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PERCEPTUAL RENDERING OF HDR IN PAINTING AND PHOTOGRAPHY

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ABSTRACT

Pictures can be drawn by hand, or imaged by optical means. Over time, pictures have changed from being rare and unique to ubiquitous and common. They have changed from treasures to transients. This paper summarizes many picture technologies, and discusses their dynamic range, their color and *tone-scale* rendering and their spatial image processing.

High Dynamic Range (HDR) image capture and display has long been an interest for artists and photographers. The discipline of reproducing scenes with a high range of luminances has a 5-century history that includes painting, photography, electronic imaging and image processing. HDR images render high-range scene information into low-range reproductions. This paper studies the artistic techniques and scientific issues that control HDR image capture and reproduction. Both the artist and the scientist synthesize HDR reproductions with spatial image processing. The artists paints, or dodges and burns, the image he visualizes based on his human visual processing. The scientist, using algorithms that mimic vision, calculates perceptually correct renditions with inaccurate reproductions of scene radiances. The paper will discuss artists' techniques used in both painting and photography for HDR compression. It will also describe how optical veiling glare severely limits the range of luminance that can be captured and seen. The improvement in quality in digital HDR reproductions, as in HDR in art, depends on the spatial rendering of details in the highlights and shadows.

Keywords: HDR imaging, scene rendition, veiling glare, human dynamic range, painting, photography, Retinex

1. INTRODUCTION

The history of HDR scene capture covers images from Renaissance paintings to modern digital photos. By way of definition, this paper defines HDR imaging as the reproduction of scenes with a high range of luminances. More specifically, these scenes have a greater range of luminances than reflected, or emitted, from the reproduction media. This definition includes a great many scenes, because print and emissive display minima are controlled by their ambient surface reflections. Even if the display does not emit light at a pixel, the room light reflected from the surface of the display is that pixel's minimal luminance. A black in a print may have an optical density of 2.2, measured with a 0/45 densitometer, it can have a density of 1.5 with a spot photometer in a normal room. Also, this definition has relevance to human vision. Although retinal receptors respond to a luminance range of more than 10 log units, the signal reaching the cortex has a much lower range. First, intraocular scatter spreads light from the high luminance pixels across the retina. Second, the optic nerves carrying the retinal response to the cortex has a 2 log unit range. Vision makes a low dynamic range representation of HDR luminances in scenes in the cortex. There must be reasons, other than accurate luminance reproduction, that explain the image quality improvements found in HDR images. The multiple exposure technique significantly improves digital quantization. The improved quantization allows displays to present better spatial information to humans. When human vision looks at high-dynamic range displays, it processes scenes using spatial comparisons.

2. PAINTING

The earliest examples of painting are preserved in rock art. Lascaux cave painting have been dated to 13,000 to 15,000 BC. As best we can tell, these are the artistic expressions of individuals, with possible social implications.

In North America petroglyphs are as old as 3000 BC. Anasazi Indians in Chaco, New Mexico around 1000 AD used a camera-like cave with a small slit so as to project light onto a spiral petroglyph to identify summer solstice, equinox and the cycles of the moon.[1,2]

For centuries the picture makers were artists who painted them for themselves, or for noble clients. Pictures were rare; their users were few. Figure 1(left) shows a thousand year old Sung dynasty scroll.[3]

Figure 1 (left) shows a detail of Children Playing on a Winter Day, Sung dynasty scroll (960-1297). The portrait shows children have no background and appear to be in uniform illumination. Figure 1 (center) shows Ugo da Capri's *Diogenes*, (c. 1528), chiaroscuro woodcut printed from four blocks. Figure 1 (right) shows Caravaggio's *The Musicians*, (1595-6). This fine example of chiaroscuro painting portrays both the subjects and the illumination.

In the Italian renaissance, art became more public. Family dynasties such as the Medicis supported public art as today benefactors support public parks. This led to artists' workshops that resembled 20th century research laboratories. These workshops were well funded and well staffed and generated a considerable volume of images available to a wider range of viewers. The practice of portraying people and objects without an accurate rendition of the surrounding scene and lighting environment changed in the Renaissance. First, Brunelleschi's perspective rendered the geometry of the spatial environment. Later chiaroscuro techniques rendered the high-dynamic-range (HDR) illumination environment. Pre-renaissance paintings render people and scenes in uniform illumination. Leonardo da Vinci is credited with the introduction of, the painting of light and dark. His portraits of Benois Madonna, in 1478 and Lady with an Ermine, in 1483-1490 capture the illumination as well as the figures. One sees that the illumination comes from a particular direction and that there are highlights and shadows. Shortly after the invention of multiple-plate chiaroscuro woodcut printing in Germany, Ugo da Capri expanded chiaroscuro printing to four printing plates[4] (Fig.1- center). Caravaggio's paintings, such as *The Musicians* (1595-6), portrayed people and illumination with equal importance (Fig.1- right). In turn, Caravaggio influenced several Dutch painter, among them Gerrit van Honthorst (Fig.2 left).

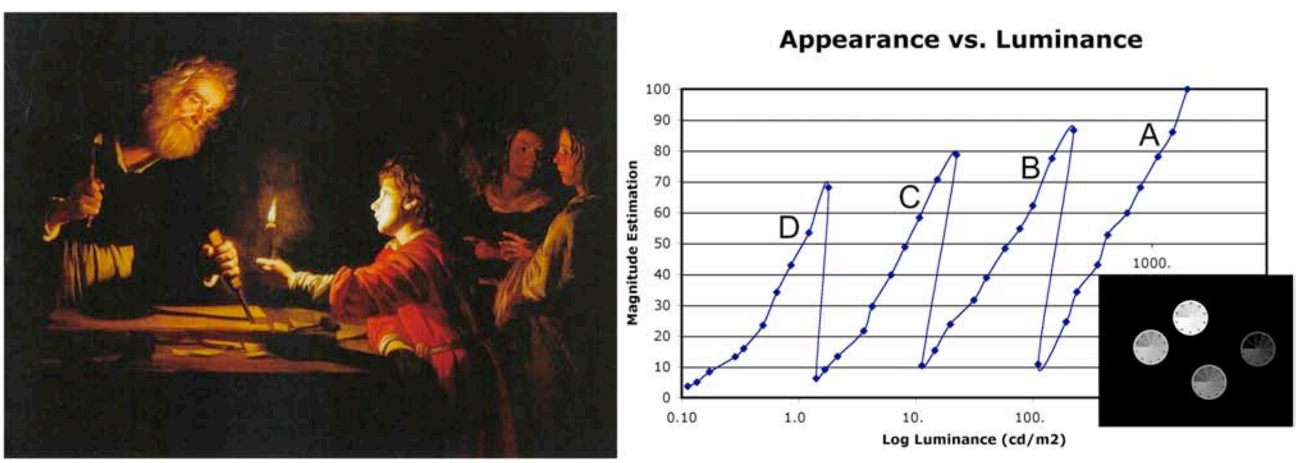

Figure 2(left) shows van Honthorst's 1620 painting "The Childhood of Christ". The boy holding the candle has the lightest face. The father, further from the light, is darker. The other children, progressively further from the light are darker.

Figure 2(right) shows measurements of appearance of four identical pie-shaped targets in different illumination. The horizontal axis plots log luminance: the vertical axis plots appearance (magnitude estimate). Each circular scale on the right approximates each figure in the painting on the left. Each figure is slightly darker, yet uses almost the same range of painted reflectances.

Artist's Rendering, Luminance and Appearance

In recent experiments, we measured the appearance of four identical transparent targets with four levels of illumination in the same scene in a black surround.[5] This is the experimental equivalent of van Honthorst's painting. Observers measured appearance by making magnitude estimates (MagEst) between white and black. They were asked to assign 100 to the whitest area and 1 to the blackest areas in the scene.

