MEASUREMENTS OF LIGHTNESS:
DEPENDENCE ON THE POSITION OF A WHITE IN THE FIELD OF VIEW

John J. McCann
Vision Research Laboratory, Polaroid Corporation
750 Main Street, Cambridge, MA, 02139, USA

ABSTRACT

We used quantitative lightness matching to measure changes in achromatic lightness as a function of the separation between a bright White (1000 mL) and a nearby 3 or a 300 mL Test Field. The experiments varied size, angular subtend and separation of the White area. All variables showed some influence on the matching lightness to the Test Field. Of particular interest are substantial changes in lightness from White areas that have 7.5 degrees separation. This paper will describe the quantitative results and their implications for models of lightness.

1. INTRODUCTION

Human vision is similar to photographic films and charge coupled devices in that all three have arrays of highly sensitive photodetectors. However, human vision, unlike photographic films and charge coupled devices, is noted for its complex properties of spatial interactions. Photographic films and charge coupled devices have the property that their response is dependent almost exclusively on the quantum catches at each point in the image. Vision exhibits a number of mechanisms that demonstrate significant departures from simple correlation between the quanta caught and the sensation observed. Color constancy demonstrates the largest departures from a quantum catch model[1]. A particular triplet of long-, middle- and short-wave quantum catches was matched by nearly the entire gamut of color sensation in a standard display. Land and McCann's Black-and-White Mondrian[2] showed sensations of both black and white from the same quantum catch in a single display. Both Color and Black-and-White Mondrians experiments adjust the illumination so as to control the flux at the eye. Both Mondrians showed that quantum catch, and hence colorimetric measures, are inappropriate to describe color appearance, since nearly the entire gamut of sensations is produced by a single triplet of quantum catches at a pixel. These experiments are powerful arguments for global mechanisms in human vision.

One of the most fascinating properties of human vision is that it has both local and global properties. Many experiments clearly demonstrate the powerful influence of local changes[3]. The area surrounding a Test Field can influence its appearance even if it does not change the global properties of the image.

The goal of this paper is to measure both global and local influences of a variable White on a Test Field. In particular, the goal is first, to maximize the changes due to global mechanisms and second, to measure the local influence of very bright areas in the field of view with variable separations and sizes. The largest change in appearance in uniform illumination is an experiment described by Gelb[4]. A black paper appears white when an intense light is projected only on the black paper. As soon as Gelb added a white paper to the field of view, the observer reports that the white paper is white and the black paper is black. Gelb's experiment is very important for two reasons. First, it demonstrates that particular quantum catches at a pixel can be matched by a white and by a black. Gelb's experiment showed that other pixels in the field of view can change the appearance from black to white. The second important lesson from Gelb's experiment is that human vision is not symmetrical.[5] The experiment used a black paper with an intense spot of light to make black paper appear white. The inverse experiment is to use a white paper with a weak spot of light to make white paper appear black. This does not happen. As one reduces the intensity of the light on a white piece of paper that is the only thing in the field of view, the paper stays white. It looks darker or dirtier, but it is white all the way down to an intensity at which it goes below threshold and disappears. This simple asymmetry is a critical observation for evaluating models for calculating sensations. Models that fail to mimic this asymmetry cannot be regarded as successful because the magnitude of the Gelb's experiment and the smallness of the lightness change for the Inverse Gelb Experiment.

Heinemann's[6] excellent review article summarizes many measurements on Luminance, Induction Field Size, Test Field Size, Distance between the Test and the Inducing Field, and Luminance Differences. In addition papers by Walraven[7], Cicerone et. al.[8] have measured the influence of local surrounds. Reid and Shapley have measured the effects of surrounds in the presence of a gradient and in the context of a Mondrian.[9]

