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REPORT DOCUMENTATION PAGE

(2)

AD-A225 357

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1a. REPORT	1b. RESTRICTIVE MARKINGS
2a. SECURI	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLAS	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 90 0810
6a. NAME OF PERFORMING ORGANIZATION LAWRENCE E. AREND EYE RESEARCH INSTITUTE / 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
6c. ADDRESS (City, State, and ZIP Code) BOSTON, MA 02114	7b. ADDRESS (City, State, and ZIP Code) BUILDING 410 BOLLING AFB DC 20332
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR / 8b. OFFICE SYMBOL (If applicable) NL	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR-89-0377
8c. ADDRESS (City, State, and ZIP Code) Bld 410 Bolling AFB, DC 20332	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
61102F	2313	A5	

11. TITLE (Include Security Classification)

EYE MOVEMENTS AND SPATIAL PATTERN VISION (U)

12. PERSONAL AUTHOR(S) AREND, LAWRENCE E.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
ANNUAL	FROM 5/1/89 TO 4/30/90	90 JULY 15	13

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	SPATIAL PATTERN VISION, VISUAL ILLUSIONS, COLOR CONSTANCY, COLOR VISION.

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Models of human lightness and color perception must take account of color constancy, a tendency for apparent surface color to be relatively independent of the color and intensity of the illuminating light source. Our observers matched the lightnesses (apparent reflectances) and brightnesses (apparent luminances) of regions in simple and complex achromatic spatial pattaerns. The data showed that the observers' knowledge of the surface reflectances was unaffected by brightness changes due to varying illuminance.

A third perceptual dimension, local brightness contrast, was different from both lightness and brightness. In further experiments we found that moving a patch from a black background to a white background could produce an error of apparent surface color of about 1.5 Munsell Value steps.
Similar experiments at mesopic mean luminances revealed that the brightness contrast produced by a fixed luminance contrast declines with mean luminance.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION
22a. NAME OF RESPONSIBLE INDIVIDUAL JOHN F TANGNEY	22b. TELEPHONE (Include Area Code) (202) 767-5021 / 22c. OFFICE SYMBOL NL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

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ANNUAL TECHNICAL REPORT
5/1/89-4/30/90

GRANT AFOSR 89-0377

Lawrence E. Arend
Principal Investigator

I. OBJECTIVES

A. Lightness and Color Constancy

We proposed to complete two experiments. The first was a study of lightness and brightness in achromatic Mondrian patterns with smoothly graded illumination. This experiment was designed to extend our published work in which we used pairs of achromatic Mondrians with uniform, but different illuminations. Smooth illumination gradients require more sophisticated visual processing than uniform illuminations because they have no regions with a single illuminant falling on multiple reflectances, a condition required by many constancy algorithms.

The second was a study of slow chromatic adaptation, using a magnitude production method that avoids a number of shortcomings of most previous chromatic adaptation experiments. The experiment also included a strategy for assessment of the size of the observed color changes relative to those required for hue to be illumination invariant.

We proposed a new experiment using a paradigm designed to allow assessment of the influence of immediately surrounding colors on both the sensory color and perceived surface color of a test area. The achromatic version involves measurement of lightness and brightness of a test patch surrounded by an annulus of uniform reflectance. This annulus is in turn surrounded by a patchwork of surfaces spanning the gray scale, from black to white. The uniform inner annulus allows assessment of immediate surround effects while the patchwork outer region provides the context necessary to accurately perceive the surface colors of the test patch and inner annulus. With this paradigm it is possible, for the first time, to clearly study the relationships among lightness, brightness, and local brightness contrast.

B. Model Development

We proposed to further clarify the role of our gradient-integration model by further analysis of the relationships between lightness and brightness. We proposed a distinction between perceptually "unasserted color" and apparent surface color. The former is the apparent color of the light coming to the eye along a sight line, the latter is the color attributed to a perceived surface. For a number of theoretical reasons we now hypothesize that our gradient-integration model predicts only unasserted colors, a brightness array in the achromatic case. The mechanisms of the model provide information in a form useful for surface color computations, but, like all competing sensory brightness models, it includes no mechanisms capable of distinguishing between suprathreshold illumination gradients and reflectance gradients.