Figure 2(right) shows the test target in the bottom right. Four identical pie shaped targets with ten different transmissions were mounted on a light box. The top A had no neutral density behind it, B on the left had 1.0; C on the bottom had 2.0; D on the right had 3.0 ND filters. The surround was opaque. In total the target had 40 test areas with a luminance dynamic range of 18,619:1. The graph plots the average of observers' magnitude estimates of the appearance of the 40 test areas vs. luminance. The results are plotted in Figure 2(right). The horizontal axis plots luminance measured with a spot photometer (cd/m^2). The vertical axis plots appearance (magnitude estimate value). The top target A has the highest luminance. It generates MagEsts from 100 to 11. The left target B, viewed through a 1.0 ND filter, has uniformly 10 times less luminance than A. It generates MagEsts from 87 to 10. The bottom target C, viewed through a 2.0 ND filter, has uniformly 100 times less luminance than A. It generates MagEsts from 79 to 6. The right target D, viewed through a 3.0 ND filter, has uniformly 1000 times less luminance than A. It generates MagEsts from 68 to 4.

If we look along the horizontal line at MagEst 50, we see that four different luminances (1.06, 8.4, 64 and 414 cd/m^2) generate the same appearance. If we look at luminance 147 cd/m^2 we see that it generated both MagEst = 17 (near black) in A, and MagEst = 87 (near white) in B. Similar examples of near white and near black appearances are found at luminance 15 (B&C), and 1.8 cd/m^2 (B&C).

Magnitude estimates of appearance in complex images do not correlate with luminance.

This Figure 2(right) experimental data shows great similarity to Gerrit van Honthorst's figures in the painting "Childhood of Christ". Each Scale (A,B,C,D) is the analog for one of the four figures in the painting. As the distance between the candle and the faces grew, the tones rendering the faces got slightly darker. Each person is rendered slightly darker, but the spatial contrasts for each are very similar. Scales A, B, C, and D behave in the same manner. The only differences was that each started and ended a few percent lower in magnitude estimates, despite the substantial decreases in luminance. Figure 2(right) just assigns numbers to 16th century observations. Chiaroscuro painters did not render luminances; rather they rendered what they saw.

3. PHOTOGRAPHY

Silver halide (AgX) photography became an active scientific topic in the early 1800's. The use of photography grew very rapidly throughout the 19th century. In the early 1900's photography was transformed from a large group of small endeavors to a large industry. Two technological issues drove this change. One was dynamic range; the other was color.

4.1 The Century of Professional Amateurs

There are so many excellent histories of early photography that it would be foolish to restate the rich and varied history of writing images with light. A particularly good simple summary is found in Mees, Photography[6] based on a course of lectures given at the Royal Institution at Christmas, 1936. It summarizes the history from 1727, when Schultze experimented with light-sensitive silver salts, through Thomas Wedgewood's and Sir Humphrey Davy's work on silver nitrates, and through the public and private studies of Niepce, Daguerre and Fox Talbot, including Sir John Herschel's major contribution of hypo, the silver-salt clearing agent. A more detailed history, including ancient Greek references to light sensitive matter and descriptions of camera obscura, can be found in Elder[7]. Other important histories are: Newhall[8], Scharf [9,10], and Frizot[11].

In the late 1830's silver halide photography took a great leap forward from the research on light sensitive material to the development of practical photographic systems. The key advance was Daguerre's discovery of silver development by mercury vapor. In 1839 Daguerre made public disclosure of his technique to the Academie des Sciences, Paris in exchange for a 6,000 franc per annum for life from the French government.

One of the early adopters of photography was Samuel Morse, inventor of the telegraph, who bought a daguerreotype camera and obtained a full description of the process. He transferred the technology to United States by teaching the process to American photographers Samuel Broadbent, Albert Southworth, Edward Anthony and Mathew Brady. In 1844 Brady opened a Gallery in New York featuring family portraits and jewelry. During the American Civil War

(1861- 1865) Brady became the portrait maker of the war, the famous generals, politicians and the common soldier. Photographic jewelry was an early business that flourished in the mid 19th century[12]. It became very fashionable in England when Queen Victoria began to wear portraits of Albert prince consort after his death in 1861.

Today's negative-positive photography descends from the experiment of 1835 Fox Talbot's Calotype process.[6,7] In the Daguerreotype, the silver plate was developed to a positive image with fuming mercury. With the Fox Talbot's Calotype the silver salts on paper were developed in a water bath to a negative image. This negative, when printed on a second AgCl paper, made the positive print when developed.

By the 1850s the fascination with making pictures led to societies for the discussion of techniques. An excellent example is the 1854 Journal of the Photographic Society of London containing The Transactions of the Society and a general Record of Photographic Art and Science.[13] . It, along with many other documents in the collection of the Royal Photographic Society of Great Britain, provides a time capsule view of life in the 1850s.

4.2 H. P. Robinson

Henry Peach Robinson was a remarkable photographer, teacher and role model. Everyone knows Lewis Carol's book, *Alice in Wonderland.* Fewer people are familiar with him as The Reverend Charles Lutwidge Dodgson, Anglican clergyman and accomplished lecturer in mathematics at Oxford (1856-1881). Still fewer are aware of his portrait photography. In Gernsheim's book *Lewis Carroll Photographer* [14] (page 23) he reports that Lewis Carol admired the photographs of H. P. Robinson.

Robinson's work is remarkable because it remains of great interest today for two completely different reasons. First, it competed directly with painters in the creation of fine art. It went beyond scene reproduction to creating images designed to evoke an emotional response. Second, to be truly competitive, it had to overcome the technical limitations of image rendering. It had to solve all the problems of today's HDR imaging.

Figure 3 shows H.P. Robinson's 1858 photographic print "Fading Away" made from 5 combined negatives.

In the mid 19th century HDR scenes presented a severe problem for films available at that time. Multiple exposure techniques for rendering HDR scenes go back to the earliest days of negative–positive photography. H.P. Robinson's (1858) composite print "Fading Away" (Figure 3) was made using five differently exposed negatives.[15] This dramatic still life was staged using actors.

This multiple negative process is described in detail in the Robinson and Abney book, "The Art and Practice of Silver printing"[16]. The negative capture and positive print is very important to this process. When the photographer developed his negative of the scene exposed for the areas with the most light, the well-exposed areas were darkened with developed silver. The unexposed areas in the negative, corresponding parts of the scene with much less light, were clear glass. That meant that the photographer could take a second, longer exposure to record details in the shadows, develop it and superimpose the two negatives. This is just like layers in Photoshop, only 150 years earlier. The shadow details were added through the nearly clear glass of the first negative. This sandwiching of negatives combined with cutting and juxtaposing different negatives of the same scene produced HDR rendition as good as today's digital techniques. With insensitive AgX print paper, these prints were made in sunlight, a good source of collimated light.

Figure 4 shows another Robinson photograph, “When the Day’s Work is Done”. It is the combination of six negatives made by six separate camera exposures. The process begins with a rough sketch, followed by a detailed actual size (32 by 22 inches) sketch of the final image. Two separate photographs were made of the left side (white wall), and the right side (black shadow wall). The glass negatives were scored with a diamond, cut and butted together and mounted to a larger clear glass plate. Robinson describes this combination of two negatives on glass as “one large negative of the interior of the cottage, into which it would be comparatively easy to put almost anything”

Figure 4 shows H.P. Robinson’s 1877 print “When the Day’s Work is Done” made from 6 negatives and 3 exposures. (Albumen print, Princeton University Art Museum).

