Spatial Contrast and Scatter: Opposing Partners in Sensations

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ABSTRACT

We are all familiar with a number of contrast experiments in which two identical reflectance patches appear different in different spatial contexts. Examples are Simultaneous Contrast and White's Effect. The Simultaneous Contrast experiment places a gray patch in a white surround to make the gray appear darker. In this case, identical radiances at the target are not identical radiances at the retina. If we want equal retinal radiances, we need, with the aid of an intraocular scatter model, to make a display that has lower display radiances in a white surround. This paper compares a number of scatter-corrected contrast experiments with their uncorrected counterparts. In Simultaneous Contrast, correcting for scatter shows that the underlying spatial interactions have a larger effect on sensations than in uncorrected displays. Scatter and contrast tend to cancel, but in this case, they just reduce the apparent size of the spatial interaction.

White's Effect is just the opposite. The contrast effect and scatter add. In this case, correcting for scatter reduces the size of the effect, but does not overpower it. This paper describes a number of contrast experiments corrected for scattered light. The paper further discusses the magnitude of lightness shifts due to spatial interactions after scatter has been corrected. Scatter cannot explain White's Effect, although correction for scatter reduces its magnitude.

Multi-resolution vision models are proposed to provide an Early Vision mechanism for White's Effect.

Keywords: Lightness, sensation, perception, Early Vision, Simultaneous Contrast, White's Effect, intraocular scatter.

INTRODUCTION: LOOKING FOR AN EARLY VISION UNDERSTANDING OF WHITE'S EFFECT

Simultaneous Contrast and White's Effect[1] are a fascinating pair of visual displays (Fig. 1). One is very old and generally understood to be caused by local spatial interactions. The other is relatively new, and is believed by some to have significant implications on how we see lightnesses. In both cases, the grays in the displays are identical. The grays on the left of each display appear darker that those on the right.

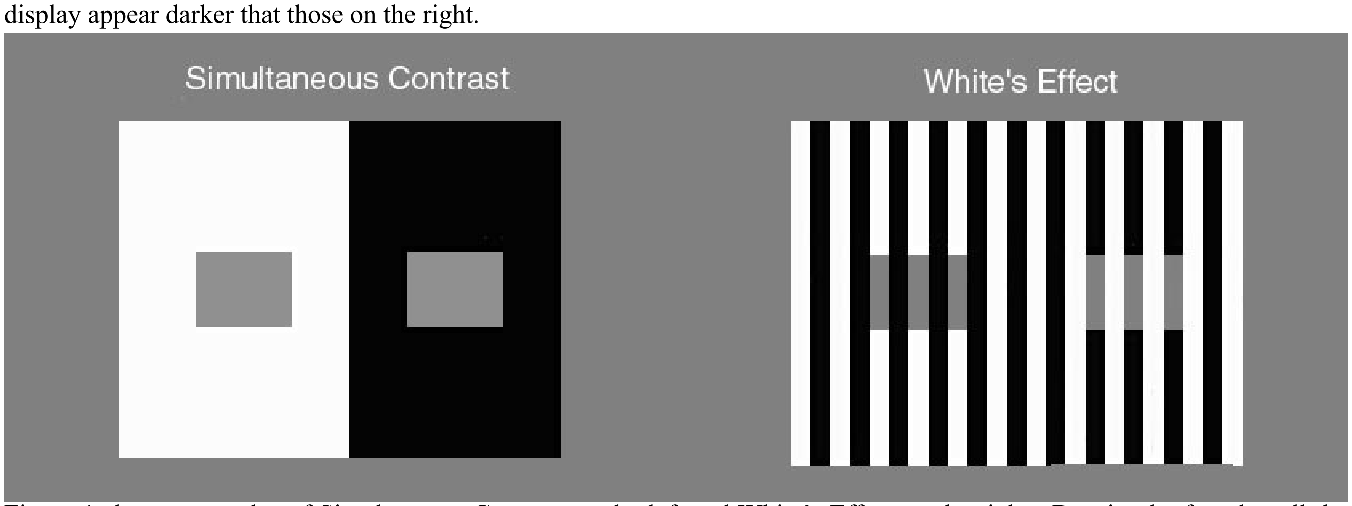

Figure 1 shows examples of Simultaneous Contrast on the left and White's Effect on the right. Despite the fact that all the central gray areas are the same radiance, the central grays on the left side of each display look darker than those on the right. This paper explores a variety of Early Vision hypotheses to understand both displays.

