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Perception of surface color plays an important part in many everyday visual tasks. Psychophysical and neurophysiological data on early visual processes suggest a number of potential sensory limitations on the accuracy of surface-color perception. A new paradigm has been used to clarify the relationships between early visual processes and perception of achromatic surface colors (shades of gray). Psychophysical measurements of perceived surface color were made using achromatic stimulus patterns that were complex enough to support unambiguous perception of surfaces and lights. Lightness (apparent reflectance), brightness (apparent luminance) and local brightness contrasts were all measured using the same stimulus patterns. According to a number of models, lightness is closely related to local brightness contrast, but the data indicated that the relationship is more complicated than previously supposed. The brightness contrast data are well described by Stiles' threshold-vs-radiance curve, which is widely thought to be a characteristic of retinal adaptation processes. Both brightness and lightness are slightly higher on dark gray backgrounds than on white backgrounds. This perceptual error appear to be independent of illumination level.

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ANNUAL TECHNICAL REPORT
5/1/91-4/30/92

GRANT AFOSR 89-0377

Lawrence E. Arend
Principal Investigator

I. OBJECTIVES

In previous project periods we have examined laboratory methods that can be confidently applied to practical viewing situations without giving up the experimental control needed for comparisons with traditional psychophysical and neurophysiological work. We developed a paradigm for psychophysical measurement of perceived surface colors in complex images. Our published achromatic experiments have shown that previous attempts to apply sensory concepts to complex images have been incorrect and that more perceptual experiments have often been misinterpreted.

The research proposed for this period consists of extensions of that project with the same general goals. Brightness-contrast data from our pilot work were found to be closely related to well-known data from psychophysics and neurophysiology experiments (e.g., Whittle and Challands, 1969; Shapley and Enroth-Cugell, 1984), curves thought to be characteristic of retinal adaptation processes. However, our experiments differ from most previous psychophysical work in two important ways: 1) by using stimuli sufficiently complicated to allow unambiguous perception of surface colors and illuminations and 2) by having subjects judge several perceptual dimensions in each stimulus.

We proposed in this extension of the project to pursue two research lines suggested by the previous grant period. In the first we examine limitations on accuracy of surface perception that are imposed by early contrast-encoding mechanisms. We proposed to measure the *lightness*, *brightness*, and *brightness contrast* of a test field embedded in a complex scene, using a lightness constancy paradigm:

1) We proposed to measure the three response variables over a wide range of adapting luminances and relate the measurements to threshold-vs.-radiance curves.
2) We proposed to show that both brightness (apparent luminance) and lightness (apparent reflectance) are affected by local background reflectance, but not in the way suggested by previous experiments from other laboratories, which were deficient in several respects.

For the second line we proposed to measure brightness distributions in patterns with shallow luminance gradients. The Arend/Blake model highlighted the importance of two kinds of gradient illusions. a) A low contrast luminance sawtooth in a dark

surround produces a brightness staircase (Arend and Goldstein, 1987, fig. 1). Abrupt brightness steps separate the pattern into bands of uniform brightness. In the "ring" version of the illusion the bands are uniform in brightness for all surround luminances, but in the 1D "bar" version the bands are uniform only when the surround luminance is greater or less than the luminances in the sawtooth. The model revealed important structural differences between the two forms of the illusion. b) When a rectangle of uniform luminance is placed in the middle of a larger field in which there is a shallow luminance gradient, one sees a strong brightness gradient in the central rectangle and no brightness gradient in the surrounding larger field. That is, brightness gradients are perceived where there are no luminance gradients and vice versa. This lends support to an interesting interpretation of the integration in the Arend/Blake model. The model suggests that some of the brightness gradients perceived have locations and magnitudes dictated by relaxation of the 2D inconsistencies in the distribution of thresholded gradients.

II. STATUS OF RESEARCH EFFORT

The past year was one of intense effort and great productivity, but, due to unforeseen events, most of the low luminance experiments were deferred to the second year of the project. Through much of the year I worked on reducing the backlog of unpublished experiments from previous grant periods, and for several of the experiments I decided that further data were necessary or desirable. The experiments on lightness, brightness and brightness-contrast matches were elaborated with several new conditions that greatly strengthened the evidence for our new interpretation of achromatic surface color perception. Our measurements of constancy of unasserted colors were strengthened by running a new subject and adding conditions. Those experiments were completed and three articles describing them were submitted.

In addition, collaborations produced several experiments on closely related topics not included in the original proposal. Branka Spehar, a graduate student in Alan Gilchrist's laboratory at Rutgers, completed her nine month visit during the first half of the year. Her contribution far exceeded expectations. Discussions with her contributed significantly to the design of the extensions of the lightness, brightness, and brightness-contrast experiments, and she was an observer and discussant on the chromatic adaptation experiments as well. We ran two further experiments on suprathreshold contrast perception following up her ideas and

design, one on a phenomenon called "contrast contrast", the other on White's Illusion. Both phenomena raise serious and difficult questions for all existing analyses of suprathreshold contrast perception. I also continued collaboration with Dr. Eliezer Peli on his contrast perception project directed toward producing an improved approach to image quality. The work has great promise of producing image descriptors far superior to those in current use.

A. Lightness and Color Constancy

With the disk/annulus stimuli of traditional sensory psychophysics the retinal stimulus is perceptually ambiguous (fig. 1).

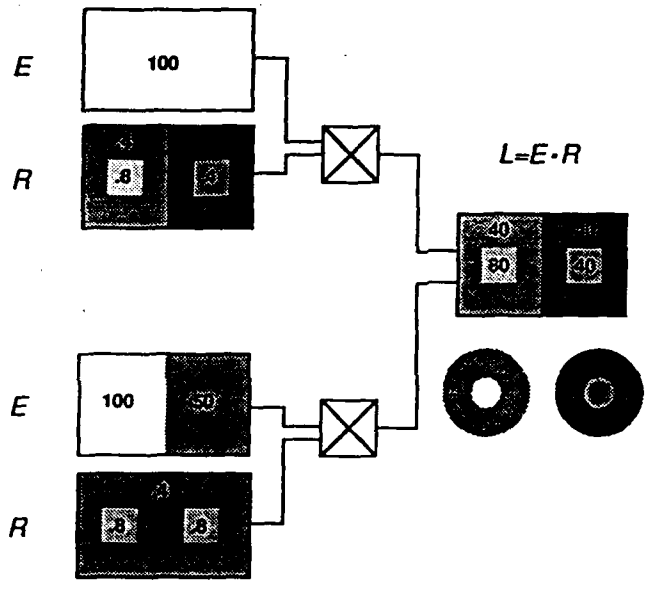


Figure 1. Disk/annulus is perceptually ambiguous. Either physical situation (left) could cause the retinal stimulus (center).

It is as likely that the image was caused by one illuminance falling on different reflectances as two illuminances falling on the same reflectances. There is no visual information to make one explanation more likely than the other. It is therefore impossible to confidently interpret subjects' responses to such stimuli in terms of perceived illuminances and lightness.