The third negative printed contained the old man, the table and chair with the matting under his feet. The man was photographed against a black background. The edge of the negative ran along the square back of the woman’s chair and up the wall. On the other side the joint runs along the table down the leg and across the floor at the edge between the carpets. The fourth photograph was the old lady. The fifth photograph was the group of baskets in the right in the corner, and the sixth was the view of the village through the window. The old man and the window were mounted on a second large glass plate. The old woman and the corner baskets were mounted on a third glass plate. Robinson used marks on the glass to register the three combined negative plates.

H. P. Robinson used photographic to images to generate emotions. These photographs were used as paintings were used in Victorian Britain. The intent was not to capture the real scene and reproduce it, rather the intent was to synthesize images that generate feelings of sadness, or nostalgia.

4.3 Scientific Calibration of AgX Film Sensitivity

Robinson’s techniques were empirical. In the 1870’s and 1880’s Hurter and Driffield[17] established the field of photographic sensitometry. They measured the response of the AgX film (density) to exposure to light. Hurter’s notebook B (page 1) plots log time of exposure vs. density and finds a strait line fit for the data. He wrote: “If the experiments be made in which the times of exposure is prolonged in geometrical progression, the density of the plate is found to be in arithmetic progression” (page 23). Their first publication, in 1890, describes the characterization of silver halide films as the plots of density vs. exposure. This work quickly recognized and became known as the “H&D curve”. English film manufactures marked their product with H&D ratings. Hurter and Driffield wrote a long series of papers starting in 1881, and continuing through 1903 that studied all aspects of film sensitometry. In addition to measuring films, these journal articles include experimentation with instrumentation, techniques for measuring density, and the accuracy of grease spot photometers. The final paper by Driffield, after Hurters death, entitled “The Hurter and Driffield System: Being a Brief Account of their Photo-Chemical Investigations and Method of Speed Determination[18] is fascinating for two very different reasons. First, it is beautiful science from an time in which scientist had to create their own tools of analysis. Second, it is a time capsule for imaging. It makes apparent the remarkable progress in imaging in the last century.

Sir William de W. Abney's book *Instruction in Photography*[19] became a popular reference. It was originally written in the mid 1880's with a dozen new editions over the next 20 years. Abney describes a number of measurements recording film response data for lantern slide transmission vs. exposure.

In 1900, C. E. K Mees became an undergraduate at University College London. He met another student S. E. Sheppard who shared many of his interests. The two of them worked under Sir William Ramsey, a physical chemist.[20] They were both interested in photography, and found that equations in Captain Abney's "Instructions in Photography " did not add up. Training as physical chemists they wanted to know the kinetics of the AgX development reaction. They then read Hurter and Driffield "Photochemical Investigations and a New Method of Determination of Sensitivities of Photographic Plates"[21]. They had found a "model for attack on the nature of the photographic process" [20](page 13). They repeated Hurter and Driffields's experiments with newer apparatus including an acetylene burner as standard light source. Mees modestly described this undergraduate research by saying: "We made little progress beyond what Hurter and Driffield had put on the record".[20] Nevertheless it earned them their B.Sc. degree and first scientific article, published in the Photographic Journal at the age of 21. Sheppard and Mees continued their collaboration earning their doctorates in 1906, and the publication of this work is found in a book *Investigations of the Theory of the Photographic Process*[22].

There is no better example of the vast diversity of 19th century photography than the search for color photography[23]. In the late 19th century color photography used large beam splitting cameras to make three simultaneous color separation images. In the early 20th century these bulky cameras could be replaced by additive color transparent films. They worked on the same principle as our LCD laptop displays. Very small adjacent patches of R, G, and B images viewed at a distance merge into a three-color image, hence the name additive.[24] Friedman and Coe describe a number of successful additive color films. John Wood's *The Art of the Autochrome*[25] and Brian Coe's *Color Photography*[26] display many fine examples of single sheet additive photography.

The disadvantage of these processes was that they had to be illuminated by a bright light and lacked to convenience of color printing. Four color subtractive printing, using yellow, magenta, cyan and black inks, was universally available and, more important, universally viewable because they were prints. Whites in subtractive color images reflect all incident light. (Subtractive color transparencies are much brighter than additive ones; subtractive colors are essential for prints.) Since additive films remove all the green and blue light to make red; remove all the red and blue light to make green; and remove all the red and green light to make blue, their combination to make white is only one third of the incident light.

Nineteenth century photography started with a few scientists experimenting with light changing matter. It ended with the beginnings of the massive industrialization of photography. Over most of the century photography was developed by thousands of individuals and small groups who painstakingly made each photograph from start to finish. There were many steps needed to make a picture; many of these steps were performed in complete darkness. Photography required the commitment of time, the investment in facilities and equipment, beyond just film and camera. By the end of the century there were innumerable small businesses, each in unique niches, finding independent solutions to common problems.

4.4 The Century of Corporate Photography

In 1900 Kodak introduced the Brownie Camera. It cost $1 ($0.15 for film). The ads read 'You press the Button, We do the rest'[6](page29). It was the corporate organization that put simultaneous advertisements in every US newspaper that changed photography. It universalized the photographer. Up until then photography was a small industry occupation, or a serious avocation. The new Brownie photographer clicked the shutter, mailed the camera to Kodak, and received by mail their photos and their camera loaded with fresh negatives. All the dangerous chemicals, and the bulky dark tents were taken away by a large corporation. Eastman introduced convenience into photography.

In 1905 Kodak published a 190 page, hard-covered book, *The Modern Way in Picture Making*"[27]. In the Preface, it said,

> "In its compilation we have endeavored to cover fully and clearly every point on which he should have information. With equal care we have avoided useless discussion of theory and have given no space to topics that would not appeal to those who take picture for the love of it.", EASTMAN KODAK CO.

This states quite clearly the change from 19th century skilled amateur hobbyist, interested in understanding the processes, to the new 20th century consumer, who was assumed to be disinterested.

Just after the introduction of the Brownie, George Eastman went on a different quest, an industrial research lab. It took several years, but in 1912 he persuaded C. E. K. Mees to move from London to Rochester and become Kodak's Director of Research. Mees's condition was that Eastman buy his present employer Wratten and Wainwright.[20]

4.5 Twentieth Century Control of Dynamic Range in AgX Photography – The *Tone Scale* Curve

Mees, in his 1920 book "The Fundamentals of Photography (first edition)[28], described the reproduction of Light and Shade in (Chapter VII). The description starts by showing the reproduction of a cube using two, three, four, five and six tones (Figure 5). Mees used "*tones"* to explain in simple terms the progression from white to black in a photo. His chapter gives a detailed discussion of how the shape of the photographic *tone-scale* curve affects the photographic print.

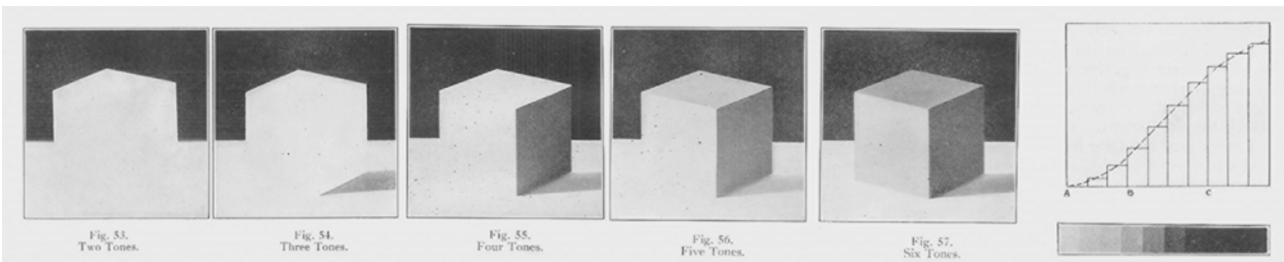

Fig 5 shows illustrations from Mees's chapter "Reproduction of Light and Shade".