The usual explanation for Simultaneous Contrast states that gray adjacent to white looks darker. In White's Effect grays mostly adjacent to white are lighter, the opposite. High order visual processes can be implied as follows:
1. Interpret the left side of White's Effect as gray on white, behind black fence bars.
2. Interpret the right side of White's Effect as gray on black, behind white fence bars.
3. White's Effect looks similar to Simultaneous Contrast
4. The gray appearance is calculated without the influence of the bars.
5. Therefore, the human visual system generates Simultaneous Contrast after isolating lightness information into different depth planes.

There are a number of different experiments that suggest that apparent lightness is calculated using perceived depth information.[2] In this paper we will use the following definitions.

Early Vision: Spatial comparisons determine *lightness*
Lightness clues helps compute depth at higher levels
High Vision: Spatial comparisons determine *depth*
Depth helps compute lightness
Mid Vision: Local Spatial comparisons determine *depth operators that are used to compute* lightness

The old Simultaneous Contrast explanations would place its mechanism as an Early Vision process. The new White's Effect explanation would place its mechanism as a High Vision process. Models of Early Vision are easy to incorporate in computer simulations,[3] whereas cognitive models that are able to isolate white and black fences from the square-wave grating are hard to reduce to computer code. One wonders if there is a simpler, Early Vision explanation of White's Effect.

EQUAL ENERGY ON THE RETINA

Simultaneous Contrast experiment places a gray patch in a white surround to make the gray appear darker. The fundamental assertion of this experiment is that the grays are equal. In this case, identical radiances at the display are not identical radiances at the retina. If we want equal *retinal radiances* we need to make a new display, with the aid of an intraocular scatter model, that has lower display radiances in a white surround. Such experiments give us a better understanding of the visual process. This paper compares a number of scatter-corrected contrast experiments with their uncorrected counterparts.

Stiehl, et. al.[4] developed a very efficient computer model for calculating the retinal radiance from the radiance at the display. It used Vos and Walraven[5] and Campbell and Gubisch[6] data for the eye's point spread function. For small distances from the pixel of interest the effect of scatter was calculated for each minute of arc. At greater distances from the pixel of interest the input image was averaged into 3, 5, 15 and 225 minute patches. The scatter from these larger, more distant patches was added to the sum of the 1 minute contributions. This technique gives fast and accurate retinal radiances every minute of arc for entire 25° by 30° displays.

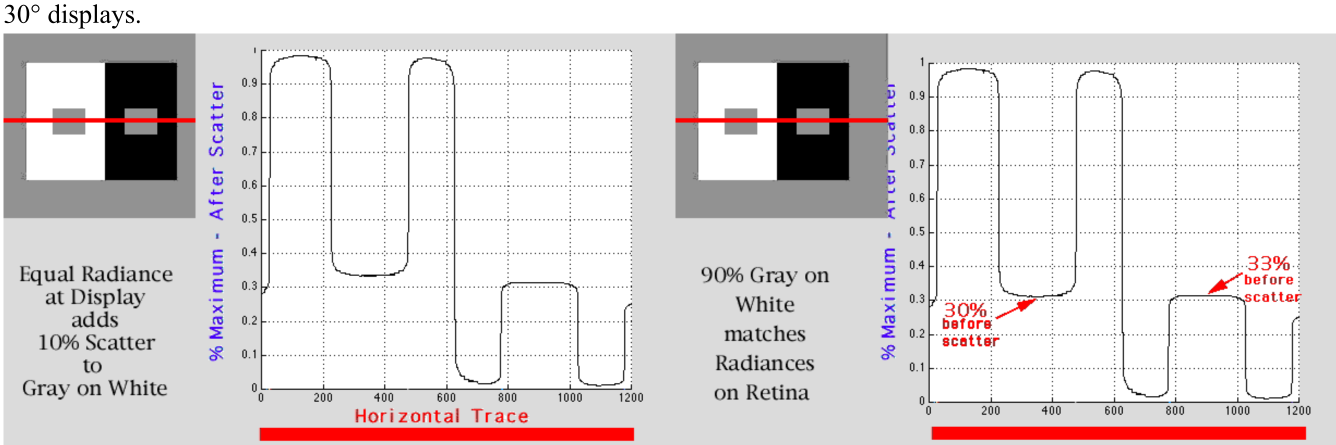

Figure 2a shows plots of retinal radiances on the vertical axes (% Maximum- After Scatter). It plots a horizontal trace (indicated by the line) starting in the gray surround, moving across the gray, white, gray, white, black, gray, black, gray areas. On the left it plots the retinal radiances of a display in which the gray areas are the same radiance at the display. Intraocular scatter from the white surround makes the retinal radiance on left greater than that on the right. On the right it plots the retinal radiances of a display created to have equal radiances on the retina. The two displays are shown in Figure 2b.