In our paradigm less ambiguous surface perception is obtained by using more complex stimuli (Fig. 2). Such stimuli provide enough information for the visual system to attribute components of the luminance gradients to reflectance changes and illumination changes. At the same time the stimuli are simple enough to let us test

hypotheses based on concepts from conventional psychophysics and neurophysiology (e.g., simultaneous contrast and adaptation).

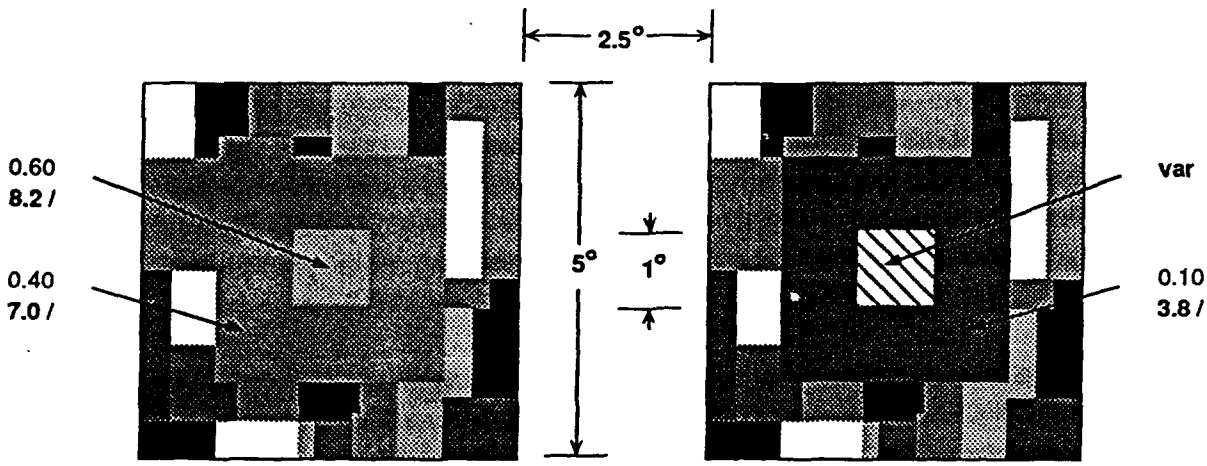


Figure 2. Diagrams of stimulus patterns. Increment Condition. Plain type: Reflectance. Bold Face: Equivalent Munsell Value.

A. Lightness and Color Constancy

1. Theory. We have made further progress in analyzing the role of sensory processes in surface color perception. The logical analysis underlying fig. 1 showed that subjects viewing disk/annulus stimuli cannot make veridical reflectance matches because there is insufficient visual information for them to know whether or not the annuli have the same reflectances. The experiments of the previous grant period showed that subjects viewing a sufficiently rich stimulus pattern can match two global dimensions of achromatic color experience, brightness (apparent luminance) and lightness (apparent reflectance) and one local dimension, brightness contrast at an edge. If the subjects in the disk/annulus experiments were not matching apparent reflectances, what were they doing? Given the experimental conditions and the forms of the data in the literature on disk/annulus experiments we believed that subjects matched either brightness or brightness contrast or sometimes each in different parts of the same experiment. We lent empirical support to those logical arguments by matching the three dimensions with ambiguous disk/annulus stimuli and comparing the results with the data for the same tasks with unambiguous stimuli. The structure of the experiments with the ambiguous experiments is inherently controversial, thereby posing some threat to acceptance of the stronger experiments with unambiguous stimuli. However, we

decided to take the risk in order to make the logical flaws of the classical brightness and lightness work more obvious and explicit.

2. Experiments.

We completed and wrote up for publication experiments that delineate the dimensions of achromatic color experience of simple and complex patterns. The experiments are fully described in the attached manuscripts (also previously sent to AFOSR in May).

We also designed and completed two new experiments, one on the "contrast-contrast" phenomenon and one on White's Illusion.

a. Contrast-Contrast. The apparent contrast of a pattern is lower when it is surrounded by patterns with high physical contrast than when surrounded by lower-contrast patterns. Chubb, Sperling and Solomon (1989) found that a test patch of random visual texture had lower apparent contrast when surrounded by a high-contrast background of similar texture than when surrounded by a uniform gray field (Figure 3). They called this phenomenon "contrast-contrast" in analogy with classical simultaneous brightness contrast. The phenomenon shows that the brightness at a point in the image is a more complex function of the surrounding image structure than had previously been suspected. The contrast suppression of the test patch surrounded by high contrast texture cannot be attributed to the mechanisms responsible for simultaneous brightness contrast because the space average luminance of the test patch and surrounds are equal.

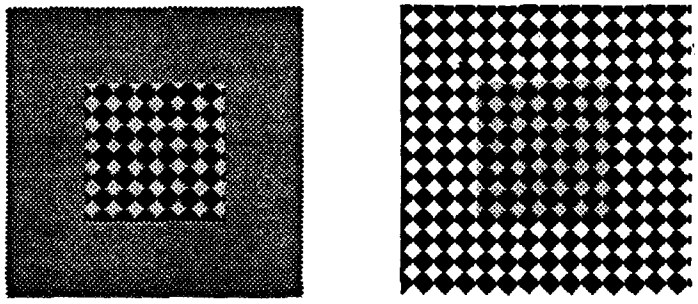


Figure 3. Contrast-contrast: On the experimental display the two texture disks were identical, with contrast = 0.5. The left disk has higher apparent contrast than the right.

To measure contrast-contrast Chubb et. al. temporally modulated the contrast of the surrounding texture, thereby inducing a temporal modulation of the apparent contrast of the test patch. The observers nulled the apparent modulation of the contrast in the test patch by adjusting a physical contrast modulation (in temporal counterphase) of the test pattern.

Contrast-contrast has been attributed by previous investigators to neural interactions among contrast gain signals. We found several configurations that seemed to be more consistent with transparency and lightness constancy mechanisms than with pattern-specific neural interactions.

Our measurements showed that there are two components to contrast-contrast. There is a pattern-specific component in which the surrounding high contrast pattern influences the apparent contrast of test patterns that are similar in spatial frequency spectrum and phase to the inducer but has no effect on the apparent contrast of other patterns. There is also a pattern-non-specific component in which the high contrast inducing pattern reduces the apparent contrast of any test pattern. The two components are roughly equal in magnitude.

While we found and measured the non-specific component we were particularly interested in the pattern-specific component. In some of the prior work the apparent contrast of the test patch reportedly decreased monotonically as surround contrast increased from zero. This applied even when the surround contrast was identical to the test contrast; the apparent contrast of a pattern decreased as its area was increased. We have found several counterexamples that seem to be connected to lightness constancy and transparency. We found that the pattern-specific component is limited only to a restricted range of the luminance relationships between the test patch and background elements, namely, to the range of luminance relationships that are compatible with a transparency appearance. In that case the display has the appearance of one large, continuous grating with a superimposed transparent veiling luminance over the region of the test patch.