Although Mees was exemplary in publishing his fine research in scientific journals, and in supporting published industrial research, he followed the Kodak philosophy of instructing a new kind of customer. He used "tone-scale curve" to replace the then universal term "H&D curve" in his and subsequent Kodak publications. In fact, the terminology is used today in digital high-dynamic-range imaging.

In Mees's *The Fundamentals of Photography*[28], he shows a 1920 example of a print made from multiple negatives with different exposures. This example of multiple exposures was not so much an artistic technique, as it was a demonstration of an improvement in image quality.

4.6 Adams' Zone System

In 1939 Ansel Adams first described the zone system for photographic exposure, development and printing. It described three sets of procedures: first, for measuring scene radiances; second, for controlling negative exposure to capture the entire scene range, and third, spatial control of exposure to render the high-range negative into the low-range print. [29]

Adams used a spot photometer to measure the luminances of image segments and assigned them to zones in the scale from white to black in the final photographic print. The zone system imposed the discipline of visualizing the final image by assigning image segments to different final print zones prior to exposing the negative. Adams was a professional performing pianist. He often described the negative as the analog of the musical score and the print as the performance. It was essential that the negative record all the information in the scene and that the printing process render this information in the print.

Photographic contrast is the rate of change of density vs. exposure. In the negative, the low-zone values are controlled by exposure, and the high-zone values are controlled by development and exposure. The zone system provided the necessary information to select appropriate exposure and processing for each scene's dynamic range.

The final stage was to control the amount of exposure for each local part of the image (dodge and burn) to render all the desired information from a high dynamic range scene into a low-dynamic range print. This process starts with a preliminary test print using uniform exposure. Examination of the print identifies the areas with overexposed whites and underexposed blacks that have lost spatial detail. Dodging refers to holding back exposure from areas that are too dark. Less exposure lightens this local region of the negative-acting print paper and gives better rendition in the blacks. Burning refers to locally increasing the exposure to make an area darker. This is a local spatial manipulation of the image. Not only can these techniques preserve detail in high and low exposures, they can be used to assign a desired tone value to any scene element.

Adams described the dodging and burning process in detail for many of his most famous images. He executed remarkable control in being able to reproducibly manipulate his printing exposures so that the final print was a record of his visualization of his desired image, not a simple record of the radiances from the scene. In fact, Ansel's Zone System process was the 1940's equivalent of an *all-chemical* Photoshop™.

Ansel Adams Zone System combined the chemical achievements of capturing wide ranges of luminances in the negative with dodging and burning to synthesize Adam's aesthetic intent. Controlling exposure and development captured all the desired scene information. Spatial manipulations (dodging and burning) fit the captured range to the limited dynamic range of prints.

4.7 Twentieth Century Color Photography and universal Tone-Scale Curves

Although artists continue to be fascinated with image synthesis using the tools of Robinson, Adams and now Photoshop, industrial photography moved towards universal processing for all scenes. Over the years the science of silver-halide imaging improved rapidly. Mees and colleagues established standards for high-dynamic range image capture on the negative, and high-slope rendering on prints[30] Negatives are designed to capture all the information in any scene. The negative response function changes very slowly with change in exposure (low-slope film). This property translates into the fact that negatives capture a wide range of scene luminances. Further, it is relaxes the requirements for cameras to make accurate film exposures. Once the scene is captured and the negative is developed, the final print can be made under optimal conditions at the photofinishing facility. The print paper has a nonlinear response to light (high slope). The resulting positive print is higher in contrast than the original scene. The loss of scene detail occurs in this high-contrast print rendering. Films with low contrast responses in the highlight and shadows preserved some of the edge information from the scene.

Mees, as director of Research at Kodak for nearly half a century, led the development of negative films that can capture a greater range of luminances than possible on camera image planes for the vast majority of scenes.[6] This film design was the result of extensive photographic research.[30] This work led to a *single tone-scale reproduction function for color prints.* Essentially the same *tone-scale* function was used by all manufacturers of color print films. This universal *tone scale* was determined by innumerable experiments that measured customers' print preferences. Even digital camera/printer systems mimicked this function.[31] It is important to note that this *tone-scale* function is not slope 1.0. It does not accurately reproduce the scene. It compresses the luminances in both whites and blacks, enhances the mid-tones (increased color saturation) and renders only light skin tones accurately. This one *tone-scale-fits-all-scenes* was very successful and became the basis of all color prints made in the second half of the 20th century.

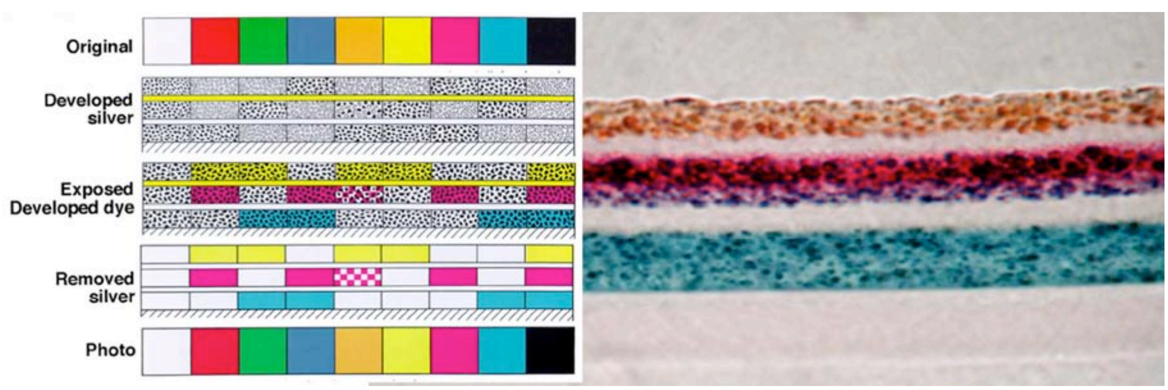

Figure 6 (left) shows the diagram of the Kodachrome process Figure 6 (right) shows Mary McCann's cross-section micrograph of a Kodachrome transparency taken by Mannes and Godovsky (from the Jack Naylor Collection). When viewing the slide, light passes from the top through the layers to the observers' eye at the bottom. This cross section is of black area in the photograph and shows the superimposed yellow, magenta and cyan dye layers.

The selection of a universal *tone-scale* function for color prints was not a haphazard event. It was the conclusion of work started by Mees as a student in 1900 and continued as a major research program at Kodak. Mees along with Pledge, L. A. Jones, Condit and others, carefully measured the response of AgX films to light at different wavelengths, measured the flare in lenses, measured the range of light in scenes. All these studies over 40 years led to the universal *tone-scale* function. Mees credits extensive work of L. A. Jones for the development of optimal *tone-scale* curves. The Jones and Condit[32] study of 128 outdoor scenes provided two important benchmarks in HDR imaging. First, it compared photographic images (measured camera luminances) and spot photometer measurements from scenes. Second, they devoted a significant portion of the paper to the careful analysis of flare in the image falling on the camera's image plane. The limit of film response to no light exposure is called the fog level of the film. This is the equivalent of the various noise limits in blacks in CCD and CMOS sensors. Jones and Condit showed that the AgX fog limit was significantly lower than the camera flare limit. Although many papers discuss digital camera noise limits, few discuss flare limits. Flare, not sensor signal-to-noise ratios of noise limits, sets the usable dynamic range of cameras. In 1935 Kodak introduced the Kodachrome process that set the standard for all color films for the rest of the 20th century. The project was led by Mannes and Godovsky. Kodachrome was made up of multiple layers of R, G, B sensitive emulsions to capture three-color separations in a single layer. The film was processed to form a different color dye image by reacting with the silver in each color separation layer using coupler developers (Figure 6). 'A coupler developer is one that in which the oxidation product of the developing agent combines with a chemical agent in the solution to form an insoluble dye'[6](page193).