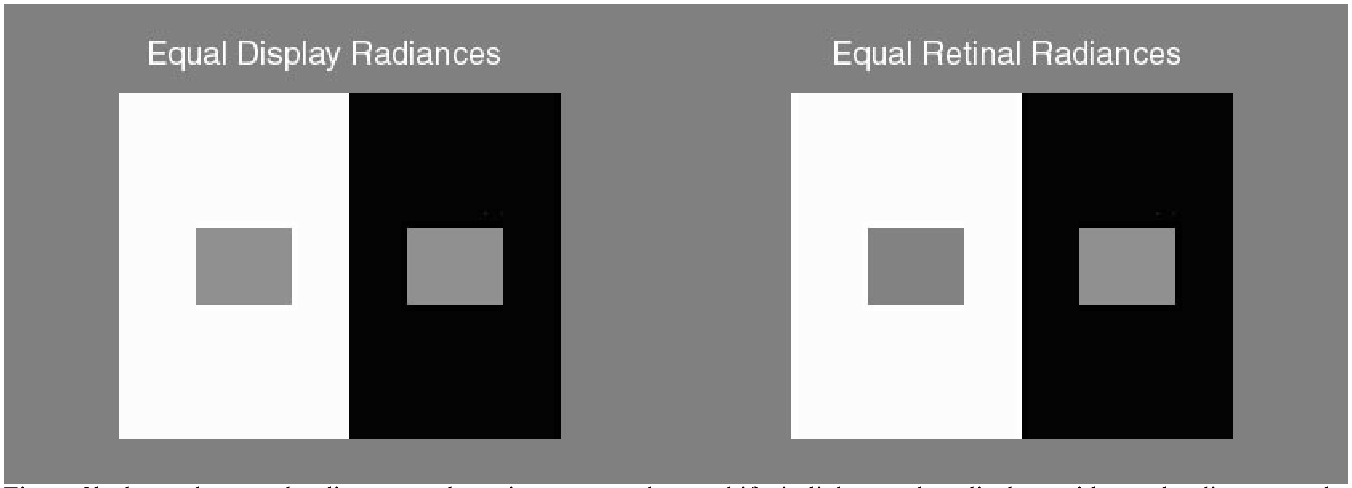

Figure 2b shows that equal radiances on the retina creates a larger shifts in lightness than displays with equal radiances on the display. Intraocular scatter reduces the magnitude of simultaneous contrast, because scatter and contrast tend to cancel each other. NOTE: The images reproduced here will not have the same calibration as the hardcopy displays used in these experiments:

The retinal radiances for the half-height horizontal traces of displays in Fig. 2b are plotted in Fig. 2a. They were calculated using a MATLAB® version of Stiehl et. al. The left plot shows that starting with equal radiance at the display produces retinal inequalities of about 10%. Empirically adjusted gray values produced the display on the right (Fig 2b) which have equal radiances in the centers of the gray patches <u>on the retina.</u>

In Simultaneous Contrast, correcting for scatter shows that the underlying spatial interactions have a larger effect on sensations than in uncorrected displays. Scatter and contrast tend to cancel, and in this case, scatter reduces the apparent size of the spatial interaction.

White's Effect uses bars instead of patches. This can lead to larger intraocular scatter effects. The retinal radiances for the half-height horizontal traces of displays in Fig. 3b are plotted in Fig. 3a. The left plot shows that starting with equal radiance at the display produces retinal inequalities of about 20%. Empirically adjusted gray values produced the display on the right (Fig 3b) which has equal radiances in the center of the gray patches <u>on the retina</u>