We used three kinds of patterns, random visual texture; in-phase and 180 deg. out-of-phase square-wave patterns (Fig. 4). Two 1.8 cycles per deg center/surround square-wave patterns or two pairs of random visual texture patterns were presented 7.4 deg apart (center to center). For the square-wave patterns two orientation conditions were used: the central patches were either in-phase or 180 deg. out -of-phase with the square wave gratings of the surround.

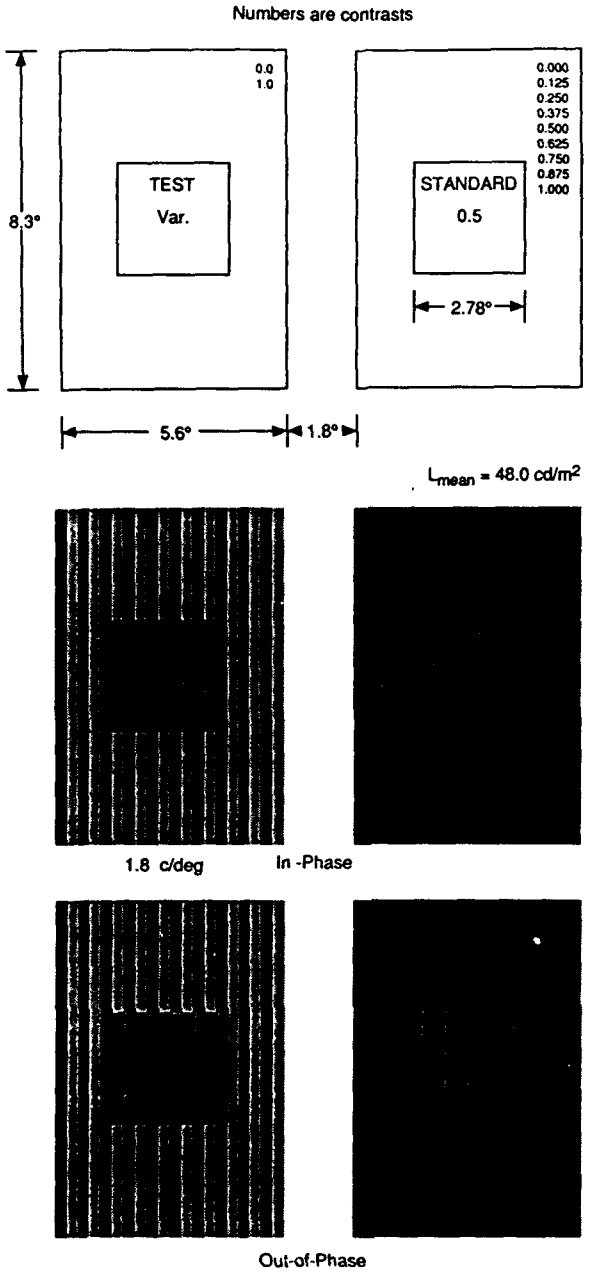
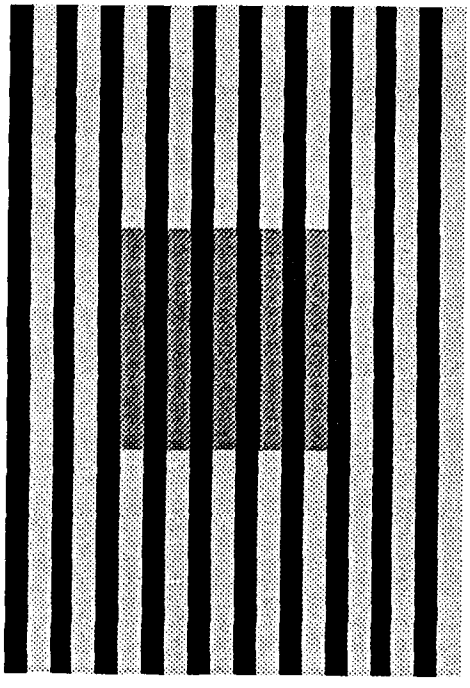


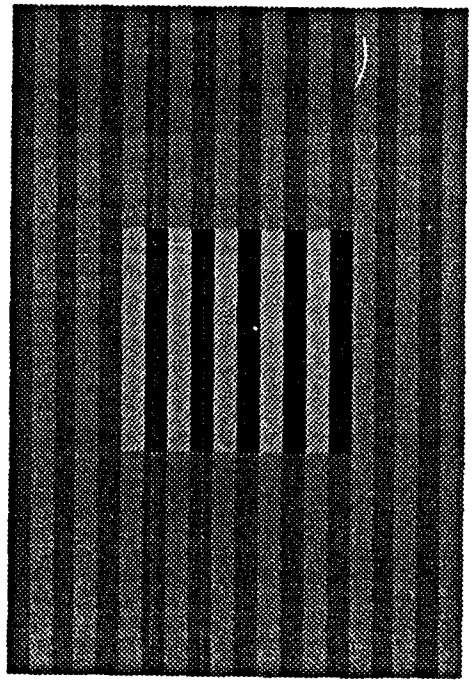
Figure 4. Test patterns of contrast-contrast experiments.

For each condition there were two subconditions: the contrast of the background of the test patch was either 0 or 1. The contrast of the background surrounding the standard patch (contrast 0.5) varied from trial to trial, ranging from 0 to 1 in 9 steps.

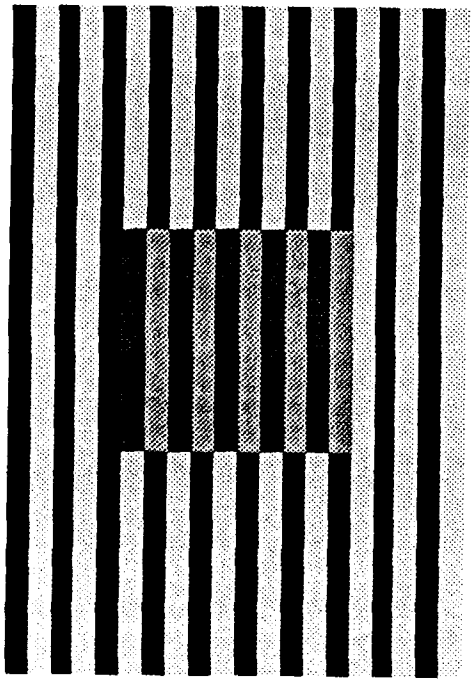
Subjects adjusted the contrast of the test patch in the left display to match the apparent contrast of the standard patch in the right display.