The process was so complex and the processing conditions so exact that only large high volume chemical processing facilities could get satisfactory results. The 19th century professional amateur continued to enjoy his dark room making black and white imagery, but convenient subtractive color processing became the job of large chemical facilities. The true significance of small adaptable amateur laboratories to controlled chemical facilities was the introduction of the universal *tone scale* into photography. Instead of taking images with negative films with different contrasts, and printing them on positive papers with different contrasts. H&D curves became universal standards in color print film. Kodak research teams selected the H&D curve of the negative (low-slope for capturing a wide range of scene radiance) and the H&D curve of the positive print paper (high slope for dramatic prints in uniform illumination). The combination two H&D curves was an S-shaped response to light. It had higher contrast than the scene in the middle-tone values, and low contrast in the white and black regions to preserve some details.

In today's digital language the *tone-scale* curves for film are the direct ancestor of the R, G, B look up tables (LUTs) used to process digital images, sometimes called *tone-scale maps*. They act in exactly the same manner. All pixels in the scene with the same input (light for film – digit for digital) are changed to a different output (density for film- digit for digital). RGB LUTs are exactly the same as film *tone-scale* functions, and H&D curves. They convert a particular radiance to a unique output, either density or digit.

5.0 HUMAN VISION IS A SPATIAL MECHANISM

Over the past century psychophysical and physiological experiments have provided overwhelming evidence that human vision is a result of spatial processing of receptor information. Hecht and others showed that threshold detection mechanism uses pools of retinal receptors.[33] Kuffler[34] and Barlow[35] showed that the signal traveling down the optic nerve has spatial-opponent signal processing. In one example, the center of the cell's field of view is excited by light (more spikes per second). The receptors in the surround of the cell's field of view are inhibited by light (fewer spikes per second). The net result is the cell does not respond to uniform light across its field of view and is highly stimulated by edges. It has the greatest response to a white spot in a black surround. Hartline and Ratliff[36] found spatial processing in the compound eye of Limulus Polyphemus. Dowling[37] showed pre- and post-synaptic behavior of the retina establishing post-receptor spatial interactions in mammals.

E. H. Land[38] proposed his Retinex theory, asserting that the three cone types act as sets, where the response was determined by their spatial interactions. The phenomenon of color constancy is best explained by independent long-, middle-, and short-wave spatial interactions. Semir Zeki[39] found color constant cells in V4 with predicted spatial properties. Hubel and Wiesel[40] have recounted their study the organization of the primary visual cortex's response to stimuli projected on a screen in front of the animal. In each small region of the cortex they found a three-dimensional array of different representations of the visual field. Each segment of the visual field has columns of cortical cells that report on the left-eye image next to a column for the right-eye image. The cells perpendicular to the left/right eye columns respond to bars of different orientations. The third dimension has cells with different retinal size segments of the field of view. Campbell and colleagues showed that there are independent spatial-frequency channels corresponding to bar detectors of different visual angle[41]. J. J. Gibson[42], the noted Cornell psychologist, described the importance of bottom-up, non-cognative spatial image processing.

6.0 ELECTRONIC IMAGING AND HDR

Many technologies invented in the first half of the 20th century became very successful businesses in the second half. Baird's mechanical television in1925, and Farnsworth's broadcast television in 1927, and Zworykin's all electric camera tube (Iconoscope) in 1929 became the basis of today's television. Carlson first described Xerography in 1937; Land introduced Instant photography in 1947. The color versions followed in 1954, 1955 and 1963, respectively. Here again, the literature is so vast that one should turn to summaries for the many interesting details of the technologies. Hornak's *Encyclopedia of Imaging Science*[43] describes each technology.

6.1 20th Century Electronic Control of Dynamic Range

Land [44] and Land and McCann[45] demonstrated the first electronic (analog) HDR rendering in his Ives Medal Address to the Optical Society of America. (Figure 7) Here, the intent was to render HDR images using spatial comparisons that mimic human vision. This paper took the ideas of Hans Wallach[46] that suggested that lightness correlated with spatial ratios and expanded it beyond the restraints of uniform illumination. The idea was that what we see was synthesized from the ratio at an edge multiplied by the ratio at all other edges. This process synthesized an image based on the relationship of all edges in the scene, independent of the luminances of each. The history of the development of this idea is found in Land[47] in a Friday Evening Discourse to the Royal Institution, London.

5.2 Digital Electronic Rendering

The practical embodiment of the principles articulated by Land and McCann needed two technological developments: first, the digital image processing hardware, and second, an efficient algorithmic concept that reduced the enormous number of pixel to pixel comparisons to a practical few, enabling rapid image synthesis. The hardware became commercially available in the early 1970's for the display of digital satellite and medical images. The efficient image processing began with the Frankle and McCann[48] patent using I^2S image processing hardware with multiresolution software. The explanation of this work and its relation to other multiresolution and pyramid processing is found in the literature.[49]

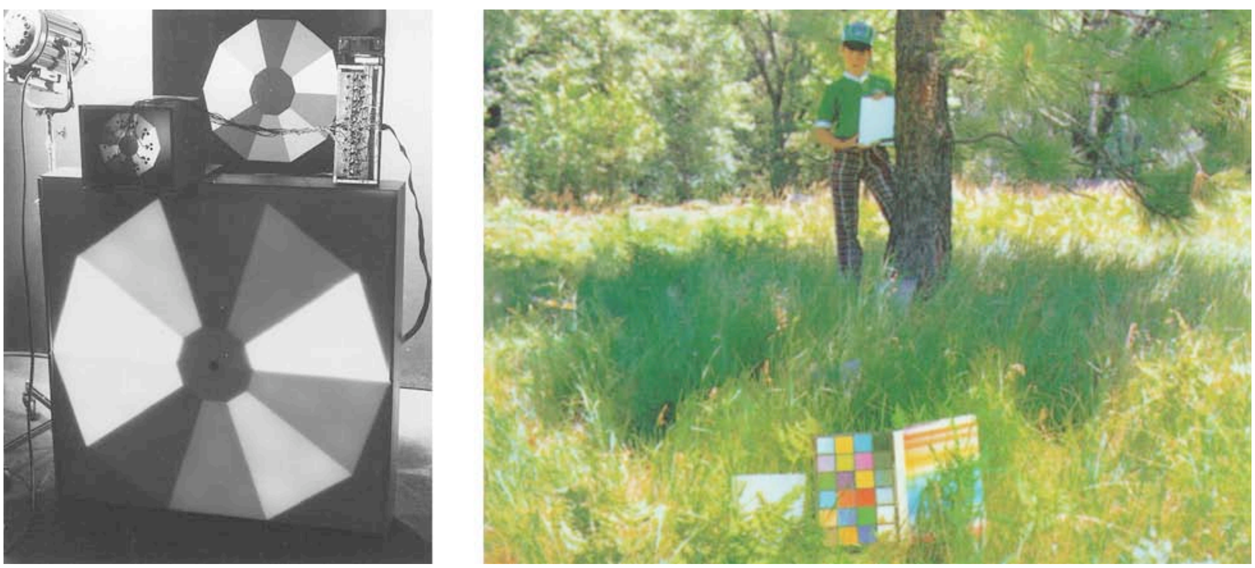

Figure 7 (left) shows Land's Retinex analog electronic image processing demonstration, using spatial comparisons. [45]
Figure 7 (right) shows an example of an HDR scene processed with spatial comparisons[45]. The illumination on the white card in the shadow is 1/32nd that on the black square in the sun. Both the white card in shade and the black square in sun have the same luminance. The spatial processing converted equal input digits (~log luminance) into very different output digits, thus reconstructing the HDR scene into the small range of the reflective print shown here.