2. EXPERIMENTAL PROCEDURES

The experimental design has been described in previous papers. The apparatus and procedure was described by McCann, Land and Tatnall[10]. The apparatus consisted of two high-intensity light boxes, 50 by 60 cm in size. The lamps are xenon gas discharge. The tube is serpentine and is 45 by 55 cm in size. Across the face of the box the 0.5 cm tube folds back on itself every 3 cm. In front of the lamp is a 6 cm air gap and a 0.6 cm plastic diffuser. We used only the central 20 by 24 cm of the light box. The periphery was blocked out by a black wooden frame, that served as the slide holder for the interchangeable 20 by 24 cm slides that contained black-and-white transparencies. We used a Gamma Scientific telephotometer to measure both the absolute luminance and to check for non-uniformity of the light box. The luminance of the White was 1000 mL. The uniformity was less than 2% across the entire field. This is as much as an order of magnitude better in uniformity that can be achieved in most video displays. The standard display we used to match all lightness sensations have been described by Stiehl, McCann and Savoy[11]. It is a display with 25 different patches, each subtended 2.5 by 2.5 degrees. All patches were surrounded by White (1000 mL) with the exception of a 1.25 by 1.25 degree opaque black patch. Near each patch with a integer Lightness Value had the number of that patch adjacent to it in opaque black.

The observers task was to find a match within 0.1 lightness units the appearance of areas in the Test Display. The observers looked with their left eye at the Test Display; they looked with their right eye at the Standard Display to assign a number the appearance of the test patches. The observers looked back and forth until they were certain about the match in appearance. In order to quantify the appearances of the color areas in a series the observer selects patches in the Standard Lightness Display. The display contains 9.0, 8.0, 7.0, 6.0, 5.0, 4.0, 3.0, 2.0, and 1.0 patches. In addition, below 9.0 and above 1.0 there are intermediate patches for 0.3, 0.6. The observers were instructed to interpolate to the 0.1 level by selecting an imaginary chip between the real chips. In addition, they could extrapolate by choosing an imaginary chip adjacent to the real chips in the Display. Two observers matched each of the test displays described below. The observers began by matching from center to outside. One observer had 20/20 and the other had corrected 20/20 vision. The data presented is the average of all trials by a single observer.

The Test Displays were a series of transparency targets that had spatially different arrangements of, at most, three different luminances. The objective was to study the properties of position, thus we severely limited the number of different luminances in the displays. The three patches were called the White, the Test Field, and the Background. The White varied in size and position, but always had the same luminance of 1000 mL. The Test Field was always in the center of the light box. It was square and subtended 2.5 degrees. In the first experiment the Test Field had a luminance of 300 mL and in all other experiments has a luminance of 3 ML. The Background was a uniform low luminance of 2 mL that covered 25 by 30 degrees. In other words, it filled in any area not covered by either the White, or the Test Field.

3. RESULTS

The following section describes the result of six series of Lightness Matching Experiments. These results were first presented by Savoy[12]. These experiments match the relatively simple Test Targets to the same complex Standard Lightness Display.

3.1. Gray on Black

The results (Figure 1) show three phases in the continuum between the extremes of the Gelb experiment. First, a rapid increase in Lightness as the Background grows from 0 to 1.25 degrees. Second, a region where the matched lightness increases only slightly with substantial increases of Background. Third, a jump in lightness when the White is removed. In summary, White darkens the Test Field over a wide range of separations and causes a rapid change of lightness at close separations. It remains to be seen if these two rates of change with separation are caused by the same mechanism. When the White is removed, there is an increase in lightness.