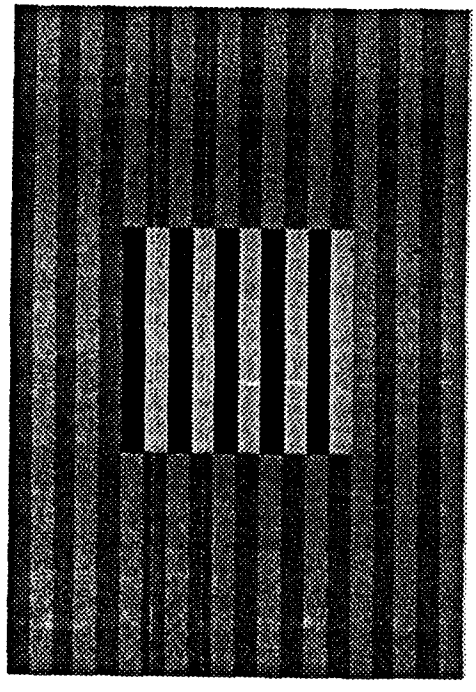
Results for the random textures are shown in Fig. 5a. The subjects' mean contrast adjustments (ordinate) are plotted against the contrasts of the surround of the standard patch (abscissa). The open and filled circles represent the adjustments for the condition where the contrast of the surround of the test patch was 0 and 1,





1.8 c/deg In -Phase





Out-of-Phase

respectively. The horizontal solid line represents the physical contrast of the standard patch. The unconnected points represent the stimulus where the standard patch contrast and its surround contrast were the same, so display had the appearance of one large random visual noise patch.

The results show that contrast-contrast (the difference between the test and standard physical contrasts at equal apparent contrast) is greater when the surround contrast was greater than the standard-patch contrast, i.e., when the relations support the appearance of a transparent luminance veil over a single large block of random texture.

Results for square waves are shown in figs. 5b and 5c. For 5b and 5c the contrasts of the surround of the test patch were 0 and 1, respectively. The circles and squares in each panel are the means for the in-phase and out-of-phase displays, respectively. The unconnected points represent the stimulus where the standard patch contrast and its surround contrast were the same, so for the in-phase square-wave pattern display had the appearance of one continuous square-wave patch the size of the surround.

The magnitude of the suppression was dependent on the relative phases and relative magnitudes of the patch and background gratings. The greatest contrast suppression was for the in-phase patterns (orientation-specific) when the contrast of the surround was greater than that of the central patch (within the luminance range that allows a transparency appearance). When these conditions were not met contrast suppression was considerably smaller. Both the orientation-specific and orientation-non-specific suppression effects were rather small compared to results reported by previous investigators. Cannon and Fullenkamp (1991) found maximum suppressions of 0.4 log units for two subjects and 0.25 for the third with the test patch and background contrasts of 0.25 and 0.50, respectively. In contrast, our maximum suppressions were 0.25 log units for BS and 0.12 for LA and DA, with higher test patch and background contrasts of 0.5 and 1.00, respectively.

We investigated the pattern-nonspecific component a bit further using demonstrations. Previous researchers have described the test pattern's appearance in terms of apparent contrast, but it can equally well be described in terms of the maximum and minimum brightnesses of its elements. We placed various uniform gray patches (spanning the gray scale) on square-wave backgrounds. The uniform bright patches are brighter and the dim patches are dimmer on low-contrast surrounds than on high contrasts. This is

hard to reconcile with any model based on pattern-specific neural interactions.

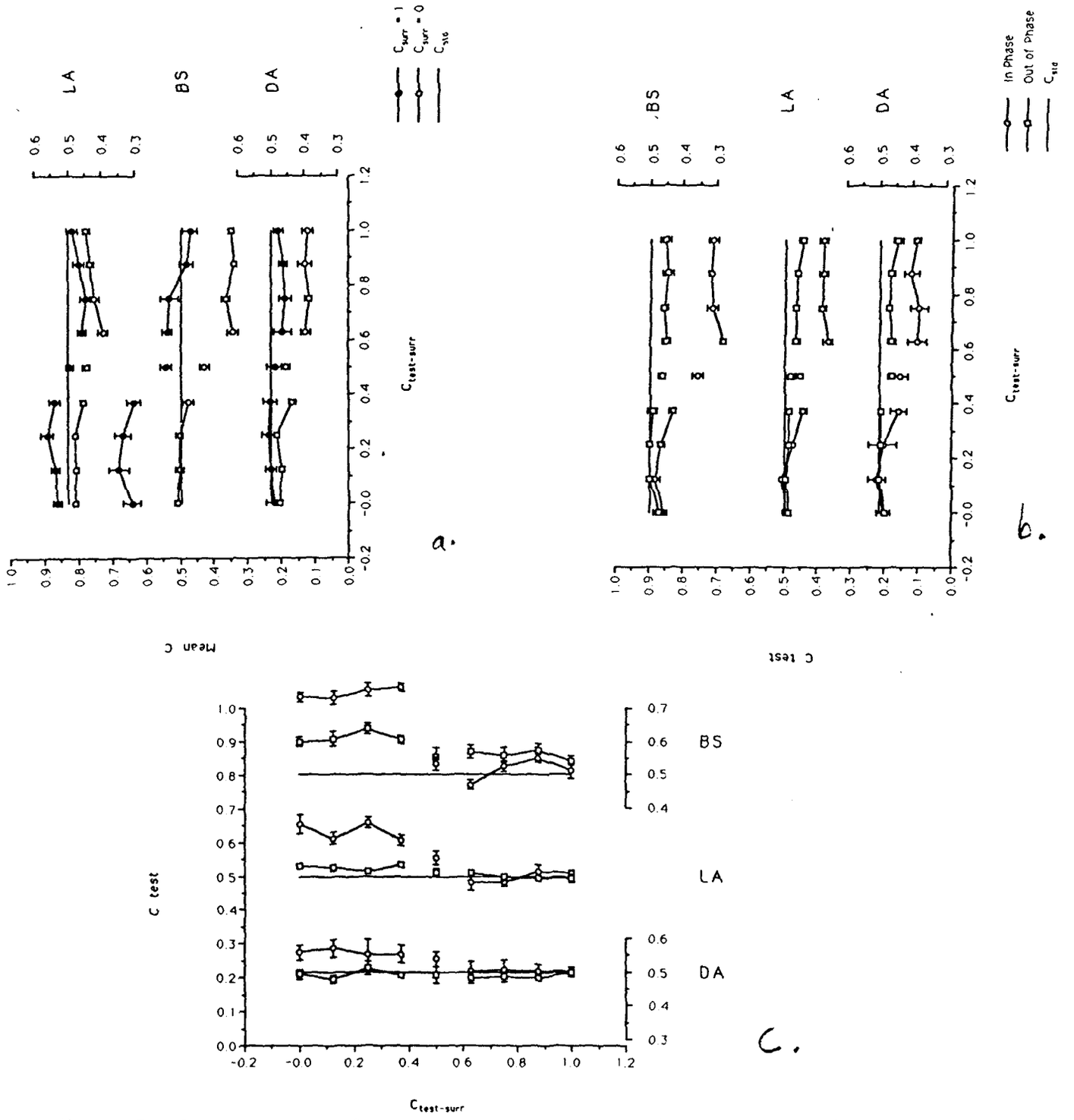
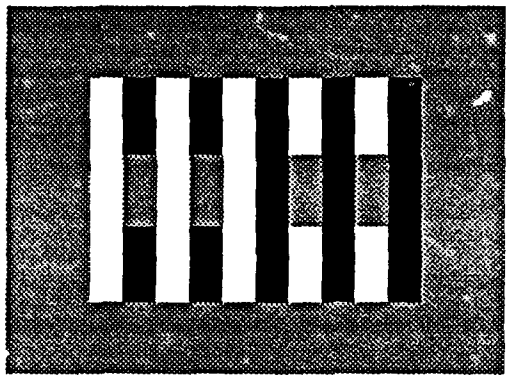


Figure 5. Mean contrasts from contrast-contrast experiments. a. Random textures. b. Square-wave gratings, $C_{tstbkgrd} = 0$. c. Square-wave gratings, $C_{tstbkgrd} = 1$.

b. White's Illusion. The experiment on White's Illusion was presented as a poster at the 1992 ARVO meeting.

