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Models of human light surface color to be reliable observers matched th simple and complex a surface reflectances v	htness and latively ind e lightness achromatic was unaffec	color perception mu ependent of the color es (apparent reflecta spatial pattaerns. T eted by brightness ch	ist take account or and intensity of inces) and brigh the data showed hanges due to va	of color consi of the illumin tnesses (appa that the obse arying illumin	tancy, a tende ating light sou rent luminanc rvers' knowle aance.	ency for apparent arce. Our ces) of regions in edge of the
A third perceptual di	mension, lo	ocal brightness contr	rast, was differe	nt 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.

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Lawrence E. Arend Principal Investigator







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I. OBJECTIVES

We proposed a three-year project of experiments on human surface color perception, guided by a two-stage heuristic model based on intrinsic images. The proposed experiments were divided into those primarily relating to a first, sensory stage and those related to a second stage in which the visual system attributes spatial gradients of brightness and color to physical causes in the viewed scene.

Proposed experiments related to the sensory stage were of several types. One type consisted of experiments further studying integration of spatial gradients. They were intended to elaborate the integration stage of the Arend/Blake brightness integration model. A second type was intended to help replace the logarithmic approximation at the tront end of the Arend/Blake model with a more realistic description of visual encoding of luminance contrast. A third type of experiment was intended to clarify the role of slow chromatic adaptation in color constancy.

Proposed experiments related to the intrinsic image stage consisted of extensions of our initial lightness and color constancy experiments and attempts to develop new experimental paradigms for studying the role of image structure in determining apparent colors of surfaces and lighting.

II. STATUS OF RESEARCH EFFORT

A. Experiments

We completed publication of papers on our chromatic constancy measurements in Mondrians spanning the entire Munsell value scale (<u>J. Opt. Soc. Amer. A</u>, 1991) and on lightness and brightness with several kinds of simulated illumination gradients (<u>J.</u> <u>Opt. Soc. Amer. A</u>, 1990).

1. Light., Bright., App. Contrast All of our previous constancy experiments have utilized displays in which the standard and test patches are surrounded by the same reflectances. While this was a necessary control in those designs, it has the disadvantage that local luminance contrast covaries with reflectance. When the test patch is set to the same reflectance as the standard patch, the local luminance ratios with surrounding patches are also identical. Some theorists (e.g., Shapley, Wallach) would argue that the excellent lightness constancy we have found is attributable to local contrast matching. While there are fairly convincing logical objections to their argument, it became clear that it was necessary to disentangle lightness and local contrast experimentally.

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We conducted the experiments we proposed, placing the test and standard patches on surrounds of differing reflectance. Preliminary results were reported in a poster at ARVO in 1990. Additional conditions and subjects have now been run and a manuscript is in preparation. The stimuli are illustrated in fig. 1. Further details are described in my 1990 renewal proposal. The test and standard patches and their surrounding annuli were placed in the center of identical Mondrians. This allows simple analysis of the local contrast relations while not giving up the subjective gray scale produced by the Mondrian region. We have recently also studied patterns with 5 deg annuli, i.e., with no Mondrian outer border. The particular reflectances were chosen to maximally separate three theoretical lines, the expected data from three tasks. The lightness (apparent reflectance) and brightness (apparent luminance) matching tasks were those we have used before. With different reflectances for the test and standard annuli the subject can do a third distinct task, setting the local brightness difference between the test patch and its annulus to that between the standard patch and its annulus.



Figure 1. Diagram of stimuli for brightness/lightness/brightnesscontrast experiments.

The results were very clear. All subjects had good lightness constancy in the lightness matching task (except for a small constant error described below). As in our earlier experiments the brightness matches varied with illumination but not as much as required for luminance matching. The brightness matches lay between the luminance-match theoretical line and the reflectance-match line. As expected the local contrast matches were very different from the lightness matches. They approximated matches of local luminance ratios, but there was a systematic dependence on illumination as well. At lower mean luminances the physical contrast had to be increased to maintain constant brightness contrast. This effect was studied further in two experiments, one complete and another just begun.

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The main conclusions are quite simple. Wallach's and Shapley's models are wrong. Lightnesses are not given by local contrast. Some form of edge integration is logically required to obtain lightness constancy, and the human visual system seems to do it. Disk-and-annulus patterns do not provide sufficient information for lightness constancy. Subjects trying to match lightnesses in disk/annulus patterns instead match local brightness contrasts, demonstrated by the magnitudes and form of our data in experiments with and without Mondrian regions.