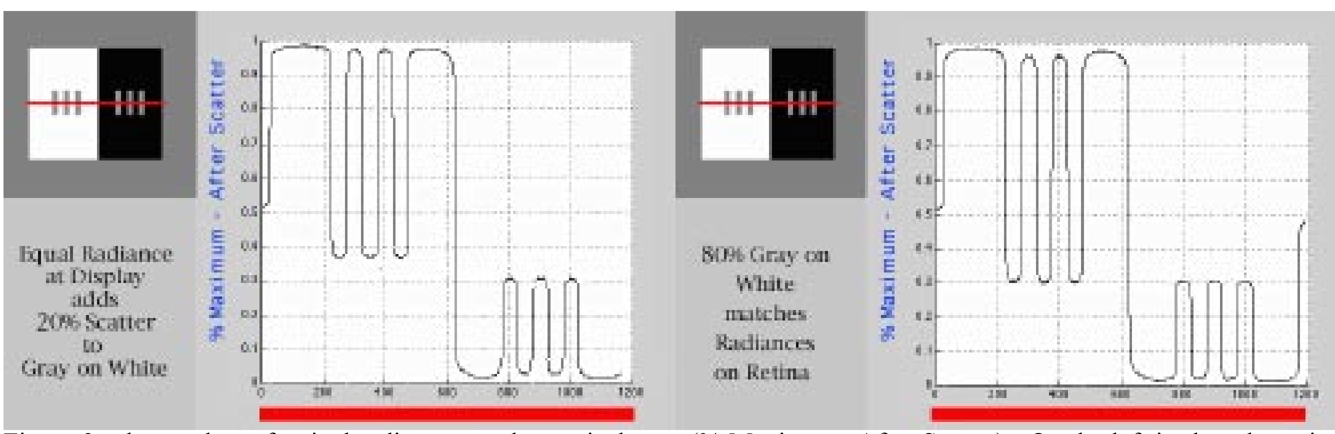

Figure 3a shows plots of retinal radiances on the vertical axes (% Maximum- After Scatter). On the left it plots the retinal radiances of a display in which the gray bars are the same radiance at the display. Intraocular scatter from the white surround makes the grays on left greater than those on the right, and greater than corresponding values in Figure 2a. A second Simultaneous Contrast display was created to have equal radiances on the retina. The two displays are shown in Figure 3b.

Figure 3b shows that equal radiances on the retina creates larger shifts in lightness than displays with equal radiances on the display.

In Simultaneous Contrast - Bars, correcting for scatter again shows that the underlying spatial interactions have a larger effect on sensations than in uncorrected displays. Scatter and contrast cancel, and in this case again reduces the apparent size of the underlying spatial interactions.

WHITE'S EFFECT EXPERIMENTS

Figure 4 plots the effect of scatter with decreasing spatial frequency of square-wave gratings.

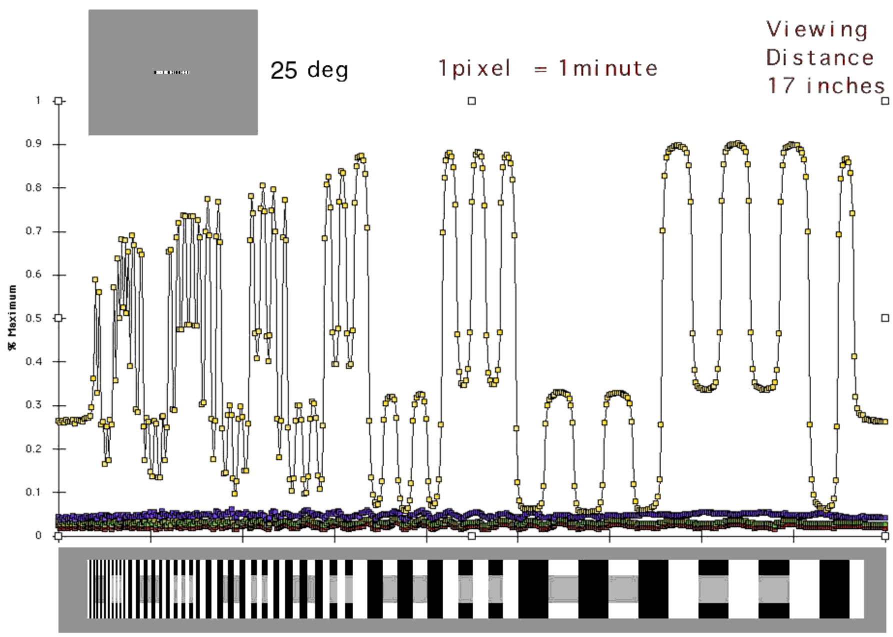

Figure 4 shows the influence of intraocular scatter on square wave displays. The entire 25° by 30° display is in the upper left corner. Most of the display is middle gray. The middle section is enlarged at the bottom. It is made up of gray patches on white/ black square wave gratings with decreasing spatial frequency from left to right. The graph plots % Maximum retinal intensity vs. position on the display. The graph shows that the large gray areas on the right have the same retinal intensity. The smaller gray areas in the middle have slightly higher retinal intensity when adjacent to white. The very small gray areas on the left have much higher retinal intensity when adjacent to white.

The retinal radiances for the half-height horizontal traces of displays in Fig. 5b are plotted in Fig. 5a. The left plot shows that starting with equal radiance at the display produces retinal inequalities of about 20%. Empirically adjusted displays produced the display on the right (Fig 5b) which is equal radiances of the gray patches on the retina. In this case radiance gradients in display intensity were introduced to flatten the retinal radiance plots.