In White's illusion (White, 1979) (fig. 6), gray bars replacing segments of black and white square-wave grating appear different in a direction opposite from what would be expected on the basis of simultaneous lightness contrast. The flanking bars share more contour with the gray patches and have more adjacent area than the bar segments at the ends of the gray patches, yet the brightness differences are opposite the expectation from contrast with the flanking bars.

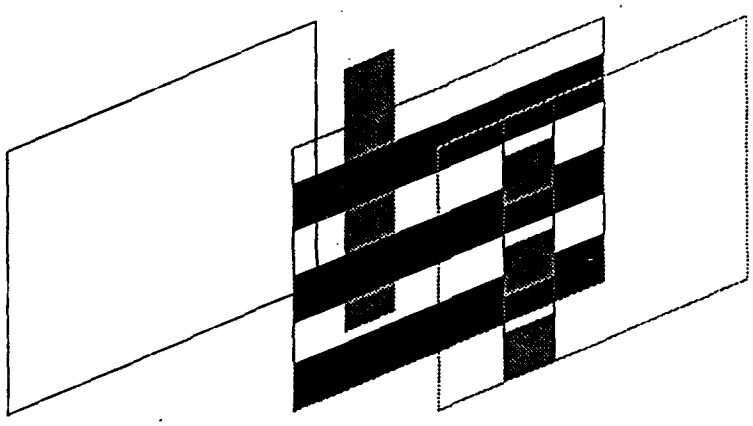


Several explanations have been offered:

White and White (1985) suggested that this is an instance of counterphase lightness induction based on the phenomenon of grating induction. Kingdom and Moulden (1989) suggested a dual mechanism involving local and spatially extensive contrast mechanisms modeled in terms of circular-symmetrical opponent filters and filters with elongated opponent surrounds. Polichar and Brown (1991) proposed a "higher-order" contrast adjustment process related to perceptual organization or to the notion of edge "belongingness".

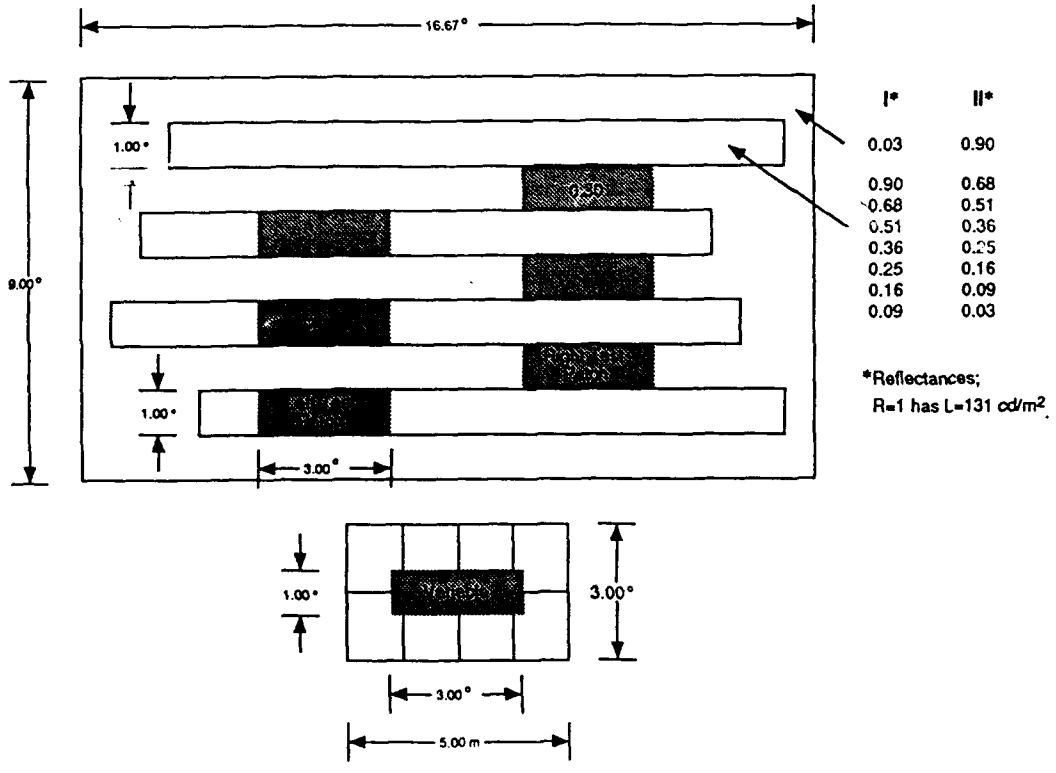
We proposed instead that White's Illusion is a result of occlusion relations and a process that assigns lightnesses as in phenomenal transparency. We found that White's Illusion requires two conditions to be satisfied. The first is that the apparent ordering

in depth of the elements of the pattern must place the gray patches in front of the long bars:



The second condition is the same luminance range constraint we found in contrast-contrast. White s Illusion occurs only when the luminance of the gray bars lies somewhere between those of the lighter and darker inducing stripes.

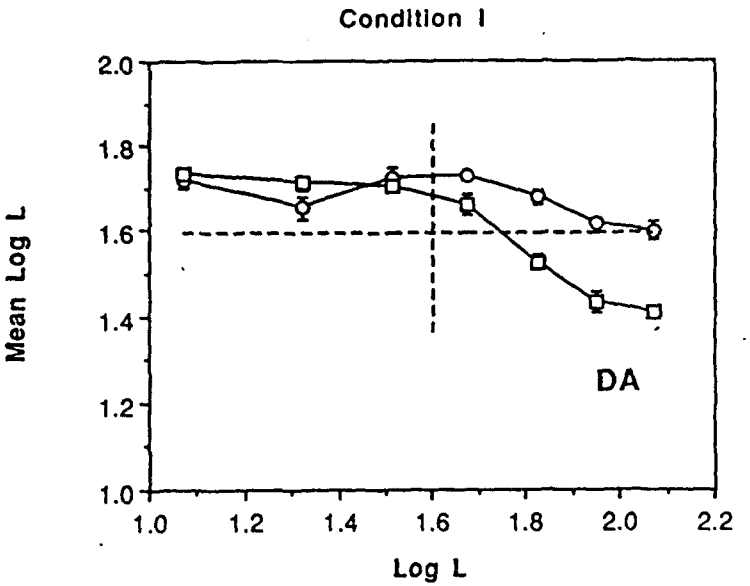
The second requirement was demonstrated by measuring the effect of the luminance of the long bars on the brightness of the gray patches. The stimuli were CRT generated:

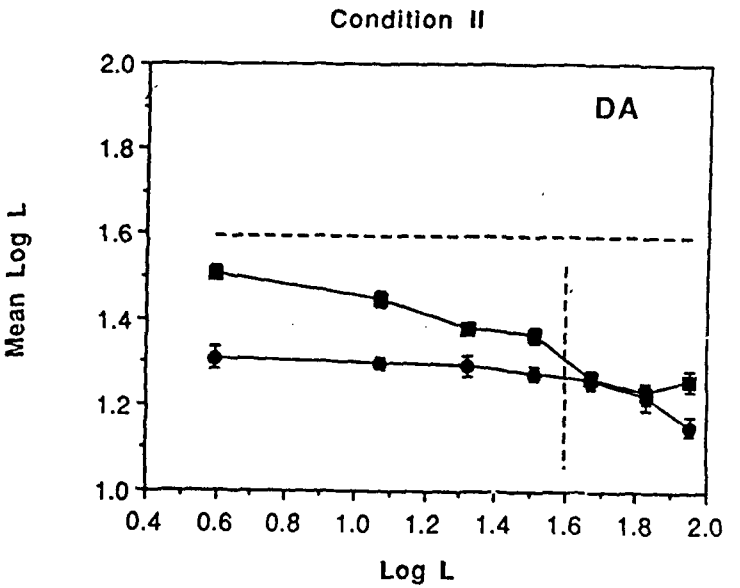


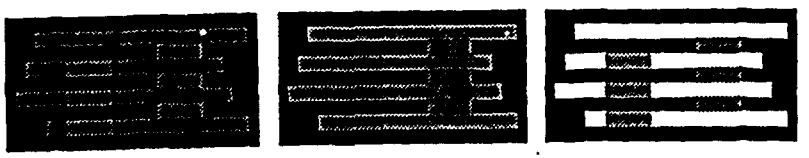
In each session the simulated reflectance of the background was either 0.03 (black) or 0.90 (white). Within each session the luminance of the long stripes varied in seven steps. The subject adjusted the luminance of the adjustable patch to match its brightness to that of the test patch indicated by cursor.

DATA :

Legend:
x : luminance of the pattern's changing elements;
y : mean luminance matches of the test patches;
—○—; —●— patch on the background;
—□—; —■— patch on the stripe;
— — — — test patch physical match;







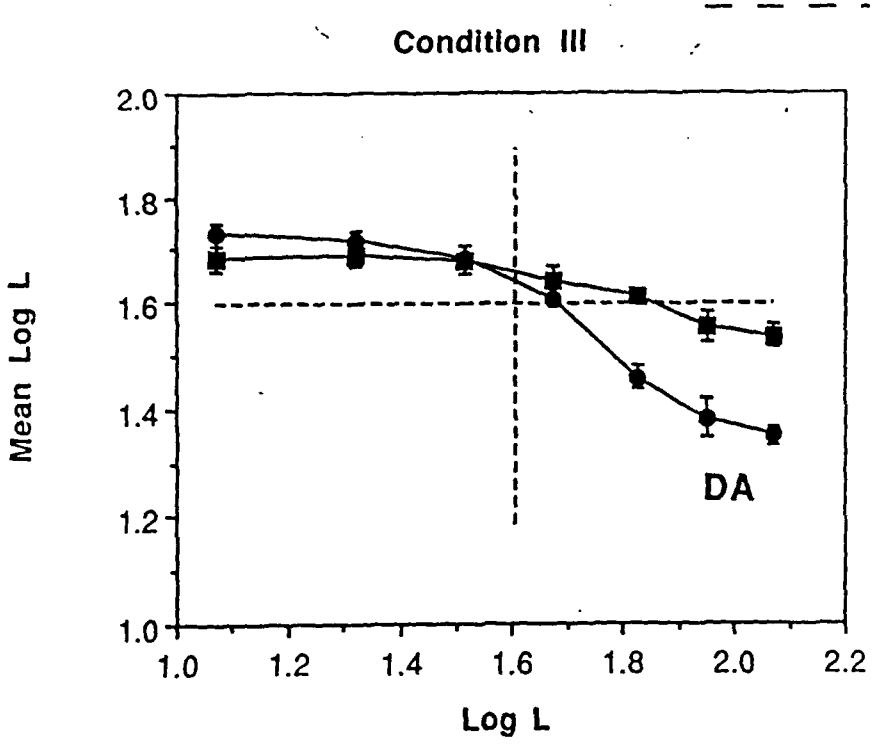
Condition I:

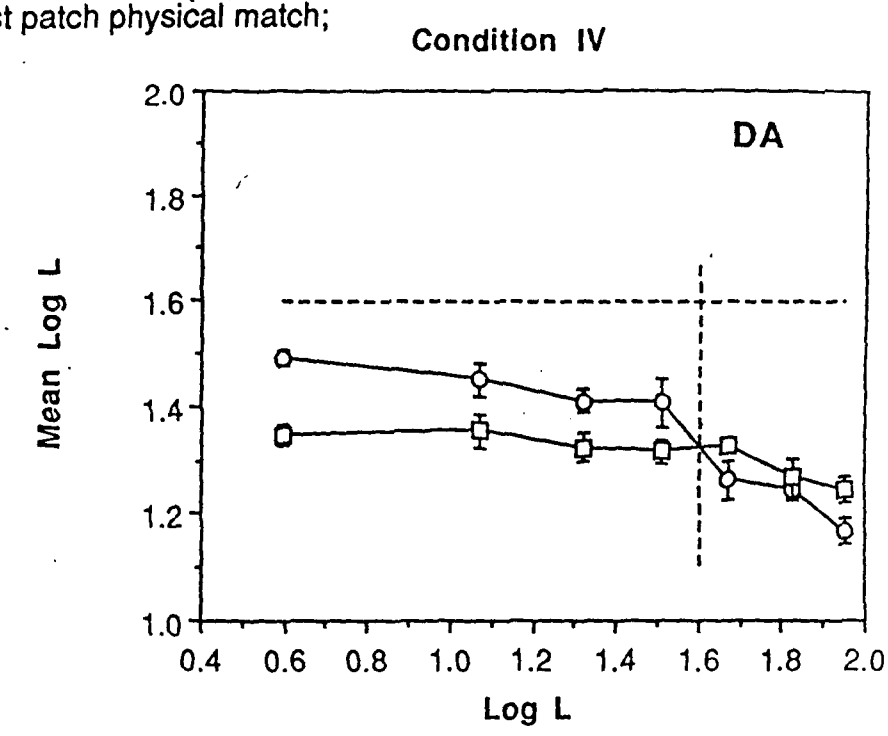
- black background constant from trial to trial
- figural stripes changing from very dark gray to white;

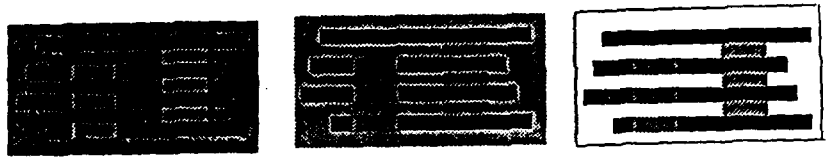
Condition II:

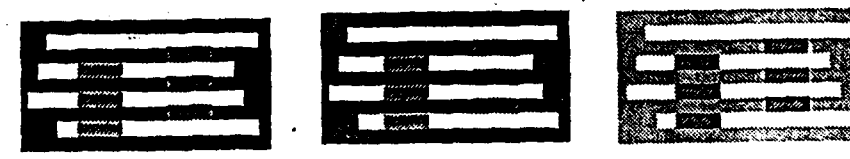
- white background constant from trial to trial
- figural stripes changing from black to very light gray;

Legend:
x : luminance of the pattern's changing elements;
y : mean luminance matches of the test patches;
—○—; —●— patch on the background;
—□—; —■— patch on the stripe;
— — — - test patch physical match;









Condition III:

- black figural stripes constant from trial to trial
- background changing from very dark gray to white;

Condition IV:

- white figural stripes constant from trial to trial
- background changing from black to very light gray;

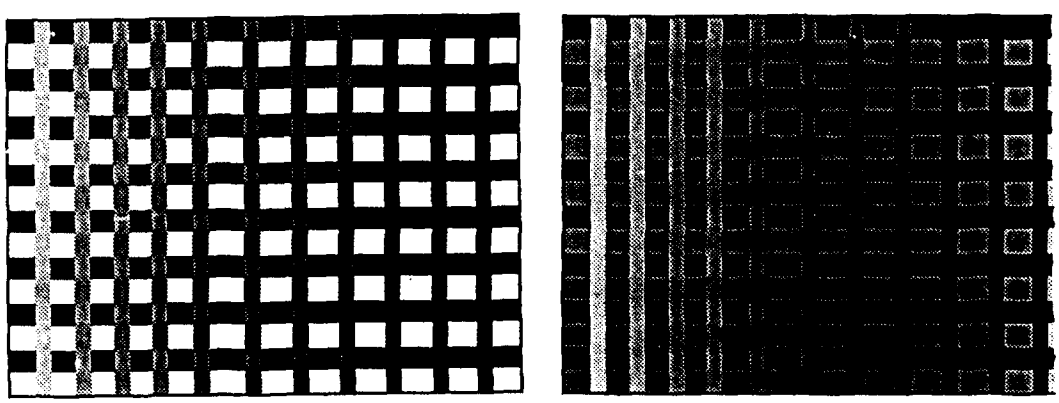
There were several novel results. First, White's Illusion was larger in our matching measurements than in previous experiments in which nulling techniques were used. The main result, however, is that the illusion did not occur when the test patch luminance was outside the luminance range of the grating stripes:

Condition I--There was no brightness difference when the test patch luminance was greater than that of the grating stripes.

Condition II--There was no brightness difference when the test patch luminance was less than that of the grating stripes.

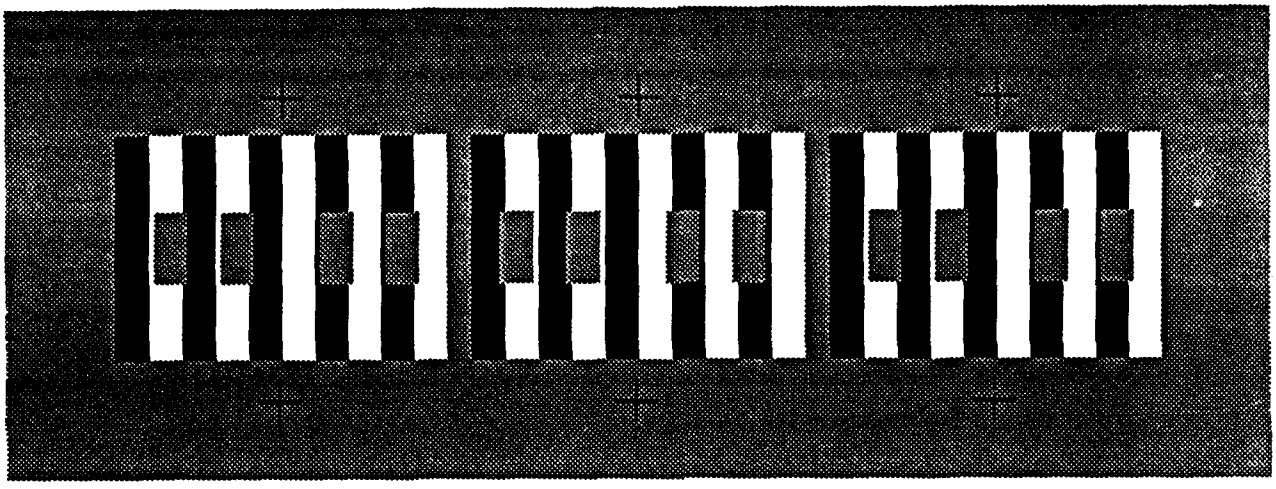
This is only one of several phenomena to which the luminance range constraint applies. As mentioned above, in contrast-contrast strong suppression of apparent contrast occurs only if the luminances of the target elements fall between those of the background elements. Under those conditions one perceives a transparent patch of veiling luminance over the uniform background texture.

Grating induction also occurs only when the luminance relationships among the target and inducing elements satisfy the range constraint. In the patterns below the induced grating is prominent only when the luminance of the vertical stripes lies between the luminance of the horizontal stripes.

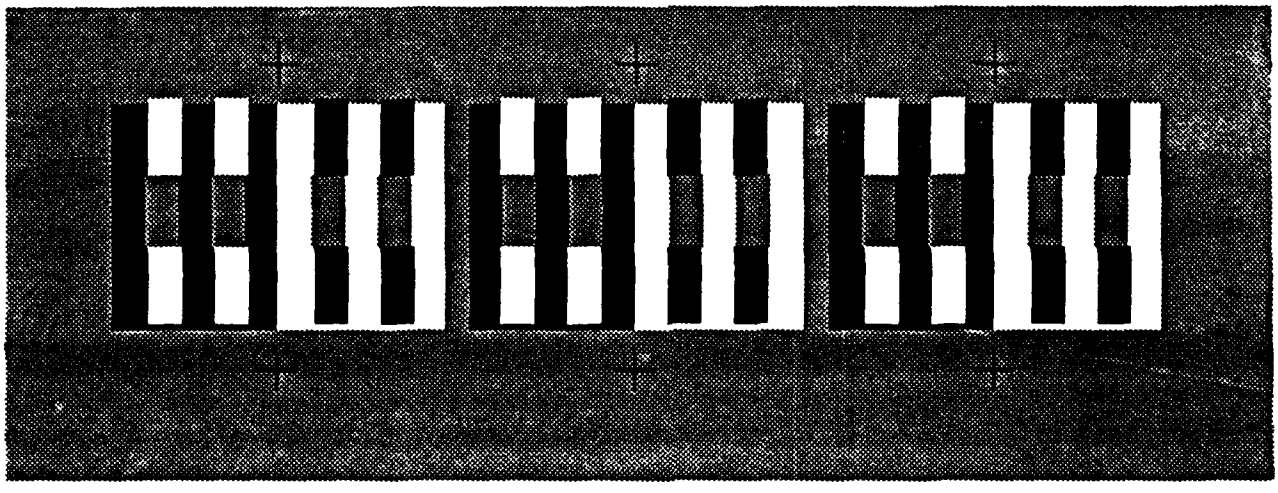


One might propose an explanation in terms of the gray bars' contrasting only with the occluded surface (see "exploded" view

above). because the black and white stripes are both occluded by the test patch (the other examples on this poster are consistent with this alternative to our transparency account). That alternative is eliminated by the following stereo demonstration:



White's Illusion occurs even when the test bars phenomenally lie by themselves in a plane nearer than the squarewave grating. The explanation is eliminated by the fact that the gray bars occlude both the white and black bars. When the test patches are occluded by the pieces of stripe collinear with the test patches the percept is different for monocular and binocular viewing. Both monocular views are approximately the original White's Illusion figure, and White's Illusion is seen. In the combined stereo view, however, the brightness relations among the test patches reverse. The test patches contrast with their uniform white and black backgrounds.