2. Maximum background influence. While the lightness matches of the lightness/brightness/brightness-contrast experiment were illumination invariant, there was a small (ca. 1.5 Munsell value steps) constant error that appears to be attributable to local contrast effects. The test patch in the decrement condition is surrounded by a higher reflectance than the standard patch, and vice versa in the increment condition. It has long been recognized that a gray patch on a white background looks darker than a patch of the same reflectance on a black background.

We undertook a systematic study of the effect of moving a test patch from one background reflectance to another. We paired small increments and decrements on white and black backgrounds and middle gray patches on black and white backgrounds. In all cases we found small lightness errors in the directions expected from background contrast. The errors were 1.5 Munsell Value steps or less and were independent of illumination. A manuscript is in preparation.

<u>3. Lightness, brightness, and depth.</u> I. Gilchrist (1980) published a widely cited study in which a target in a doorway between two

rooms could be manipulated to appear to lie in either the dimlyilluminated front room or the brightly-illuminated back room. Its luminance was such that it would correspond to a black patch in the back room and a white patch in the front room. The subjects were instructed to choose a Munsell patch to indicate the "brightness" of the target. The patch was judged darker in the back room than in the front room. No distinction was made between lightness and brightness in that experiment and it has been interpreted as an influence of apparent depth on brightness. It seemed to Jim Schirillo, his graduate advisor (Adam Reeves), and I that it was more likely that the 3D arrangement led to differences in the lightness (apparent reflectance) with little effect on brightness (apparent luminance). We built a mirror stereoscope to simulate Gilchrist's stimuli and measured lightnesses and brightnesses. As we expected, brightness was little affected by the depth manipulation, but lightness changed with the apparent context. The results were written up and appeared in <u>Perception and Psychophysics</u>.

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4. Lightness, brightness, and depth. II. In both Gilchrist's original experiment and our replication the lightness differences actually measured were significantly smaller than the black-to-white range required for lightness constancy. This seemed to conflict with our consistent result of nearly perfect lightness constancy in all our earlier experiments with coplanar arrays. One possible explanation was the local luminance contrast effect described in the experiments The test patch in the two-room experiment was always above. bordered by a very bright region when it should have appeared white and a very dim region when it should have appeared black. Jim Schirillo and I did a second experiment to test this hypothesis. The main new manipulation was that the test patch was placed either immediately adjacent (on the retina) to the patches in the other plane as in the earlier experiments, or the coplanar surround was slightly extended around the test patch to spatially isolate it from the extreme luminances. In the former condition we replicated the Gilchrist and Schirillo, Reeves, and Arend data. In the latter condition we obtained nearly perfect lightness constancy, confirming our hypothesis. The results are important beyond the immediate context because they show that the lightness of a region near an occluding edge will be misjudged if the occluding and occluded surfaces are very differently illuminated. A manuscript is in preparation.

5. Mesopic lightness, brightness, and brightness-contrast. Another secondary result of the lightness/brightness/brightness-contrast experiment was the loss of contrast efficiency at low illuminations. As the illumination decreased more physical contrast was required to maintain constant brightness-contrast. The differences were fairly small but consistent within and across subjects. We hypothesized that this effect was related to effects observed by Whittle and Challands (1969). Using disk/annulus stimuli in a complicated haploscopic paradigm they found that contrast matches followed Weber's law at high mean luminances but shifted gradually toward constant luminance at low background luminances (i.e., higher physical contrast required). To test our hypothesis we repeated the lightness/brightness/brightness-contrast paradigm with test and standard both reduced in mean luminance by 1 and 2 l.u. As hypothesized the loss of contrast efficiency increased as the mean luminance decreased. The slopes of the brightness-contrast match data increased at the lower luminances. The other main result was that lightness matches were not affected over most of the reduced mean-luminance range, even though the loss of contrast in the test Mondrian was visually obvious at the lowest luminances. The explanation is that the subject adjusted the test patch to the same location within its local gray scale as the standard patch occupied in its local gray scale. The effect was analogous to looking at surfaces through a veiling luminance. For example, when looking into a department store window, one can easily pick out a reflectance viewed through the reflection of one's white shirt that matches a reflectance in another part of the field where there is no veiling reflection. The data were reported at the Nov. 1990 annual meeting of the Optical Society of America. A manuscript is in preparation,

We are currently extending this work in a haploscopic paradigm in which much larger mean luminance differences can be examined. The goal of this work is to accurately model visual encoding of suprathreshold luminance gradients by connecting our disk-annulus-in-Mondrian paradigm to Whittle and Challand's. Their data have been widely interpreted as describing retinal adaptation processes. If the connections can be made clearly enough, the chromatic analog of Whittle and Challand's paradigm can be used to provide data that would allow modelling of encoding of suprathreshold chromatic gradients, information that has proven very difficult to obtain with any other known paradigm (though Boynton, Kaiser, and others have tried). <u>6. Chromatic adaptation</u>. The chromatic adaptation experiments described in the proposal are nearing completion and will be reported at the November, 1991 meeting of the Optical Society of America in San Jose.