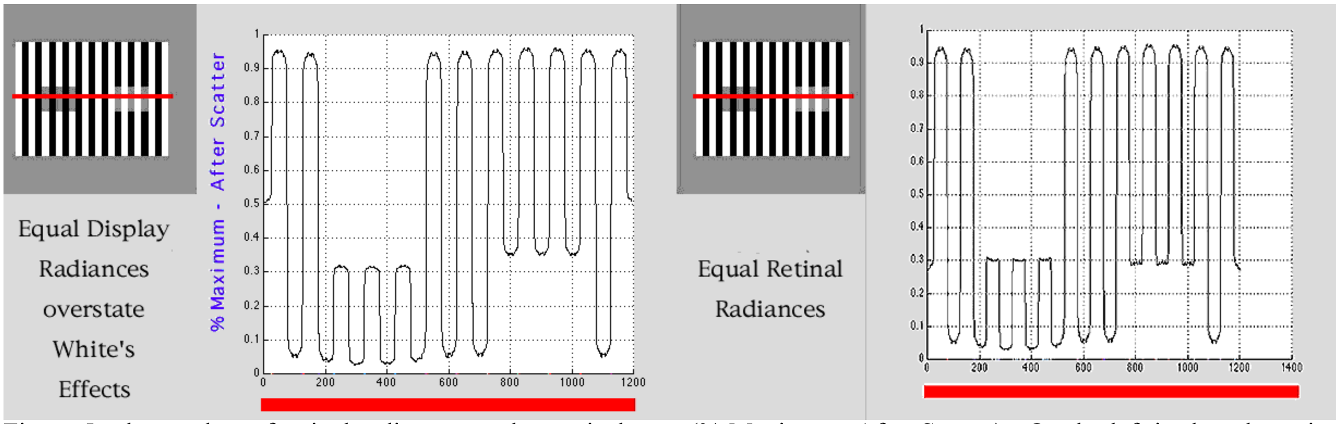

Figure 5a shows plots of retinal radiances on the vertical axes (% Maximum- After Scatter). On the left it plots the retinal radiances of a display in which the gray bars are the same radiance at the display. Intraocular scatter from the adjacent white stripes makes the grays on right greater than those on the left. A second White's Effect was created to have equal radiances on the retina. The two displays are shown in Figure 5b.

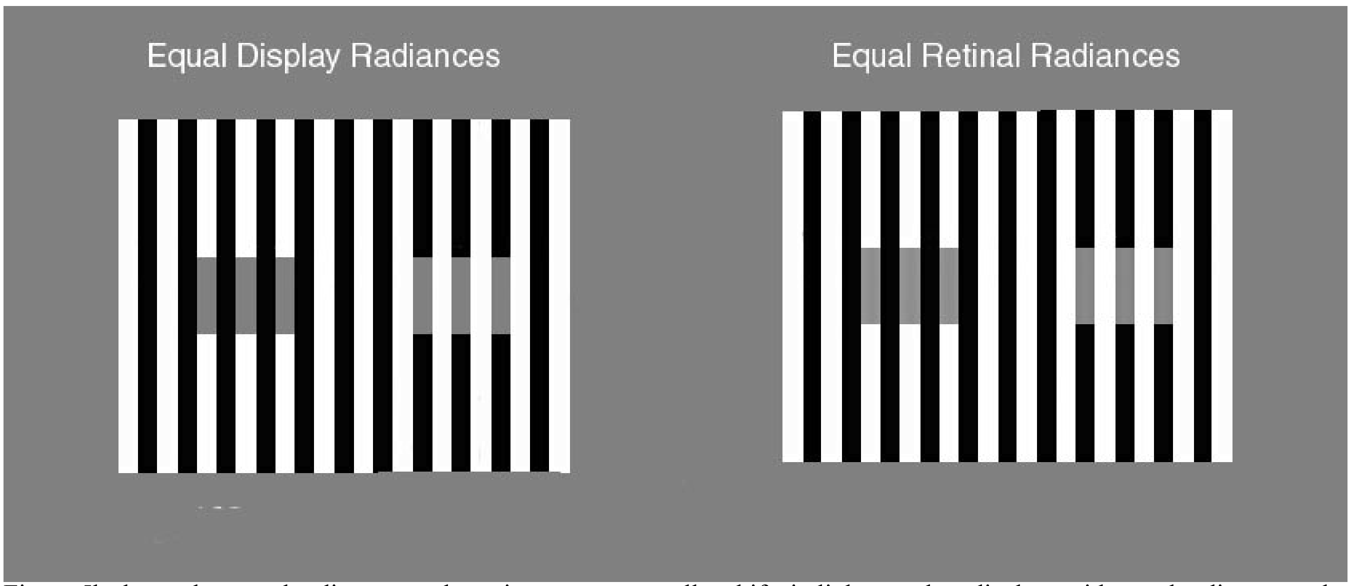

Figure 5b shows that equal radiances on the retina creates a smaller shifts in lightness than displays with equal radiances at the display. Intraocular scatter makes the magnitude of White's Effect bigger. When corrected for intraocular scatter the effect is smaller. Nevertheless, White's Effect shows the same direction of change in lightness. White's Effect cannot be explained by intraocular scatter.