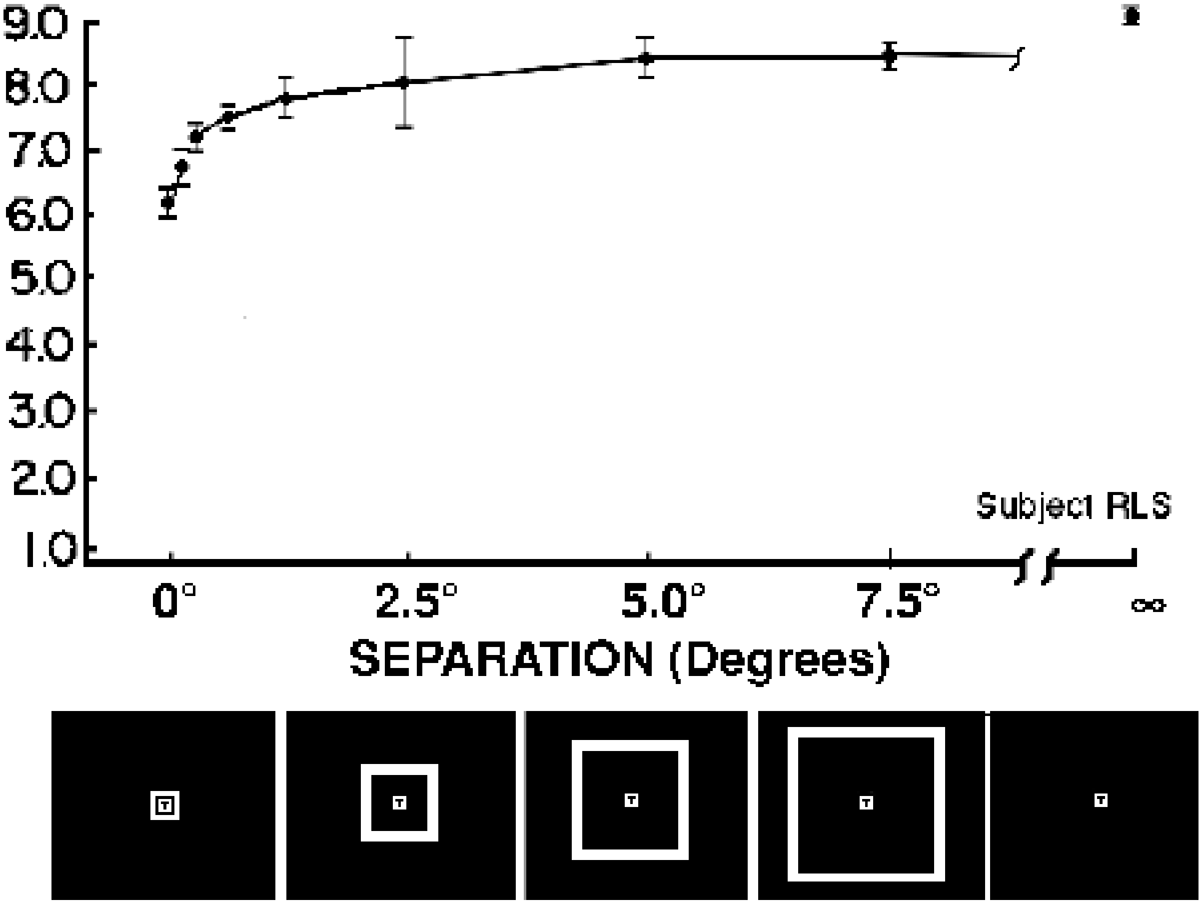

FIGURE 1 is a plot of a RLS data series. It is made up of 9 different displays. Eight displays have a concentric White square annulus surrounding the Test Field **[T]** at different eccentricities. The ninth display had no White. The first and last slides in this series are Gelb's experiment. Without the presence of the White, the 300 mL Test Field was matched by the observer to a "white" (slightly less than 1000 mL) in the Standard Lightness Display. When the White is adjacent to the 300 mL Test Field with no intervening Background, the observer matches it to a lightness slightly over 6.0. In the next five displays (separations from 0 to 1.25 degrees) the 300 mL Test Field increased to a lightness of 7.6. In the next three displays (separations from 1.25 to 7.5 degrees) the 300 mL Test Field increased in lightness only slightly. Without tthe White, the lightness of the Test Field jumps to 9.0.

3.2. Dark Gray on Black

The second series of experiments repeats the first with a 3 mL Test Field. In addition, it contains three additional sets of experiments that vary the circumferential extent of the White surround.