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The role of slow chromatic adaptation in surface color constancy is very poorly understood after hundreds of studies over a century. A major contributor to the confusion has been failure to make the distinction between the apparent color of the surface and the apparent color of the light coming from the surface (the latter depends upon the illumination color as well as the surface color). It is quite possible to see two objects as the same surface color even though the apparent color of the light coming from them is different. We do it all the time, e.g., when a curved surface is illuminated by window light and artificial light coming from different directions.

Other problems have concerned the role of spatial complexity in chromatic adaptation and the lack of proper methods for determining what behavior would constitute perfect illumination invariance.

We are examining the effect of slow adaptation on the apparent color of the light coming from simulated surfaces. We use targets of three complexities (spot, disk-and-annulus, and Mondrian), and we have developed a method for determining perfect-illuminationinvariance theoretical points.

Probably the hardest problem in evaluation of color percepts under different chromatic adaptations is provision of a stable yardstick, i.e., a standard stimulus with constant appearance. This has most commonly been done by placing a standard patch of constant chromaticity in one eye, adapted to the standard illuminant, and a test patch in the other eye, adapted to the experimental This method suffers from the possibility of illuminant. contamination due to interaction between the adaptive states of the two eyes (there is recent experimental evidence from Shevell's laboratory to justify this concern). We avoided this problem by presenting only the test stimulus, with the subject adapted to the experimental illuminant. The constant yardstick was achieved by asking the subject to always adjust the test patch to a unique hue at the saturation of a Munsell chroma /6, i.e., to provide an internal standard stimulus. Subjects require no special training to find We used red, green, yellow, blue, and neutral gray, the unique hues. complete set. The saturation criterion was established by training with color patches from the Munsell Book of Color. Subjects were shown a variety of patches of chromas /4, /6, and/8, one patch at a

time and forced to choose which chroma was being viewed. Training stopped when the subjects reached 90% correct identifications.

Three adapting illuminants were used, 4000 K, 6500 K, and 10000 K. In the experimental condition the subjects adapted to the test illuminant for 3 min. before the first trial, and the test stimuli (under the same illuminant) were presented continuously. In the control condition the subjects were kept in a relatively steady state of 6500K adaptation by preadapting always to 6500K, and presenting the test patterns under each illuminant in 1 s flashes, separated by 3 s of a 6500K uniform field.

We obtained theoretical perfect-constancy points by adapting a method developed by James Worthey. The subject adjusts the display to a chromaticity that looks, e.g., unique red under 6500K adaptation. Our method lets us derive a spectral reflectance distribution that would produce that chromaticity if illuminated by 6500K light. The reflectance model is physically realistic, closely resembling the pigments used for the Munsell samples. Having the reflectance it is straightforward to compute its chromaticity under 4000K and 10000K illuminants.

Three minute adaptation to the test illuminant resulted in much larger shifts of hue than in the control condition and larger than we observed in the apparent-light-color condition of our earlier simultaneous constancy experiments. Even for these near-white illuminants, though, the color of the light was not illumination invariant. The sense that we have that the average color of the light in our visual field is the same for indoor scenes as for outdoor is slightly inaccurate.

The data, in conjunction with our simultaneous constancy data, show that the visual system has two quite different color constancy strategies. In slightly overly simple terms, slow shifts of illumination over the entire visual field result in normalization of hues, i.e., there is a tendency for a surface to produce approximately the same hue at complete adaptation to the current illuminant. Within scenes the hues of surfaces are primarily determined by the adaptation illuminant. If there are regions in the scene with a different illuminant, the same reflectance will have a different hue, but the observer will nevertheless perceive it to be the same surface color under a different illuminant.

7. Sequential color matches. Several recent developments in other labs have increased the importance of two of our control experiments. Hayhoe has been extending her studies of achromatic rapid adaptation to chromatic stimuli. Unlike the achromatic case, she is finding very little sensitivity change in the first 3 s. Troost and de Weert have recently reported replication and extension of our first simultaneous constancy experiment (Arend and Reeves, 1986). When they presented test and standard Mondrians simultaneously, with subjects looking back and forth, they obtained our results. When they presented the two Mondrians in successive 1 s flashes, however, they obtained very large hue shifts.