White's Effect is just the opposite of Simultaneous Contrast. The contrast effect and the scatter add. In this case correcting for scatter reduces the size of the effect, but does not overpower it. Observers report that Whites Effect is still visible in the right half of Fig. 5b. The simplest Early Vision hypothesis, scatter, is not correct.

MULTI-RESOLUTION IMAGING

When you squint your eyes while studying White's Effect, it gets better. The light gray gets lighter and the dark gray gets darker. It is as if the high-spatial frequencies are inhibiting the effect and the low-spatial frequencies are producing it. There is a very good reason for this as illustrated in Figure 6. This diagram analyzes the center of the gray bars with different receptive field sizes. In the diagram it replaces the individual pixel intensities with their average for that size receptive field. The reason the right side of White's Effect looks lighter is that <u>it is lighter</u>, at least for low-resolution, or low-spatial frequency rendition of the input image. Squinting optically removes the high-resolution renditions, allowing the low resolutions to show through.

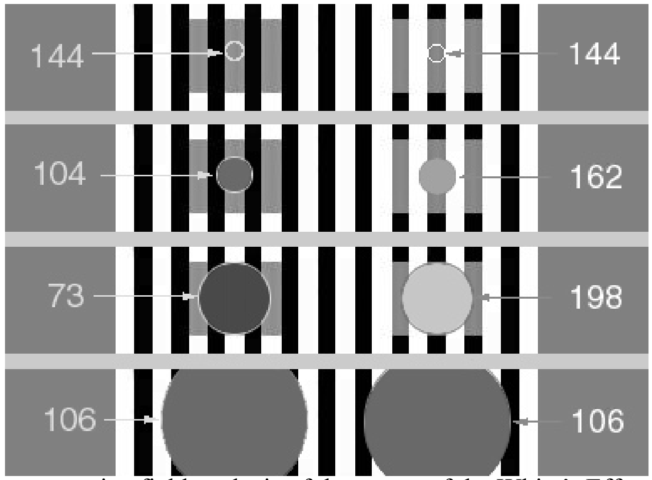

Figure 6 shows the effect of coarse receptive field analysis of the center of the White's Effect. The circular area, illustrating a receptive field, replaces the input display image with the average input value calculated in that field. The top row shows that the central grays in the display, horizontally bordered by black, have an average value of 144. These grays have equal radiances on the retina after scatter. The second row uses larger receptive fields that integrate the gray with black on the left (104), and the gray with white on the right (162). The third row uses a still larger receptive field that integrates over 5 stripes. The value on the left (73) is substantially darker than the integrated value on the right (198). The fourth row uses very larger receptive fields that integrate over the entire gray patches. Both values are the same (106).

Radiance summation using large receptive fields generates values consistent with White's Effect observed lightnesses.

PARALLEL COMBINATION OF MULTI-RESOLUTION IMAGES

There are many different multi-resolution models for human vision and for image processing. Frankle and McCann described a computer controlled apparatus that used ratio-product-reset-average processing on multiple resolutions of input image.[7] This process fed the result of the high-separation, low-resolution output images into the next level lower-separation, higher-resolution images. Burt and Adelson used spatial frequency decomposition to form image pyramids in the frequency domain.[8] Today, many image compression schemes use multi-resolution imagry.

Figure 7 shows two different strategies for Multi-resolution vision models. The first (left) builds a pyramid structure by averaging down the input image. It then processes the smallest image - interpolates up to the next level- and processes again. This operation continues through the full resolution image. The output of each level of the pyramid is used exclusively as the input to next level. So far, all models using this approach cannot predict White's Effect.