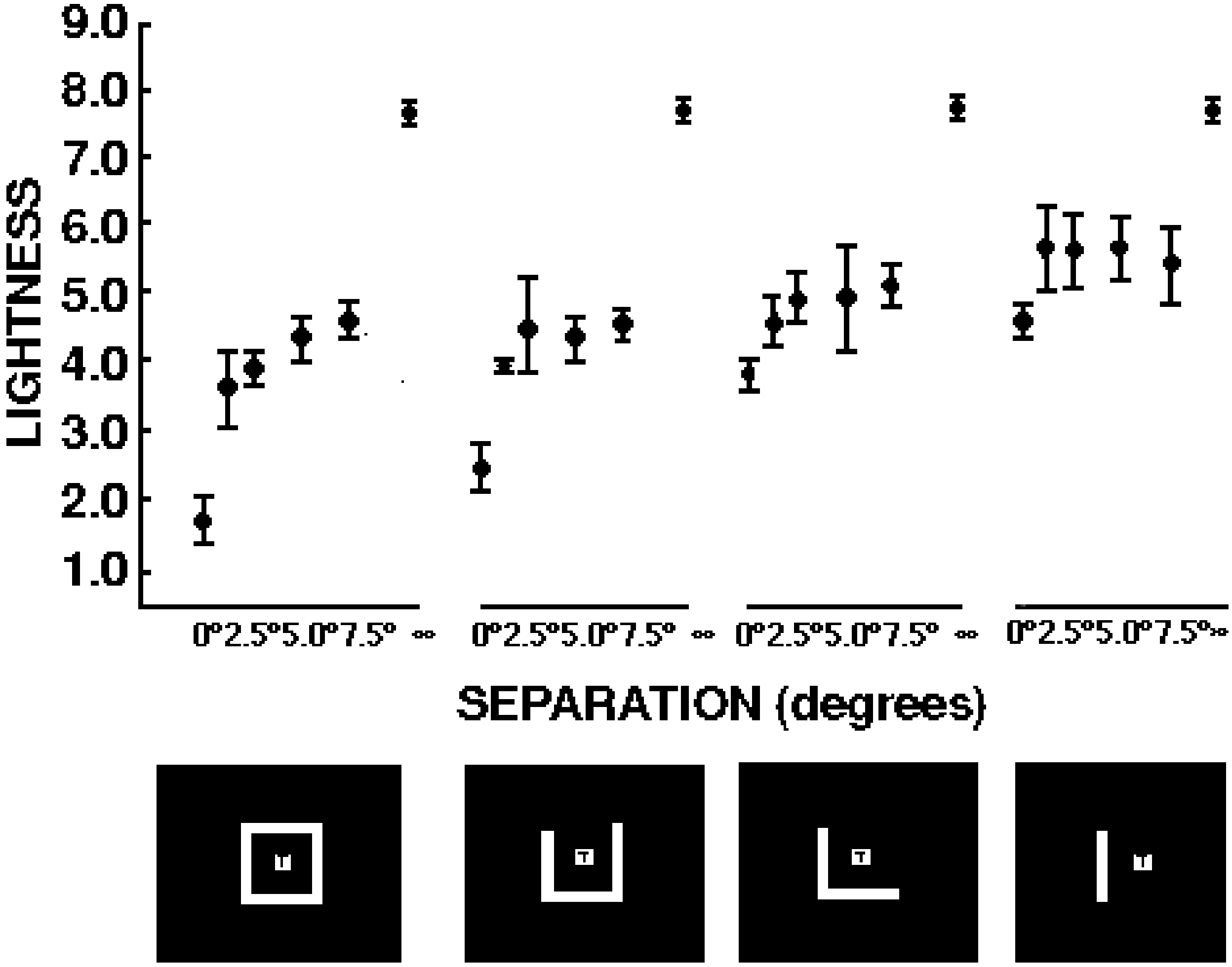

FIGURE 2 is a diagram of a KLH data series. The leftmost graph is made up of 6 different displays. Five displays have a concentric White square annulus surrounding the Test Field at different eccentricities. The sixth display had no White. Again, the first and last slides in this series is Gelb's experiment; this time with much higher contrast between the White and the Test Field.

3.2.1 Dark Gray on Black - White on Four Sides

In FIGURE 2 the leftmost graph has six targets. Five have White on four sides. Without the presence of the White, the 3 mL Test Field was matched by observer to a 7.7 "light gray" (about 800 mL) in the

Standard Lightness Display. When the White is adjacent to the 3 mL Test Field with no intervening Background, the observer matched it to a lightness of 1.7. In the next display (separations of 1.25 degrees) the 3 mL Test Field had a lightness of 3.5. In the three displays (separations from 1.25 to 7.5 degrees) the 3 mL Test Field increased in lightness only slightly to 4.5 .

The results show again three phases in the continuum between the extremes of the Gelb experiment. First, a rapid increase in lightness as the Background grows from 0 to 1.25 degrees. Second, a region where the matched lightness increases only slightly with substantial increases of Background. Third, a jump in lightness when the White is removed. These results are qualitatively like those in FIGURE 1; but, quantitatively they show much larger changes in contrast.