II. STATUS OF RESEARCH EFFORT

A. Lightness and Color Constancy

1. Theory. We have made further progress in analyzing the role of sensory processes in surface color perception. Our theoretical work over the preceding several years has made it clear that sensory processes (e.g., chromatic adaptation, simultaneous contrast) that have been widely considered to make major contributions to surface color perception are structurally incapable of distinguishing among the several environmental causes of luminance gradients in the retinal image. These sensory processes may play important roles as signal conditioning mechanisms for the input to subsequent surface perception processes. Their exact role is still not clear, in large part due to the trivial theoretical context of most of the color perception and theory of the past fifty years. Most of the experimental work from that period is literally uninterpretable with respect to surface color perception. The stimuli and responses used were so simple that it is impossible to determine which of several response dimensions was being reported by the experimental observers.

We have continued to refine our experimental paradigm for clarification of the role of sensory mechanisms in surface perception. In the past year we have begun several experiments that incorporate three crucial improvements over previous work:

a) The work was carried out in the context of a physics-based, multidimensional model of surface perception, an intrinsic images model. This made clear the need for:

b) Stimuli that were sufficiently complex to support less ambiguous attribution of image intensities to surfaces and illuminations, and

c) Task definitions and instructions that made clear to the observers how to describe (via matching tasks) the several dimensions of their perception of surfaces and lights in the stimulus scene.

We've only begun analysis of our new data, but it is already clear that they are the beginning of a whole new line of color research. A number of important sensory phenomena are likely to be reinterpreted as a result.

2. Experiments.

We completed and wrote up for publication the unevenly illuminated Mondrian experiment. The data confirmed the results of our previous achromatic Mondrian experiments in showing that lightness constancy is excellent for all of the simulated reflectance and illumination distributions. Brightnesses of the same patches covary with illumination, but illumination is consistently underestimated by various amounts depending on the reflectance distribution and the spatial illumination distribution. The visual system is reliable as a reflectometer but not as a photometer. The paper is in press at the Journal of the Optical Society of America A.

We also made progress on four new experiments. The first two are nearly complete. Partial data have been collected in the latter two.

a. Lightness, Brightness, and Brightness Contrast. Changes of annulus luminance in traditional disk/annulus patterns are perceptually ambiguous; they could be either reflectance or illuminance changes. Data from such experiments are also ambiguous: There is no way to know whether the subject was matching apparent surface color, brightness, or some combination of the two. By using Mondrian stimulus patterns we have been able to place test and standard patches on backgrounds with less ambiguous apparent reflectances.

In all of our previous experiments we have surrounded the standard and test patches with identical reflectances as a control for reflectance context. A drawback of this control is that subjects can produce data that show perfect lightness constancy just by matching the luminance contrasts at the edge of the test patch to those at the edge of the standard patch. This is potentially a local process; no integration across edges is required.

When the backgrounds for the test and standard patches have different apparent reflectances ('light gray', 'dark gray'), the two patches have different local luminance contrasts when their reflectance is the same (Fig. 1).