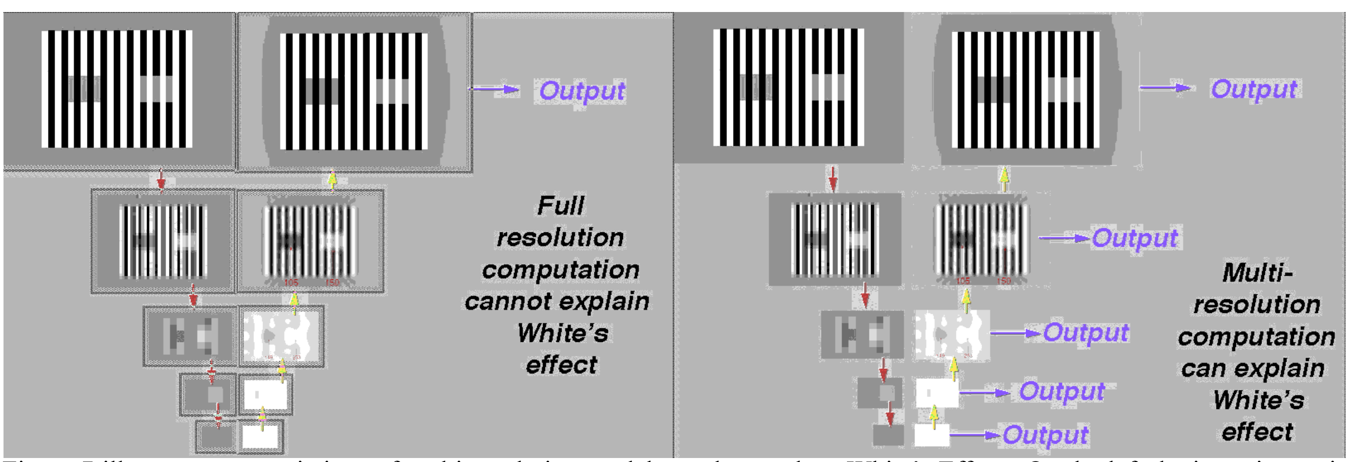

Figure 7 illustrates two variations of multi-resolution models used to analyze White's Effect. On the left the input image is shown in the upper left corner. The smaller images on the left are created by averaging down the input image. Starting with the smallest image on the bottom left this model uses ratio-product-reset-average processing to generate the image on the bottom right. This output image is interpolated up to the next bigger size where ratio-product-reset-average processing is again used. On the left the output at each resolution is interpolated to be the old product in the next finer resolution. The output is result of the full resolution computation. The multi-resolution model on the right reserves as output the information associated with each resolution. In addition to passing the new product to higher resolutions the individual outputs are reserved to be combined with other layers in parallel.

Parallel Multi-resolution Models, the second class (Fig. 7 right) uses the output of each level twice. First, it is stored for future use and it is passed on the next level. When scaled and combined with all the other level's outputs it produces an output image that agrees with observation. The right side of Whites display is lighter than the left. The image shown in Figure 5b (1200 x 800 pixels/1 pixel =1 minute of arc) is the input to a program that calculate radiance on the retina, That image is converted to image(384x256). The image is averaged down to make 192x128, 92x64, 48x32, 24x16, 12x8, 6x4, 3x2 images. Old product is set to 1.0. Ratio-product-reset-average processing[9] was done on the 3x2 image. Its output is interpolated to be the old product in the 6x4 image. The process is repeated until the 384x256 image is processed. The output image for each layer is interpolated (bicubic) to 384x256 and placed in Photoshop® with the high resolution image on the top. The opacity of the 12x6 layer as set to 100% and each higher layer was set to 30%. The image was flattened and the half-height horizontal trace was plotted in Figure 8.

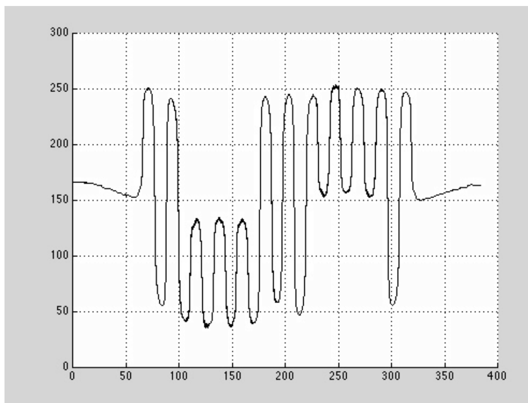

Figure 8 is the plot of the Parallel Multi-resolution model output. It reports the horizontal lightness values for a horizontal trace of pixels half-way between the top and the bottom. On the far left we see the gray background, followed by two white-black cycles, followed by three gray-black cycles (gray =130), two more white-black cycles, followed by three gray-white cycles (gray =155), followed by white-black cycles and gray. The Parallel Multi-resolution Model predicts that the grays on the right are 15 units lighter than those on the left. This plot agrees with observation.