In the control condition of the adaptation experiment we found shifts toward constancy on the order of 20% with 1 s exposures, apparently contradicting Hayhoe's results.

We also have run a successive presentation version of our Mondrian matching experiment and there too are finding about 20% shifts, apparently contradicting Troost and de Weert's results.

Troost and de Weert's experiment was flawed in several ways that we avoided. Hayhoe's paradigm is sufficiently different from ours that there are a number of possible explanations to be explored in further work. The two labs are discussing possible collaborative or coordinated experiments to sort out the differences.

8. Red and white projections at low luminances. For her Ph.D. thesis Joy Skon studied red-and-white projections using Edwin Land's original slides. She found that certain combinations of the red and white primaries acquired unusual hues at low luminances. We simulated some of her thesis stimuli on our RGB monitor and judged the color appearances of patches in a variety of spatial configurations. Most of the effects were quite subtle, but some dramatic colors did emerge. A patch which looks distinctly pink at high luminances looked saturated yellow a5 2.5 l.u. lower luminance. We have submitted a manuscript to J. Opt. Soc. Amer. A describing this work.

9. Apparent chromatic contrast. During my visit to Cambridge (September, October, 1990) Paul Whittle and I collected data in a study extending his achromatic paradigm to chromatic patterns. In his paradigm a small test patch on a large background is presented to one eye and a small standard patch on a different background is presented to the other eye. The backgrounds have corresponding contours and binocularly fuse and have a stable combined brightness. The small patches are in different locations, allowing the subject to adjust the test patch to match the standard. In the original achromatic experiments the paradigm allowed very precise brightness matches across varying adaptation levels. In our new experiments a test patch on a gray background in one eye was

adjusted to produce an exact color match to a chromatic standard patch on a chromatic background in the other eye. The chromaticity of the standard patch always equalled that of its background, but its luminance was varied as the independent variable. Red, green, and blue standards were used.

Subjects set the test patch to approximately the dominant wavelength of the standard patch and background for increments and to its approximate compliment for decrements. The required purities decreased as standard luminance contrast decreased, and for small increments and decrements the test patch was set to gray. The data are still being analyzed. Whittle will present a paper on the experiments at the September, 1991 European Conference on Visual Perception in Vilnius.

B. Theory

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1. Surface perception theory. My efforts to understand our color constancy work over the past five years have led to a heuristic model of surface perception that resembles intrinsic image models from computer vision (Marr, Barrow and Tenenbaum). A book chapter describing an early version of the model is in press. I have continued to develop the concepts over the past two years. It proved impossible to isolate surface color perception from perception of other dimensions of surfaces (illumination, orientation, range), resulting in a theory of surface perception rather than a theory of surface-color perception. The basic model leads quite naturally to a general model of human visual perception. Several papers are in the planning stage, but the arguments supporting the theory will require book-length treatment. That will have to wait until I can obtain support for a year away from research, probably several years from now.

2. Color gamut of Cohen reflectances. The Cohen basis vectors have been used in several analyses of color constancy besides our application to adaptation data, but their utility is quite general. The weights provide an n-space mapping onto a set of real world pigments, the Munsell reflectances. The space has provides a convenient linear description, with the advantage of being continuous, unlike the discrete Munsell set. It occurred to us in the course of using Cohen 3-space that little was known of its visual properties nor some of its physical properties. In particular, it is not an infinite space. Spectral reflectance is bounded by 0 and 1 at all wavelengths. For any specified illumination the permissible vectors of Cohen weights map to a color solid in tristimulus space, defined as all the chromaticities that can be generated by Cohen 3D reflectances under that illuminant.

It is of interest to compare the Cohen color solid with other color solids, for example, MacAdam's optimal color solid and the Munsell color set. It is not possible to analytically compute the color solid without analytic expressions for the Cohen vectors and the illuminant, so we wrote a program to find the Cohen solid numerically. We plan to extend the work a bit, then write a paper for <u>Color Research and Applications</u>.

3. Reanalysis of a aptation data. The Cohen-paper technique we used to analyze our adaptation data provides a new tool for analysis of classical chromatic adaptation work by Bartleson, Hunt and others. Most previous investigators have wanted to evaluate the illumination dependency of color but have lacked a technique for generating the necessary theoretical points. We have reanalyzed Bartleson's thesis data and found substantial departures from illumination-invariance that he was unable to describe. We will extend and polish this work for publication.

III. PAPERS

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Significant time was devoted during this grant period to reporting results of the research project. In addition to appearance of several articles, I gave a number of invited and contributed papers.