3.2.2 Dark Gray on Black - White on Three Sides

In FIGURE 2 the left-center graph is made up of 6 different displays. Five displays have a concentric White square annulus surrounding the Test Field on three sides at a different eccentricities. The sixth display had no White. Without the presence of the White, the 3 mL Test Field was 7.7. When the White is adjacent to the 3 mL Test Field with no intervening Background, observers match it to a lightness of 2.1. In the next display (separations of 1.25 degrees) the 3 mL Test Field had a lightness of 3.9. In the three displays (separations from 1.25 to 7.5 degrees) the 3 mL Test Field increased in lightness only slightly to 4.5. With only three sides of White, the Test Field is lighter than with four sides. The results show again three phases. First, a rapid increase in lightness as the Background grows from 0 to 1.25 degrees. Second, a region where the matched lightness increases only slightly with substantial increases of separation. Third, a jump in lightness when the White is removed.

3.2.3 Dark Gray on Black - White on Two Sides

In FIGURE 2 the right-center graph is made up of 6 different displays. Five displays have an L-shaped concentric White around the Test Field at different eccentricities. The sixth display had no White. Without the presence of the White, the 3 mL Test Field was matched by observer to 7.7. When the White is adjacent to the 3 mL Test Field with no intervening Background, observers match it to a lightness of 3.7. In the next display (separations of 1.25 degrees) the 3 mL Test Field grew slightly lighter to a lightness of 4.2. In the three displays (separations from 1.25 to 7.5 degrees) the 3 mL Test Field increased in lightness only slightly to 4.9. With only two sides of White, the Test Field is lighter again. The results show again three phases. First, a much smaller increase in Lightness as the Background grows from 0 to 1.25 degrees. Second, a region where the matched lightness increases only slightly with substantial increases of Background. Third, a jump in lightness when the White is removed.

3.2.4 Dark Gray on Black - White on One Side

In FIGURE 2 right-most graph is made up of 6 different displays. Five displays have a White bar at a different eccentricities from the Test Field. The sixth display had no White. Without the presence of the White, the 3 mL Test Field was matched by observer to a 7.7. When the White is adjacent to the 3 mL Test Field with no intervening Background, observers match it to a lightness of 1.7. In the next display (separations of 1.25 degrees) the 3 mL Test Field had a lightness of 5.5. In the three displays (separations from 1.25 to 7.5 degrees) the 3 mL Test Field decreased in lightness very slightly to 5.3 .

The results show again three phases. First, a small rapid increase in Lightness as the Background grows from 0 to 1.25 degrees. Second, a region where the matched lightness decreases slightly with substantial increases of Background. Third, a jump in lightness when the White is removed. In summary, White anywhere in the 25 by 30 degree field of view darkens the Test Field. Over a wide range of separations from 7.5 to 1.25 degrees lightness changes gradually with separation. White between 0 and 1.25 degrees exhibits rapid change of lightness with changing separation.

3.3. Dark Gray on Black: Varying White's Position

Figure 3 shows the results of 6 different experiments in which the 3.0 mL Test Field is touched by the same area of 1000 mL White. Here we study the influence of circumferential extent. All displays have an equal area of White. The placement of the White varied from touching the Test Field along the entire perimeter, leftmost display, to only touching on one side, rightmost display.

Let us think of the White as influencing the human contrast mechanism so as to drive the lightness of the Test Field towards black. In the leftmost display the white encircles the Test Field around the entire circumference. In this experiment we see that when the White touches all four sides (leftmost); the Test Field has the lowest lightness (1.5). In the next experiment (second from the left), the White still touches all four sides, but is less homogeneously distributed around a circumference of the Test Field, then the Test Field has slightly higher lightness (1.8). In the next experiment (third from the left), the White touches three sides; the Test Field has slightly higher lightness (2.1) than the first two. In the next experiment (fourth from the left), the White still touches all four sides, but only for half the length; the Test Field has slightly higher lightness (2.5) than the first three. In the next experiment (fifth from the left), the White touches only at the four corners; the Test Field has slightly higher lightness (3.5) than the previous experiment. In the next experiment (rightmost), the White touches on only one side; the Test Field has significantly higher lightness than the first five. Similarly, the comparison of the first and second displays shows that having no White in the corners allows the Test Field to be less dark. This data shows that the absence of White in the near periphery affects the outcome. A model for lightness needs to respond to the influence of the presence of a White in the near vicinity of the Test Field.