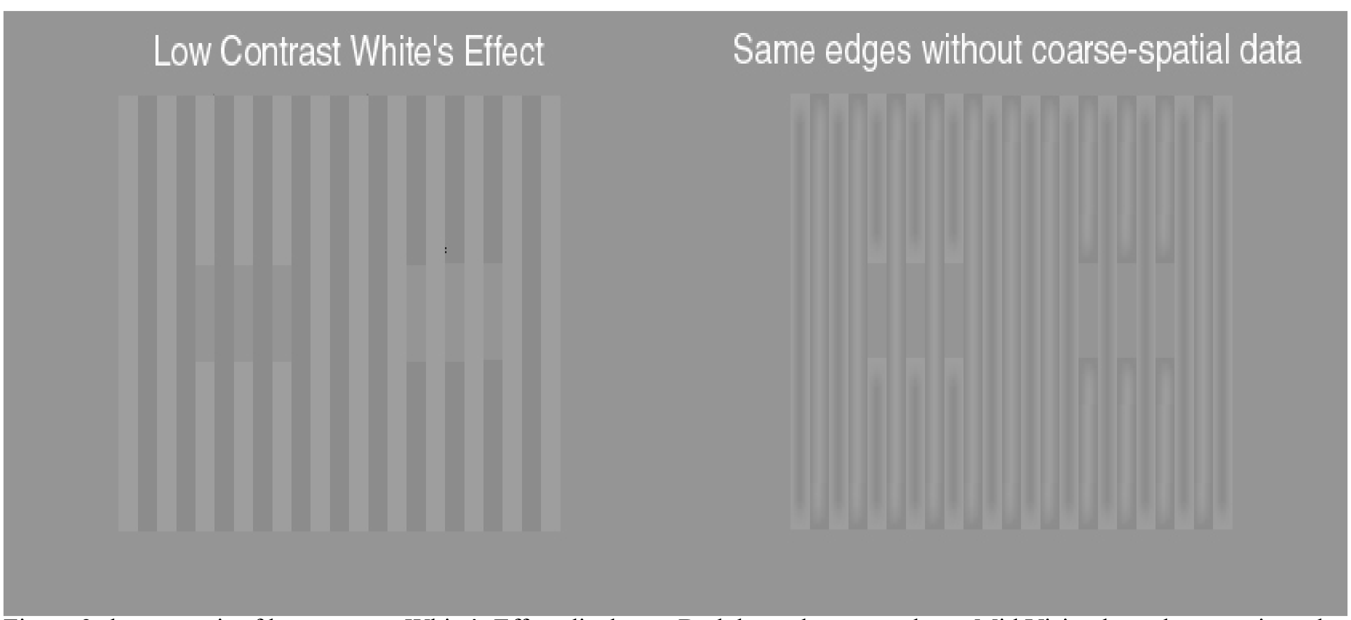

Figure 9 shows a pair of low contrast White's Effect displays. Both have the same edges. Mid Vision hypotheses, using edge operators, predicts that the grays in both displays will be the same, namely the grays on the right half are significantly lighter than the grays on the left half of both displays. The display on the right has gradients in place of flat regions, so as to remove the low-spatial frequency differences in the standard White's Effect. Low-spatial frequency explanations predict that the grays in both halves of the right display will be the same. NOTE:If the display on the right is enlarged. White's Effect returns when the gradients no longer cancel the low-saptial frequency visual responses.

DISCUSSION

Recently, interest has shifted away from the global explanations of High Vision to studies of the local operators in Mid Vision[10] We can do a simple test to see if local edge operators are controlling White's Effect. We can make a new pair of displays shown in Figure 9. The display on left is the similar to White's Effect, except that it is very low in contrast. Nevertheless, the effect works well and the grays on the right half are significantly lighter than those on the left half.

The display on the right has the same edges at those on the left. The right image has gradients introduced between edges to remove the coarse-summation image inputs seen in Figure 6. Imagine a square-wave grating created by the sum of sine-wave gratings. Imagine removing the third-harmonic sine wave. All the edges remain the same, but all the flat areas are now gradiants. Working in the spatial domain, we have made the display on the right. If edges control apparent depth, which in turn controls lightness, then the grays should match White''s Effect (left display). If the above low-spatial frequncy explanation is correct, then this display (right) should not exhibit White's Effect.

SUMMARY

This work attempted to find an early vision explanation for White's effect. The first idea was that intraocular scatter plays the opposite role as it does in Simultaneous Contrast. In White's Effect scatter adds to the magnitude, instead of reducing it. The effect of scatter in Simultaneous Contrast displays is large. It is 10% for ordinary displays and 20% for bars (Figure 3). Nevertheless, a target designed with compensating intensities at the display, so as to generate equal radiances at the retina still demonstrates White's Effect. Intraocular scatter cannot explain White's Effect.

A second attempt was more successful. Using scatter corrected displays for input, Multi-resolution vision models were tested. The results showed that parallel Multi-resolution approaches can account for White's Effect. The reason is that low-resolution images of White's Effect renders the gray next to black as much darker than gray next to white. Any human vision model that incorporates low-resolution, or low- spatial-frequency, information directly in the output can model White's Effect. Models that pass all the low resolution information into higher resolution images lose the required information.

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