- Arend,L. Apparent surface color is more than color appearance. In Perceiving, Measuring, and Using Color, Brill, M.H. (Ed.) <u>Proc.</u> <u>SPIE</u>, 2-8, 1990.
- Arend, L. and Goldstein, R. Lightness and brightness in unevenly illuminated scenes. <u>Proceedings of the 6th Scandinavian</u> <u>Conference on Image Analysis</u>. Vol. 1, 499-506, 1989.
- Arend, L. and Goldstein, R. Lightness and brightness over spatial illumination gradients. J. Opt. Soc. Ann. A., 7, 1929-1336, 1990.
- Arend L., Reeves A., Schirillo J., and Goldstein R. Simultaneous color constancy: Patterns with diverse Munsell values. <u>J. Opt. Soc.</u> <u>Amer. A</u> 8, 661-672, 1991.

- Peli, E., Goldstein, R.B., Trempe, C.L., and Arend, L.E. Face recognition for visually impaired is improved with digital image enhancement. <u>Tech. Digest Series</u>, Opt. Soc. Am., 7, 64-67, 1989.
- Peli, E., Goldstein, R.B., Young, G.M., and Arend, L.E. Digital image enhancement for the visually impaired: Simulations and results. In Buus, S. (Ed.) <u>Proceedings of the 15th Annual</u> <u>Northeast Bioengineering Conference.</u> IEEE, 45-46, 1989.
- Peli, E., Goldstein, R., Young, G. and Arend, L. Contrast sensitivity functions for the analysis and simulation of visual perception. <u>Noninvasive Assessment of the Visual System, Tech. Digest</u> <u>Series, Opt. Soc. Am.</u>, 126-129, 1990.
- Schirillo, J., Reeves, A. and Arend, L. Perceived lightness, but not brightness depends on perceived depth information. <u>Perception_and_Psychophysics.</u>, 48, 82-90, 1990.
- In Press and Submitted:

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- Arend, L. Multidimensional models of surface color perception. To appear in Gilchrist, A. (Ed.) <u>Lightness</u>, <u>Brightness</u>, and <u>Transparency</u>. Lawrence Erlbaum Assoc., Hillsdale, NJ.
- Arend, L. Apparent contrast and surface color in complex scenes. In Brill, M.H. (Ed.) <u>Proc. SPIE</u>, 10 pp., 1991. In Press.
- Arend, L.E. Review of "Perceiving, Measuring, and Using Color", 1991 SPIE/SPSE Conferences on Electronic Imaging. <u>Color Research</u> and <u>Application</u>, In Press.
- Larimer, J., Piantanida, T., Arend, L. and Varner, D. Separation of chrominance and wavelength in color perception. Submitted for publication.
- Skon, J. and Arend, L. Influence of luminance and complexity on appearance of two-primary patterns. Submitted to JOSA A.

IV. PROFESSIONAL PERSONNEL

Arend, Lawrence E., Principal Investigator

Goldstein, Robert, Research Assistant

Reeves, Adam, nonsalaried part-time collaborator

Schirillo, James, nonsalaried part-time collaborator

Skon, Jov, nonsalaried part-time collaborator

Whittle, Paul, nonsalaried part-time collaborator

V. PROFESSIONAL INTERACTIONS

Papers presented:

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- 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.
- Arend, L. "Lightness, Brightness, and Apparent Contrast", Invited talk, Kenneth Craik Club, Cambridge University, September, 1990.
- Arend, L. "Speculations on Surface Perception", Invited talk, Kenneth Craik Club, Cambridge University, October, 1990.

- Arend,L. "Mesopic lightness, brightness, and brightness contrast", Annual Meeting of the Optical Society of America, Boston, November, 1990.
- Arend,L. "Toward a Theory of Surface Perception", Human Resources Laboratory, Williams AFB, AZ, February, 1991.
- Arend, L. "Apparent contrast and surface color in complex scenes," Invited symposium paper, SPIE/SPSE Symposium on Electronic Imaging, Santa Clara, CA, February, 1991.

Other interactions:

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Visited Craik Laboratory, Cambridge University for eight weeks, September, October, 1990. Principal contacts:

Cambridge University Paul Whittle John Mollon Oxford University Anya Hurlbert Bruce Cummings Andrew Blake David Forsyth

Visited Soviet Union and Scandinavia, June, 1989. Principal Contacts:

Moscow Gave paper at Academy of Sciences Alexander Petrov Vadim Maximov Alexander Bonch-Osmolovsky Finland Gave paper at Scandinavian Conference on Image Analysis Sweden Sten Sture Bergstrom Denmark Gevene Hertz John Hertz

VI. INVENTIONS

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There were no patentable inventions under this project.

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