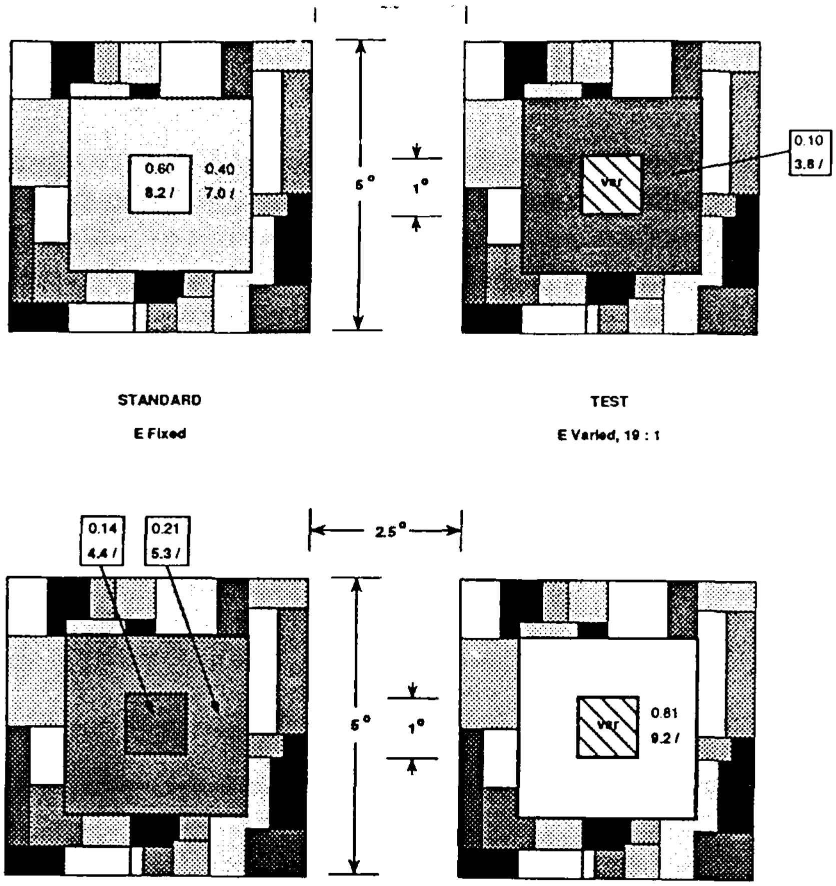

Figure 1. Mondrians from our new experiment. Test and standard patches are surrounded by different reflectances. a) Increment Condition. b). Decrement Condition.

Under these conditions the subject can set the test patch according to one of three distinct criteria. Our subjects matched the apparent amounts of light coming from the patches (*brightness*), their apparent reflectances (*lightness*), or the brightness difference between the patches and their immediate backgrounds (*brightness contrast*). The three criteria produced different results, all simply related to the physical variables of the simulated scene (Fig. 2).

Lightness matches were illumination-invariant but were not reflectance matches; the different backgrounds of test and standard produced an illumination-invariant error. This constant error was very small for increments, but for decrements was approx. 0.3 l.u, equal to 1.0-1.5 Munsell Value steps. We performed a second experiment (described below) to take a closer look at the influence of background reflectance on lightness.

Brightness matches depended substantially on illuminance. They lay between the reflectance-match and luminance-match lines. *Brightness contrasts* matched when the disk/annulus luminance ratios of the test and standard were approximately equal. The contrast match line for increments has a negative slope, indicating that the subject had to increase the physical contrast at low illuminances to maintain a constant brightness contrast between the disk and annulus. Previous work (Whittle and Challands, Vis. Res., 1969) has shown a decline in contrast efficiency at low luminances. We have begun an experiment (described below) to further investigate the effect of mean luminance on brightness contrast, brightness and lightness.