Figure 7 (right) shows an example of a very efficient digital, multi-resolution HDR algorithm, using spatial-comparisons first shown in the Annual Meeting of Society of Photographic Scientists and Engineers in 1984. Here, spot photometer readings show that the illumination in the sunlit foreground is 32 times brighter than in the shade under the tree. That means that the sunlit black square has the same scene luminance as the white card in the shade. Prints cannot reproduce

32:1 in sun, plus 32:1 in shade, (dynamic range 32^2) because the entire print range is only 32:1 in ambient light. Using the spatial comparison algorithms, described in detail by Frankle and McCann[48], it is possible to synthesize a new 32:1 image that is a close estimate of what we see.

Land and McCann's Retinex, starting with analog electronics and quickly expanding to digital imagery, used a new approach. It assumed the initial stage of Mees's and Adam's wide range information capture for its first stage. Instead of using Adam's aesthetic rendering, it adopted the goal that image processing should mimic human visual processing. The Retinex process writes calculated visual sensations on print film, rather than a record of scene luminances.[50] To this aim, Retinex substitutes the original pixel luminance values with the results of a spatial computation that takes into account ratios among areas. In computing these spatial relationships the reset step is essential to mimicking vision. It is a powerful non-linear operator that applies the equivalent of a scene-dependent spatial frequency filter[51]. Stockham's (1972) spatial filtering of low-spatial frequency image content combined Land's Black and White Mondrian experiments with Fergus Campbell's multi-channel spatial-frequency model of vision[52]. This concept was the basis of a great many image processing experiments and algorithms. It differs from the original Retinex algorithm because it lacks the non-linear reset, which locally normalizes images to maxima and generates the equivalent of automatic image-dependent spatial filtering.[51]

Calculating scene luminances using Multiple exposures

The use of multiple exposures in electronic imaging for HDR scene capture was described by Ochi and Yamanaka (1985)[53], Alston et al.(1987)[54], Mann(1993)[55], Mann & Picard(1995)[56] and Debevec & Malik(1997)[57]. Debevec and Malik, and many subsequent papers, had a new and different rendering intent, namely, accurately record scene luminances. This led to proposals for digital image files covering extended dynamic ranges up to 76 log units[58] (chapter 3). It also led to the development of Brightside technology[59] with a modulated DLP projector illuminating an LCD display. This raised the luminance level of display whites. Raising the luminance of white increases the display's range between white and ambient black. By increasing the range of luminances of the display one can make use of the extended range from HDR capture. There is a simple tautology, namely a display that accurately reproduces all scene radiances must look like the scene.

Recalling Figure 2(right) is very helpful here. There was no correlation between luminance and appearance in a complex image. Pixel-based global *tone-scale* functions cannot improve the rendition of both the black and the white areas in targets A, B, C, D with the same luminances. *Tone-scale* adjustments designed to improve the rendering of one luminance region make other luminance regions worse. Land and McCann[45] made the case that spatial algorithms can automatically perform spatial rendering, doing what Adams did to compress HDR scenes into the limited range of prints. Such spatial rendering is not possible with *tone-scale* manipulations. By their design, global *tone-scale* functions have the same effect on all pixels with the same digital input value.

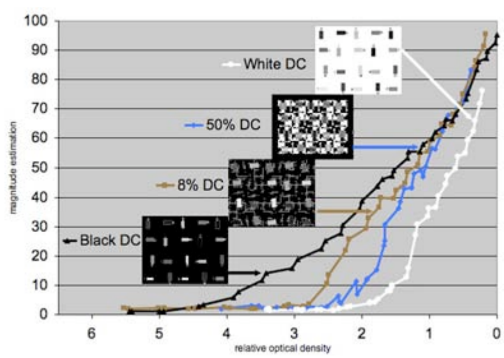

Figure 8 plots appearance (magnitude estimates) vs. log luminance(O.D.) for gray areas in 100%, 50%, 8% and 0% white surrounds.

Rizzi, Pezzetti and McCann [60] measured the combined effect of scattered light and simultaneous contrast in a series of HDR test targets. They asked observers to make magnitude estimates of appearance between white (100) and black (1). They estimated the appearance of gray areas in different surrounds. Figure 8 plots appearance verses log luminance (optical density). Figure 8 shows that increases in percentage of white in the surround increased the apparent contrast. Increasing white in the surround increases scattered light so as to reduce the contrast on the retina. Nevertheless, the human simultaneous contrast mechanism used spatial neural interactions to make the lower contrast physical image appear to have more contrast. Simultaneous contrast works in opposition to scattered light. In summary, there are a number of issues associated with the above tautology. If we want to capture and reproduce the actual scene radiances we see there are problems. If we use lenses to capture scene radiances, their veiling glare limits the range of light on the image plane. Veiling glare makes it impossible in practice to accurately capture scene radiances beyond 3 log units, except in a few scenes made of mostly black pixels. Intraocular scatter reduces the range of scene radiances dramatically. Stiehl et al.[61] showed that an opaque/white edge in a white surround calculates to 2 log unit edge on the retina. The retina does not have access to the dynamic range of radiances in the world. However, physiological spatial processing makes lower retinal contrast, mostly white, images appear higher in contrast.

HDR rendering using spatial comparisons

Electronic imaging made it possible and practical to spatially manipulate images. Such spatial processing is not possible with chemistry in silver halide photography. (Silver halide development processes using chemical restrainers can affect local departures from quanta-catch proportionality. These local chemical mechanisms have never been demonstrated over a wide enough spatial region to mimic human vision.) Quanta catch at a pixel determines the system response, namely density of the image. Digital imaging processing, or its equivalent, had to be developed in order for each pixel to be able to influence each other pixel. Digital image processing unchained imaging from being bound to universally responsive pixels. Spatial interactions, by computational means, became technologically possible. Ironically, recent HDR *tone-scale* processes impose pixel-value-dependent global restrictions on digital systems. Global *tone-scale* functions rechain *Prometheus unchained*.

Details in the shadows are necessary to render objects in shade to humans. Clearly, the accuracy of their luminance record is unimportant. The spatial relationships of objects in shadows are preserved in multiple exposures. Spatial-comparison image processing has been shown to generate successful rendering of HDR scenes. Such processes make use of the improved differentiation of the scene information. Therefore, one can make the case that improved quantization is key to successful image processing.[5]

Figure 9 shows Fox Talbot's first Calotype negative image taken out a window in his home near Bath, England. The image in the middle is a conventional digital camera image of the same window using *tone-scale* mapping. Each pixel with the same digital value is rendered the same. The picture on the right is shows the result of spatial image processing that reconstructs the image depending on the spatial content. Each pixel with the same digital value is rendered the differently depending on other pixels' values. Both the middle and the right images were taken with a commercial HP 945 camera. The pictures are hand-held single-exposure images. The image on the right uses Retinex based *Adaptive Lighting*/*Digital Flash* camera options. The spatial processing removes the over-exposure of the windows while lightening the flowers and the interior.

There have been many different examples of spatial algorithms[62] used to synthesize improved images from captured image plane luminances. Digital spatial algorithms, such as Frankle and McCann[48], have been used to display high-range scenes with low-range media. HDR imaging is successful because it preserves local spatial details. This approach has shown considerable success in experimental algorithms[63],[64] and in commercial products[65]. Figure 9 shows the results of spatial image processing from a single exposure using automatic firmware in an amateur camera.