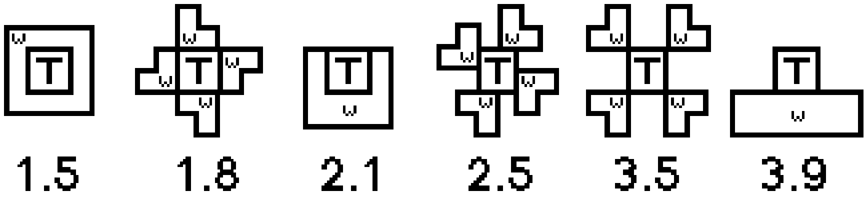

FIGURE 3 is a diagram of six targets; the numbers refer to lightness matches made by RLS. Here the experiments measure the changes in lightness as a constant area of White is spatially repositioned. The Test Field (T) is darkest when surrounded by White (W) on all four sides. It is lightest when White is on only one side. The comparison of the two leftmost experiments as well as the comparison of the two rightmost experiments shows that having a common border with a White is not the only constraint on the contrast mechanism.

4. DISCUSSION

Although you can characterize film in a physical pointalistic calculation in which all pixels react to light in exactly the same manner, human vision is fundamentally different. The problem of appearance in human vision requires a more complex class of model because all pixels in the image can influence appearance of all the others. Human vision is a field phenomenon. Appearances are determined relative to all other pixels in the field.

There seems to be four different mechanisms that control the lightness of a dark Test Field when influenced by a very bright White. First is the Gelb phenomenon. Whenever the White is removed from the field of view, the appearance is reset to the new lightest area in the field of view. Second, the circumferential angle is important. At all separations the greater the percentage of the circumference encircled by White the darker the sensation of the Test Field. Third, the lightness of the Test Field is nearly constant beyond 1.25 degrees separation for a constant circumferential angle. Fourth, in the region between 0 and 1.25 degrees separation, the appearance is controlled by the physical image on the retina. Intraocular scattered light controls the contrast of the retinal stimulus. The 3 mL Test Field is indistinguishible from the 2 mL surround. As the White areas moves further away from the dark gray Test Field, then the Test Field rapidly becomes lighter, between 0 and 1.25 degrees.

As calculated by Stiehl et. al.[5] an opaque patch surrounded by a 1000 mL area, has a retinal radiance of 30 mL at the center. The luminance image of the opaque patch on the retinal is entirely due to intaocular scatter. The scatter contribution is U-shaped across the opaque area , 30 mL at the center. The 3 mL Test Field simply adds a constant luminance to the greater than 30 mL scattered luminance. At 0 degrees separation scattered light into the dark Test Field is substantially larger than the real light from that area from the target. As the separation increases, the scatter decreases with distance from the White and the luminance from the Test Field becomes a larger percentage of the light on the retina. If the scattered light is 30.0 and Test Field is 3 on a 2 Background, then the stimulus is 32 on 33 Background (a ratio of 1:1.03). If the scattered light is 3.0 (increased separation) and Test Field is 3 on a 2 Background, then the stimulus is 6 on 5 Background (a ratio of 1:1.2). If the scattered light is 0.3 and Test Field is 3 (more separation) on a 2 Background, then the stimulus is 3.3 on 2.3 Background (a ratio of 1:1.43). If the scattered light is 0.0 and Test Field is 3 on a 2 Background, then the stimulus is 2.0 on 3.0 Background (a ratio of 1:1.50). As the ratio of radiances on the retina increase, the Test Field becomes visible against the Background and the Test Field increase in lightness. As the scatter approaches a very low number the ratio of radiances on the retina at the boundary between the 2 and 3 mL areas approaches a constant and the appearance of the Test Field approaches a constant appearance.

The experiments by Reid and Shapley studied the region for 0.0 to 0.7 degrees separation. They conclude that decline of influence is so great from 0 to 0.7 degrees that it is unlikey that one edge of the Mondrian can influence the next. Our data, however, shows a dramatic influence from stimuli 7.5 degrees away. Informal experiments indicate similar results for 15 degrees. Reid and Shapley's experimental data is most likely in closer agreement to our data, than their conclusion. The region from 0 to 0.7 degrees is highly influenced by scattered light. We see dramatic change in appearance from 0 to 1.25 degrees. Our conclusion however is that this data supports the long-distance interaction hypothesis rather than discredits it.