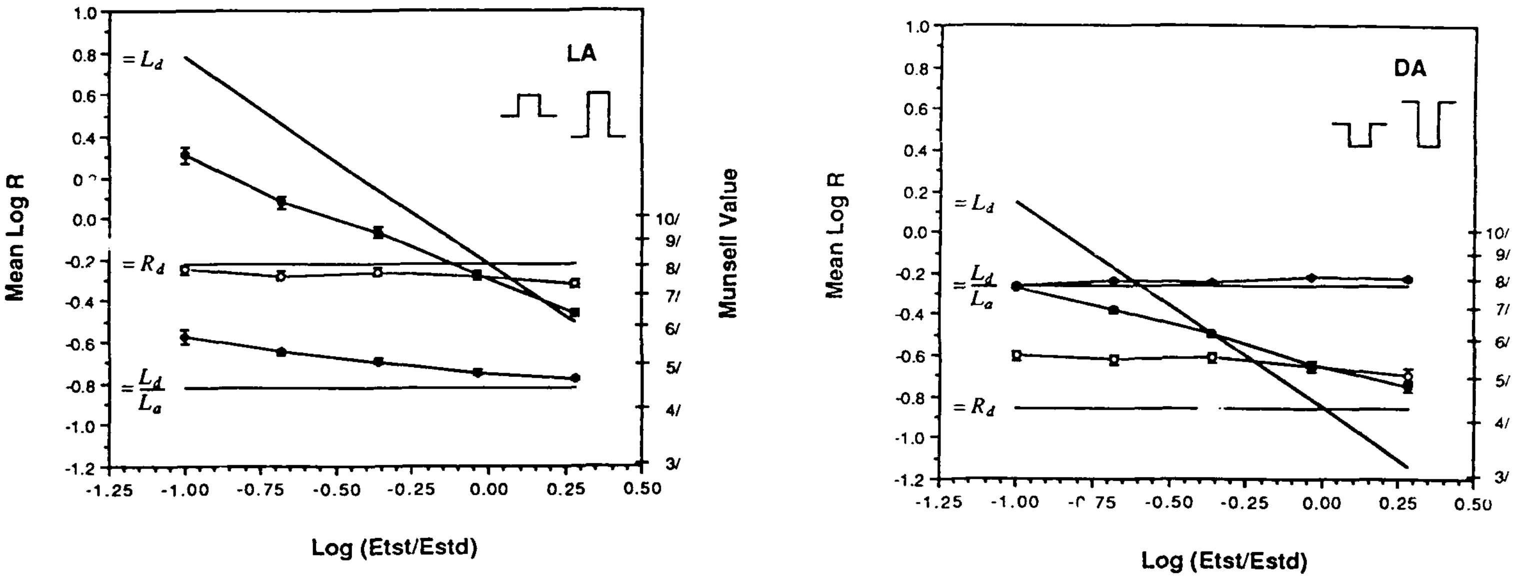

Fig. 2. Mean log reflectances for three criteria, as a function of the log of the ratio of test array illuminance to standard array illuminance. a. Increments. b. Decrements. Open circles: Lightness match. Closed circles: Brightness match. Crosses: Brightness contrast match. Solid lines are theoretical, the loci of matches of reflectance, luminance, and disk/annulus luminance ratio.

b. Background-Dependence of Lightness and Brightness.

In the experiment just described the annulus reflectances were chosen to give maximal separation of the theoretical lines for lightness, brightness, and brightness contrast. As a result, the observed effects of local background reflectance on brightness and lightness (about 1.5 Munsell Value steps) were not necessarily the largest that could occur in natural vision. We did a second experiment specifically designed to measure the largest influence of immediate background on apparent surface color and brightness.

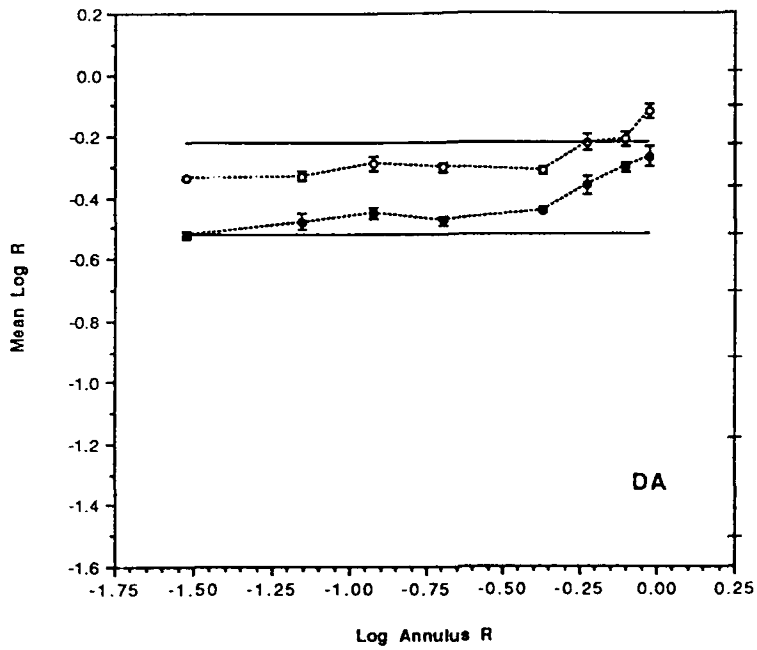

Fig. 3. Mean reflectances matching a constant standard in brightness (open symbols) or lightness (closed symbols) as a function of surround reflectance.