6. DISCUSSION

This paper is a brief and selective survey of picture making technology. Painters rendered HDR scenes by matching the appearance on their low-dynamic range canvas to the HDR scene. Early photographers did the same by incorporating multiple exposures and *dodge and burn* printing techniques. The mass marketing of color print films replaced the artist's flexible rendering of an image with a fixed response to light. These universal H&D, or *tone-scale*, curves removed all adjustments to images except exposure. A pixel in the film responded to fixed amount of light; the film then rendered that pixel to a fixed density on the print. In AgX photography the behavior of a single pixel can be generalized to describe the behavior of all pixels in the scene.

Human vision is different; it uses spatial comparisons to generate appearance. The behavior of a single pixel depends on all the other pixels in the image. The painter's visual system, used to render HDR scenes, was indifferent to the amount of light at a pixel. The painter just painted the edges. The *dodge and burn* techniques does the same. It overcomes the films fixed response to light. Electronic imaging replaced the set of single pixels with an array of digits that can be programmed to interact. Spatial interaction over long distance was not possible in AgX film. Spatial image processing allows us to turn back the clock to incorporate digital spatial rendering mimicking human spatial rendering. Spatial image processing has unchained imaging from the universal *tone-scale* curve. The camera's new challenge is to optimize its algorithm to be more like human vision.

The two hundred year history of photography began as the work of a very few who formed small groups of like-minded colleagues. As the number and size of these groups grew they spawned hundreds of cottage industries that prospered in small niche markets. The user of photography began with a few chemists, spread to devoted amateurs and a small number of professionals. Gernsheim[14](page 5) reported that London had 3 registered professional photographers in 1841; it had 51 in Great Britain in 1851 and 534 in 1861. He comments that this list of register photographers " is certainly an understatement, since it does not take account of the legion of petty dabblers, or the thousands of employees engaged in the trade".

By 1900 the mature small photographic business exploded by expansion of the number of users. Kodak and many other large corporations improved the performance, convenience and quality of pictures taken by completely amateur photographers. These improvements came from research and development sponsored by large corporations, in turn supported by massive growth in usage.

Today's imaging technology is breathtakingly beautiful. The displays are very bright; the prints are clean and sharp. The colors are fully saturated. The process is instantaneous. The availability is global. Who could possibly complain?

The unique property of 21st century imaging is becoming increasingly democratic and less individualistic. Today's cell phone has in it CMOS sensors, digital image processing, storage, display and transmission functions, each the results of sizable development teams. It is not possible to build any of these devices in a small lab. It is the result of large teams making tiny modular components integrated into a single device. The more universal the device is, the larger the market, the greater the profit, the more successful the endeavor. But, what would H.R. Robinson think about replacing his AgX film and camera with a cell phone? Color could be an advantage, but he might be uncomfortable with the assigned fixed *tone-scale* rendering of color in the scene, as did Ansel Adams. Multiple exposure techniques might emulate those he developed in the 1850s, but the dynamic range of light on camera's image plane is limited by veiling glare.[5] Glare is dependent on camera size and aperture so that the cell phone's small, fast lenses will limit dynamic range more than his old cameras. Multiple exposures give improved quantization of details, but do not affect the camera & scenes' veiling glare limit. Robinson could use Photoshop to fuse and manipulate his multiple exposures. That certainly would be an advantage over cutting and fitting glass plates by hand.

7.0 CONCLUSIONS

This review includes the evolution of painting, photography and electronic image-processing including multiple exposures, *tone-scale* functions and spatial image processing in rendering HDR scenes. HDR imaging has limitations to the range of scene capture and the range of human perception. Cameras cannot capture scene luminances beyond a 3 to 4 log unit range. Optical veiling glare limits the dynamic range of luminances on the camera image plane. Human intraocular scatter transforms scene luminances to a much lower range of retinal luminances. Both capture and viewing are major issues in understanding HDR reproduction.

Nevertheless, artists and spatial image processing algorithms that preserve the original scene's edge information are successful in rendering HDR scenes. Accurate HDR luminance capture, in most scenes, is impossible in practice, and unnecessary. Spatial reconstruction of captured images allow observers to see details in the shadows that are lost in conventional imaging. Spatial techniques have been used by painters since the Renaissance. Photographers have used multiple exposures and dodging / burning for 160 years. Spatial image processors have been rendering HDR scenes into low-dynamic range media for 40 years. Their common approach has been to reconstruct an image on low-dynamic-range media that contains the same edge information as the HDR image, and has the same perceived appearance.

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REFERENCES

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[1] Solstice , <http://www.solsticeproject.org/research.html.> 2007.

[2] Sinclair, R. M., A. Sofaer, J. J. McCann, and J. J. McCann, Jr. (1987) 'Marking of Lunar Major Standstill at the Three-Slab Site on Fajada Butte' *Bulletin of the American Astronomical Society* vol. 19, pp. 1043.
Sinclair, R. M., A. Sofaer, J. J. McCann, and J. J. McCann, Jr. (1988) 'Marking of Lunar Major Standstill at the Three-Slab Site on Fajada Butte' at *17th Annual Meeting of the American Astronomical Society*, Austin.

[3] Ch'in Hsiao-I, *The National Palace Museum in Photographs* The National Palace Museum, Taipei, pp. 95, 1986.

[4] M. M. Grasselli, Colorful Impressions: The printmaking Revolution in Eighteenth-Century France National Gallery of Art, Washington, 2003.

[5] J. J. McCann, & A. Rizzi, 'Camera and visual veiling glare in HDR images', *J. Soc. Information Display,* vol. 15 (9), 721-730, 2007.

[6] C.E.K. Mees, *Photography*, The Macmillian Co., New York, 1937.

[7] J. M, Elder, *History of Photography, 1932* E. Epsteam, Translator *4th* Ed., Dover Publications Inc., New York, 1978.

[8] B. Newhall, *The History of Photography*, Little Brown & Co, Boston, 1982

[9] L. J. Scharf, *Records of the Dawn of Photography: Talbot's Notebooks P&Q*, University of Cambridge Press, Cambridge, 1996.

[10] L. J. Scharf, *The Photographic Art of William Henry Talbot,* Princeton University Press, Princeton, 2000.

[11] M. Frizot, (ed.) *A New History of Photography*, Koln: Konemann, 1998.

[12] L. J. West, & P. A. Abbott, *Antique Photographic Jewelry: Tokens of Affection and Regard,* West Companies Inc., New York, 2005.

[13] A. Henfrey, (*Journal of the Photographic Society of London containing The Transactions of the Society and a general Record of Photographic Art and Science.* vol. **1** Taylor and Francis, London, facsimile (1976) London: Royal Photographic Society of Great Britain, 1854.

[14] H. Gernsheim, *Lewis Carroll Photographer*, Chanticleer Press Inc., New York, 1950.

[15] T. Mulligan, & D. Wooters, Eds, *Photography from 1839 to today, George Eastman House, Rochester, NY*, Koln: Taschen., pp 360, 1999.

[16] H. P. Robinson & Capt. Abney, *The Arts and Practice of Silver Printing, The American Edition* New York: E& H.T. Anthony & Co. facsimile (2007) Bradley IL: Lindsay Publications Inc., pp74, 1881.

[17] F. Hurter, & V. C. Driffield, *The Photographic Ressearches of Ferdinand Hurter & Vero C. Driffield* W. B. Ferguson, Ed., Morgan and Morgan Inc., Dobbs Ferry, 1974.

[18] F. Hurter, & V. C. Driffield, F. Hurter and Driffield System: Being a Brief Account of their Photo-Chemical Investigations and Method of Speed Determination, Photo. Miniature, No 56, November, 1903.

[19] W. de W. Abney, *Instruction in Photography, 10th edition*, Sampson Low, Marston & Company, London, 1900.

[20] C. E. K. Mees, *An Address to the Senior Staff of the Kodak Research Laboratories*, Rochester: Kodak Research Laboratory, 1956.

