T and the Artists Foundation, Boston. He served as Secretary of the Inter-Society Color Council, the USA Member body of AIC. In 2012, he and Alessandro Rizzi published the Wiley/ IS&T book, The Art and Science of HDR Imaging. He was a papers chair of the first CIC conference in 1992.