Fig. 3 shows the mean lightness matches (closed symbols) for a test patch at fixed illuminance and reflectance levels, with the independent variable, the reflectance of the surrounding annulus, varied from black (R=0.03) to white (R=0.95). Since the illuminance on the test Mondrian was half that on the standard Mondrian, the brightness of the test patch was less than that of the standard patch when their lightnesses (apparent reflectances) matched. The subject's brightness matches are shown by the open symbols in fig. 3. The upper horizontal line is the reflectance of the standard patch, and the lower horizontal line is the luminance of the standard patch. As the right-hand ordinate scale indicates, the reflectance of the test patch required to match the lightness (apparent reflectance) of the standard patch increased slightly less than 2 Munsell Value steps as the annulus reflectance ranged from black to white. The test annulus had the same black reflectance as the standard annulus at the leftmost data point. Brightness matches showed the same pattern. As in our previous experiments, the brightness matches lay between physical luminance and reflectance matches.

In other conditions we surrounded the test patch with a white annulus and the standard patch with a black annulus and varied the illuminance on the test Mondrian. The background difference produced a lightness error of 1.5 Munsell Value steps, but the error was found to be independent of illuminance in all conditions.

Previous studies of the influence of background on lightness have used ambiguous, disk-annulus stimuli. Ours is the first experiment capable of giving unambiguous measurements of apparent surface color and brightness as a function of background. Important features of the previous work did not replicate in our improved experiment.

c. Parafoveal Lightness and Brightness at Mesopic Luminances.

It appears from previous experiments (e.g., Whittle and Challands, 1969) that physical contrast becomes less efficient at low mesopic luminances and lower, i.e., a fixed luminance contrast at an edge produces less and less brightness contrast as the mean luminance decreases over this range.

This is of great practical importance because most image display devices and printed images have regions with mean luminances extending over this range. The peak luminances of common CRT displays are around several hundred Cd/m^2 and their useful dynamic range extends downward by 3-5 log units. Since most natural images contain detail throughout this range, visual contrast efficiency may vary appreciably over the image.

We have begun experiments to sort out the influence of mean luminance on lightness, brightness, and brightness contrast. The work completed to date involves repeating the lightness, brightness, and brightness contrast experiment described in section II.2.a with mean luminances of both the test and standard Mondrians lowered by one and two log units. The brightness contrast matches showed the loss of contrast efficiency pointed out above, with even steeper losses at the lower mean luminances (fig. 4). Haploscopic apparatus is now being built to let us look at larger differences of adaptation between test and standard stimuli.

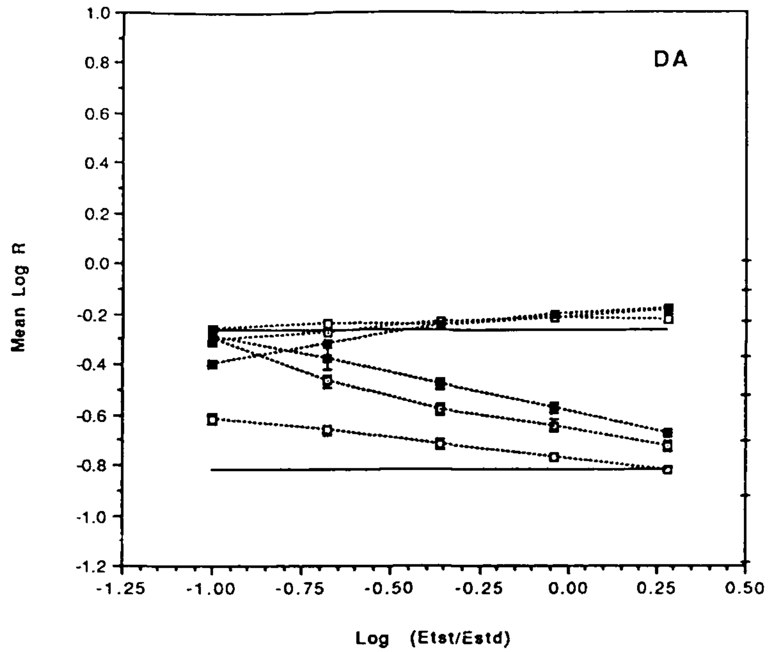

Fig. 4. Brightness contrast matches as a function of the ratio of test illumination to standard illumination for 0.3 (filled symbols), 3.0 (dotted symbols), and 30 Cd/m^2 (open symbols). Solid line is theoretical, the locus of matching $L_{disk}/L_{annulus}$ in the test and standard Mondrians.

d. Lightness and Brightness in Chromatic Arrays.