[21] C. E. K. Hurter and Driffield "Photochemical Investigations and a New Method of Determination of Sensitivities of Photographic Plates", Journal of Society of Chemical Industry, 31ST May, 1890.

[22] C. E. Sheppard and Mees, *Investigations of the Theory of the Photographic Process,* Longmans, Green, and Co., London, 1907.

[23] J. S. Friedman, *History of Color Photography*, Boston: The American Photographic Publishing Company, 1945.

[24] J. J. McCann, 'Color Imaging Systems and Color Theory: Past, Present and Future', *J. Imaging Sci. and Technol.* vol. **42**, pp. 70-78, 1998

[25] J. Wood, *The Art of the Autochrome*: *The Birth of Color Photography*, Un. Iowa Press, Iowa City, 1993.

[26] B. Coe, *Colour Photography: The first hundred years1840-1940*, Ash & Grant Ltd., London 1978.

[27] Eastman Kodak, *The Modern Way in Picture Making,* Eastman Kodak C., Rochester, 1905.

[28] Mees, C. E. K., *The Fundamentals of Photography* Rochester: Kodak Research Laboratory, 1920.

[29] A. Adams, *The Negative*, New York Graphical Society, Little, Brown & Company, Boston, pp. 47-97, 1981.
[30] C. E. K. Mees, From Dry Plates to Ektachrome Film;: A Story of Photographic Research, Ziff-Davis Pub. Co, New York, 1961.
[31] J. J. McCann, 'Color Imaging Systems and Color Theory: Past, Present and Future,' in *IS&T/SPIE Electronic Imaging, Proc. of SPIE* vol. 3299, pp. 36-46, 1998.
[32] L. A. Jones & H. R. Condit, 'The Brightness Scale of Exterior Scenes and the Computation of Correct Photographic Exposure', *J. Opt. Soc. Am.*, Vol. 31, 651-678, 1941.
[33] H. Davson, *The Eye: The Visual Process*, vol. **II**, New York: Academic Press, 1962.
[34] S. W. Kuffler, 'Discharge Patterns and Functional Organization of the Mammalian Retina, *J. Neurophysiol.* vol. **16,** pp. 37-68, 1953.
[35] H. B. Barlow, 'Summation and Inhibition in the Frog's Retina', *J. Physiol*., vol. **119,** pp. 69-88, 1953.
[36] F. Ratliff, *Mach Bands: Quantitative Studies on Neural Networks in the Retina*, San Francisco: Holden-Day, 1965.
[37] J. E. Dowling, *The Retina: An Approachable Part of the Brain*, Belknap Press, 1987.
[38] E. H. Land, 'The Retinex', *Am. Scientist*, vol. 52, pp. 247-264, 1964.
[39] S. Zeki, *Vision of the Brain*, Blackwell Science Inc, Williston, Vermont, 1993.
[40] D. H. Hubel, and T. N. Wiesel, *Brain and Visual Perception*, Oxford University Press, Oxford, 2005.
[41] C. Blakemore, & F.W. Campbell, 'On the existence of neurons in the human visual system selectively sensitive to the orientation and size of retinal images*' J. Physiol., Lond*. vol. **203**, pp. 237-260, 1969.
[42] J.J. Gibson, The *Senses Considered as Perceptual Systems***,** London: Allen & Unwin, 1968.
[43] J. P Hornak, (Ed.), *Encyclopedia of Imaging Science and Technology*, John Wiley & Sons, Inc., New York, 2002.
[44] E. H. Land, (1967:1428A) 'Lightness and Retinex Theory', *J. opt. Soc. Am* vol. 57 p. 1428A; For citation see (1968) *J. opt. Soc. Am*, vol. 58 p 567.
[45] E. H. Land, & J.J. McCann, 'Lightness and Retinex Theory', *J. Opt. Soc. Am*., vol. 61 pp. 1-11, 1971.
[46] Wallach, H, (1948: 310) 'Brightness constancy and the nature of achromatic colors'*, J. Exptl. Psychol,* Vol. 38 pp. 310-324, 1948.
[47] E. H. Land, 'The Retinex Theory of Colour Vision', *Proc. Roy. Institution Gr. Britain*, vol. **47** pp. 23-58, 1974.
[48] J. Frankle & J. J. McCann, 'Method and apparatus of lightness imaging' *U.S. Patent*, 4,384,336, May 17, 1983
[49] J. J. McCann, 'Capturing a black cat in shade: past and present of Retinex color appearance models', *J. Electronic Img.*, vol. 13, pp. 36-47, 2004.
[50] J. J. McCann, 'The Application of Color Vision Models to Color and Tone Reproductions' in *Proc. Japan Hardcopy'88* pp. 196-199, 1988.
[51] McCann, J. J. (2006) *'High-Dynamic-Range Scene Compression in Humans'*, in *IS&T/SPIE Electronic Imaging, Human Vision and Electronic Imaging XII,* (eds.) B. Rogowitz, T. Pappas, S. Daly, *Proc. SPIE* Bellingham WA, Vol. *6057-47*, 2006.
[52] Stockham, T.G. (1972) "Image processing in the context of a visual model' *Proc. IEEE*, Vol. 60(7) pp.828-842, 1972.
[53] S. Ochi, & S. Yamanaka, 'Solid state image pickup device' *US Patent*, 4,541,016, filed Dec 29, 1982, issued Sep 10, 1985.
[54] L. E. Alston, D. S. Levinstone, & W. T. Plummer, 'Exposure control system for an electronic imaging camera having increased dynamic range', *US Patent* 4,647,975, Filing date: Oct 30, 1985, Issue date: Mar 3, 1987.
[55] S. Mann, "Compositing Multiple Pictures of the Same Scene", in *Proc. IS&T Annual Meeting*, vol. **46** pp. 50-52, 1993.
[56] S. Mann, & P.W. Picard, "On Being "Undigital" with Digital Cameras: Extending Dynamic Range by Combining Different Exposed Pictures", in *Proc. IS&T Annual Meeting,* vol. **48**. pp. 442-448, 1995.
[57] P. E. Debevec & J. Malik, 'Recovering high dynamic range radiance maps from photographs', *ACM SIGGRAPH'97* pp. 369-378, 1997.
[58] E. Reinhard, G. Ward, S. Pattanaik, & P. Debevec, *High Dynamic Range Imaging Acquisition, Display and Image-Based Lighting*, Elsevier, Morgan Kaufmann, Amsterdam, 2006.
[59] H. Seetzen, W. Heidrich, W. Stuerzlinger, G. L. Ward, Whitehead, M. Trentacoste, A. Ghosh, & A. Vorozcovs, 'High dynamic range display systems' *ACM Transactions on Graphics*, vol. 23(3) pp. 760-768, 2004.
[60] A. Rizzi, M. Pezzetti, and J. J. McCann, "Intraocular glare controls the visible range of High Dynamic Range Images (HDRI)", Proc IS&T/SID Color Conference, 2007.
[61] W.A. Stiehl, J. J. McCann, R.L. Savoy, "Influence of intraocular scattered light on lightness-scaling experiments", *J. opt Soc .Am*., **73**, 1143-1148, 1983
[62] J. J. McCann,.(ed.) 'Retinex at Forty', *J. Electronic Img.*, vol. 13, pp. 1-145, 2004.
[63] J. J. McCann, 'Rendering High-Dynamic Range Images: Algorithms that Mimic Human Vision', in *Proc. AMOS Technical Conference*, Maui, pp. 19-28, 2005.
[64] J. J. McCann, 'Art Science and Appearance in HDR images', J. *J. Soc. Information Display*, vol. **15**, (9) pp. 709-719. 2007.
[65] R. Sobol, 'Improving the Retinex algorithm for rendering wide dynamic range photographs', *J. Electronic Img*, Vol. **13** pp. 65-74, 2004.