Ratio, Product, Reset models of lightness[2,13] can provide a suitable model for the results described in this paper. Normalizing to white (Reset) accounts for the change in lightness when the White is removed and for the asymmetry associated with the Gelb phenomenon. Variable probability of encountering a White, and hence having a Reset, can account for the circumferential extent lightness dependence. Long-distance integrations (Ratio Product) account for nearly constant lightness from 1.25 to 7.5 degrees separation. The most difficult data to model is the region controlled by scattered light. Here each target must be evaluated for the real stimulus and the scattered light image so as to determine the real luminance on the retina. Here at least the qualitative argument seems to hold. As described above, with 0 degrees separation the retinal stimulus is virtually all due to scattered light. The Test Field appears darkest when it has its highest luminance. As the separation increases, the Test Field has a lower luminance since the scatter is less. Nevertheless, it appears lighter. At very small separations the observer cannot differentiate the 3 ml Test Field from the 2 mL Background. As the separation increases further, the Test Field appears still lighter from a still lower luminance. At about 0.5 degrees separations the observer can differentiate the 3 ml Test Field from the 2 mL Background. As described above, the magnitude of the ratio between the Test Field and the Background increasing as the scatter contribution decreases. The Test Field must look lighter because the edge ratio between Test Field and the Background is greater. After the influence of scatter has passed, the Ratio-Product model generates a nearly constant lightness up to 7.5 degrees.

5. ACKNOWLEDGMENTS

The author wants to thank Bob Savoy for his collaboration on these experiments some time ago. In addition, I want to thank both Bob Savoy and Karen Houston for their meticulous accumulation of data.

6. REFERENCES

---

[1] J. J. McCann, S. McKee, and T. Taylor, "Quantitative Studies in Retinex theory : A comparison between theoretical predictions and observer responses to 'Color Mondrian' experiments," Vision Res. **16**, 445-458 (1976).

[2] E.H.Land and J.J.McCann, "Lightness and Retinex Theory," J.Opt. Soc. Am. **61**, 1-11 (1971).

[3] J.Albers, Interaction of Color, Yale University Press, New Haven, (1963). H. Wallach, "Brightness constancy and the nature of achromatic colors", J. Exptl. Psychol. **38**, 310 (1948).

[4] A. Gelb, Die "Farbenkonstanz" den Sehdinge. In handbuch der normalen und patholgischen Physiologie, **12** (ed. Bethe, A.) Berlin, Springer, (1929).

[5] J. J. McCann, "Local/Global Mechanisms for Color Constancy", Die Farbe, **34**, 275-283 (1987).

[6] E.G. Heinemann, "Simultaneous Brightness Induction," in: Handbook of Sensory Physiolpgy **VII/4,** D. Jameson and L.M. Hurvich, ed., Springer-Verlag, Berlin, 146-169 (1972).

[7] J. Walraven, "Color signals from incremental and decremental light stimuli," Vision Res, **17**, 71-76 (1977).

[8] C.Cicerone, V. Volbrecht, S. Donnelly and J. Werner, "Perception of blackness," J. Opt Soc Am A, **3**,432-436 (1986).

[9] R.C. Reid and R. Shapley, "Local contrast and spatial dependence of assimilation",Vision Res. **28**, 115-132 (1988).

[10] J. J, McCann, E. H. Land, and S.M. V. Tatnall, "A technique for comparing human visual responses with a mathematical model for lightness", Am. J. Optom. **47**, 845-855 (1970).

[11] W.A. Stiehl, J. J. McCann and R. L. Savoy , "Influence of intraocular scattered light on lightness scaling experiments" J.Opt. Soc. Am. **73**, 1143-1148 (1983).
J.J.Vos, J. Walraven, and A. van Meeteren, "Light profiles of the foveal image of a point source, Vision Res. **16**, 215-2129 (1976).

[12] R.L.Savoy and J.J.McCann, "The changes of test fields by varying the shape, distance and size of brighter fields", ARVO Spring Meeting (1975)

[13] J. Frankle and J.J. McCann, "Method and apparatus of lightness imaging," U.S. Patent 4,384,336.