One project of the second year is to make quantitative brightness matches in the stereo conditions. The phenomenon is still very poorly understood, even in terms of the relevant stimulus arrangements. Our measurements show that it is of the same general size as local simultaneous brightness contrast. Our current best guess is that it basically consists of a set of heretofore unrecognized spatial constraints on simultaneous brightness contrast. If so then it fits into our surface color perception scheme as one of the sensory factors that can produce errors of lightness perception.

III. PAPERS

In addition to completion of several manuscripts, I presented a number of invited talks.

Arend L., Reeves A., Schirillo J., and Goldstein R. Simultaneous color constancy: Patterns with diverse Munsell values. J. Opt. Soc. Am. A **8**, 661-672, 1991.

Reeves, A and Arend L. Color constancy. Advances in Color Vision Technical Digest **4**, 115-117, 1992.

Peli, E., Arend, L., Young, G. and Goldstein, R. Contrast sensitivity to patch stimuli: The effects of spatial bandwidth and temporal presentation. Spatial Vision, In Press.

Arend, L. Multidimensional models of surface color perception. To appear in Gilchrist, A. (Ed.) Lightness, Brightness, and Transparency. Lawrence Erlbaum Assoc., Hillsdale, NJ.

Arend, L. and Spehar, B. Lightness, brightness, and brightness contrast. I. Illuminance variation. Submitted for publication.

Arend, L. and Spehar, B. Lightness, brightness, and brightness contrast. II. Reflectance variation. Submitted for publication.

Arend, L.E. How much does illuminant color affect unasserted colors? Submitted for publication.

Schirillo, J. and Arend, L. Lightnesses near illumination edges. Submitted for publication.

In Preparation:

Reeves, A. and Arend, L. Successive color constancy.

Whittle, P. and Arend,L. Homochromatic Colour Induction.

Arend, L. and Arend, D. Effect of background reflectance on lightness.

Arend, L. Providing a reference grayscale for lightness judgments.

Spehar, B. and Arend,L. Perceptual factors in contrast-contrast.

Review:

Arend, L.E. Review of "Perceiving, Measuring, and Using Color", 1991 SPIE/SPSE Conferences on Electronic Imaging. Color Research and Application, **16**, 347-348, 1991.

Published Abstracts:

Whittle, P. and Arend,L. Homochromatic Colour Induction. Perception, 1991.

Arend,L. How much does illuminant color affect unasserted colors? In OSA Annual Meeting Technical Digest 1991 , **16**, 24, 1991.

Spehar, B. and Arend,L. Perceptual factors in contrast-contrast. In OSA Annual Meeting Technical Digest 1991 , **16**, 121-122, 1991.

Spehar, B., Arend, L., and Gilchrist, A. White's illusion: A new luminance distribution constraint. Invest. Ophthalmol. Vis. Sci. **33** (ARVO Issue.), 1260, 1992.

IV. PROFESSIONAL PERSONNEL

Arend, Lawrence E., Principal Investigator

Goldstein, Robert, Research Assistant

Peli, Eliezer, nonsalaried part-time collaborator

Reeves, Adam, nonsalaried part-time collaborator

Schirillo, James, nonsalaried part-time collaborator

Spehar, Branka, nonsalaried part-time collaborator

Skon, Joy, nonsalaried part-time collaborator

V. PROFESSIONAL INTERACTIONS

Recent Talks:

Arend, L. "Lightness, brightness and apparent contrast," Invited talk, I.P. Pavlov Institute of Physiology, Academy of Sciences of the Soviet Union, St. Petersburg, USSR, September, 1991.

Arend,L. "Constancy of unasserted colors", Annual Meeting of the Optical Society of America, San Jose, November, 1991.

Spehar, B. and Arend,L. Perceptual factors in contrast-contrast. Poster, Optical Society of America Annual Meeting, San Jose, 1991.

Arend,L. "Perception of unnatural images", Invited talk, US Army Night Vision Laboratory, Ft Belvoir, VA, 1991.

Arend,L. "Intrinsic images in human perception: The apparent color of the light vs. the apparent color of the surface", Invited talk, Center for Visual Science, University of Rochester, Rochester, NY, December, 1991.

Spehar, B., Arend, L., and Gilchrist, A. White's illusion: A new luminance distribution constraint. Poster, ARVO annual meeting, Sarasota, 1992.

Other interactions:

I visited vision researchers in the Soviet Union and the Netherlands. In St. Petersburg I delivered a paper on lightness constancy to a laboratory at the I. P. Pavlov Institute, Academy of Sciences and met a number of researchers from St. Petersburg working on visual psychophysics and neurophysiology. In Amsterdam I attended the

IVth International Conference on Event Perception and Action (Gibson Cult). I heard a number of interesting papers on optical flow, depth, and motion perception and met colleagues in those fields. While in the Netherlands I visited Dr. Jimmy Troost's color constancy laboratory at the Catholic University in Nijmegen. I also attended the OSA meeting in San Jose, where a poster on contrast-contrast by Branka Spehar and myself was very well received. As part of the same trip I attended the annual meeting of the Psychonomic Society in San Francisco. At that meeting Drs. Alan Gilchrist (Rutgers University), Sten Stüre Bergström (Umeå University), Walter Gerbino (University of Trieste), and I met to discuss the book we are writing (nearly complete, at last) and the lightness and color constancy work proceeding in our respective laboratories (Dr. Paul Whittle from Cambridge, UK could not be present). My interactions with this group in person and by mail continue to be very useful. Dr. Eli Peli and I visited the Army Night Vision Laboratory where we gave talks on image quality metrics and image fusion, respectively. We had useful interactions with several of the staff who are engaged in human factors issues of night vision displays. I gave a lecture to Dr. Ennio Mingolla's graduate vision course at the Center for Adaptive Systems, Boston University and contributed discussion to four or five additional classes, meeting with faculty and students of the Center. Plans are gradually taking shape for a collaborative experiment with Dr. Mingolla on lightness in shaded 3D graphics, perhaps in the fall of 1992.

VI. INVENTIONS

There were no patentable inventions under this project.