All of our experiments on brightness and lightness have involved achromatic Mondrians. There is a great deal of evidence that heterochromatic brightness matches can deviate significantly from luminance matches. Highly saturated patches are brighter than their luminance indicates. The discrepancy raises the question of the influence of saturation on lightness. Do the lightnesses of patches of various colors follow luminance relations among the patches or their brightness relations?

We've begun an experiment to sort out this issue by measuring the brightnesses and lightnesses of chromatic test patches of several hues and saturations. The results will be compared to relative brightnesses (heterochromatic matches) and relative luminances (edge minimization) of the colors in a bipartite field configuration. The data are not yet complete enough to analyze.

III. PAPERS

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

Arend, L.E., and Goldstein, R. Lightness and brightness in unevenly illuminated scenes. Invest. Ophthal. Vis. Sci., **30 (Suppl.)**, 221, 1989.

Arend L. and Goldstein R. (1989) Lightness and brightness in unevenly illuminated scenes. In Proceedings of the 6th Scandinavian Conference on Image Analysis (Edited by Pietikainen M.). Oulu, Finland.

In Press and Submitted:

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 Goldstein, R. Lightness and brightness perception in obliquely-illuminated scenes. J. Opt. Soc. Am. A. In Press.

Schirillo, J., Reeves, A. and Arend, L. Perceived depth influences lightness, not brightness of achromatic surfaces. Perception and Psychophysics. In Press.

Arend,L. Apparent surface color is more than color appearance. Proceedings of the 1990 SPIE/SPSE Symposium on Electronic Imaging. In Press.

Peli, E., Goldstein, R., Young, G. and Arend, L. Contrast sensitivity functions for the analysis and simulation of visual perception. Tech. Digest Series, Opt. Soc. Am. In Press.

Arend, L., Reeves, A., Schirillo, J, and Goldstein, R. Simultaneous color constancy: Patterns with diverse Munsell values. Submitted to J. Opt. Soc. Am. A.

Arend, L.E. Brightness, lightness, and local brightness contrast. In preparation.

Arend, L.E. Effect of background reflectance on lightness. In preparation.

IV. PROFESSIONAL PERSONNEL

Arend, Lawrence E., Principal Investigator

Goldstein, Robert, Research Assistant

Reeves, Adam, nonsalaried part-time collaborator

Schirillo, James, nonsalaried part-time collaborator

V. PROFESSIONAL INTERACTIONS

Papers presented:

Arend, L. "Perception of achromatic surface color," Invited talk, Academy of Sciences of the Soviet Union, Moscow, USSR, June, 1989.

Arend, L. "Lightness and brightness in unevenly illuminated scenes," Invited symposium paper, 6th Scandinavian Conference on Image Analysis, Oulu, Finland, June, 1989.

Arend, L. "Shades of gray: Psychophysical studies of intrinsic images," Invited talk, MIT, February, 1990.

Arend, L. "Apparent surface color is more than color appearance," Invited symposium paper, SPIE/SPSE Symposium on Electronic Imaging, Santa Clara, CA, February, 1990.

Arend, L. "Spatial integration in brightness perception", Invited talk, Rutgers University, February, 1990.

Other interactions:

I visited vision researchers in the Soviet Union and Scandinavia. In Moscow I delivered a paper on lightness constancy to a laboratory at the Academy of Sciences and met a large group working on color constancy. I also visited a neurophysiology laboratory. In Finland I delivered a paper at a conference on image analysis. In Sweden Dr. Alan Gilchrist from Rutgers University and I met with Dr. Sten Sture Bergstrom for several days, discussing the book we are writing and the lightness and color constancy work proceeding in our respective laboratories. Although Drs. Whittle (Cambridge, England) and Gerbino (Trieste, Italy) could not meet with us in person this year, my interactions with this group in person and by mail continue to be very useful. We will meet in France in 1990, prior to the fall meeting of the European Conference on Visual Perception. In Copenhagen, DK I met with Dr. Gevene Hertz.

VI. INVENTIONS

There were no patentable inventions under this project.