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THE PREDICTION OF SURROUND-INDUCED CHANGES
IN MAP COLOR APPEARANCE

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Cynthia Ann Brewer

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of the requirements for

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THE PREDICTION OF

SURROUND-INDUCED CHANGES IN MAP COLOR APPEARANCE

By

Cynthia Ann Brewer

A DISSERTATION

Submitted to
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ABSTRACT

THE PREDICTION OF SURROUND-INDUCED CHANGES IN MAP COLOR APPEARANCE

By

Cynthia Ann Brewer

The overall objective of my research was to develop a quantitative model of simultaneous contrast (induction) to aid selection of sets of easily identified map colors. Modelling induction allows use of the smaller color differences needed to design perceptually logical color schemes while avoiding surround-induced misinterpretations of mapped information. Developing objective guidance for color selection is important because most people who work with geographic data in a digital environment are confronted with the problem of choosing colors for the visual display and analysis of their data.

The research addressed two primary questions: does a color shift in the direction of the opponent complement of its surround, as suggested by review of previous literature, and what is the magnitude of the induced shift? A first experiment, with test colors embedded in hexagonal grids, was used to quantify the distances and directions in color space of changes in appearance. The resulting model of induction is an extension of the color appearance model developed by R.W.G. Hunt. Predictions from the induction model were tested in a second map-reading experiment.

The induction model can be used to provide an objective evaluation of a set of map colors. To predict lightness induction, the contrast in lightness between a center color and its surround is calculated. A small proportion of this contrast is then added to the color of the center to estimate its perceived lightness. Shifts in hue and saturation are estimated by constructing a buffer,

or zone of potential perceptions, that extends from the color toward the opponent complement of the surrounding hue. If the center and surround are similar in hue, the buffer extends a greater distance than if the center and surround are dissimilar in hue. If induction causes colors to have overlapping hue and lightness perception buffers, these colors will be difficult to distinguish on the map. The buffer approach was chosen to accommodate 90 percent of map readers' perceptions, rather than limiting conclusions to perceptions of an artificial average reader. The model developed provides a practical tool for the design of successful color schemes for computer-displayed maps.

ACKNOWLEDGEMENTS

Judy Olson's role as my advisor is acknowledged with appreciation. My year as an assistant for her NSF research provided an important model of why outside funding is important and how to conduct a full-scale research project. The pilot study for the dissertation research was a supporting investigation funded by her grant. Her sabbatical and appointment as department chair provided the positive intangible of pushing me toward becoming an independent researcher. Judy provided a year's worth of space and equipment that made the project possible: her computer, a 19-inch monitor, and her office (which I monopolized with a weird-looking black booth).

Advising from my committee members is appreciated. Dr. Winters kept me focussed on my roots in geography as I voyaged into color science. His advice on planning my future (on types of teaching positions, on service, on publication goals, on money) gave me a realistic view of my profession. Dr. Irwin's expertise in writing convincing grants was crucial to the success of my funding proposal to NSF. He also provided important analysis recommendations. From the beginning, Dr. Groop offered encouragement that this topic was important.

The people of the Inter-Society Color Council were an important source of information for me as I tackled color theory. The efforts of the ISCC Vision and Color Appearance Interest Group are appreciated; they brought R.W.G. Hunt to the U.S. for the 1989 meeting. Dr. Hunt's careful attention to what I was planning to do with his model was valuable. After that meeting, I was confident of the soundness of my proposal.

This research was supported by National Science Foundation Dissertation Research Improvement Grant Number SES-8915175. The grant was used primarily to purchase a color-measurement instrument, pay test subjects, and pay the wages of three undergraduate assistants. The funding was crucial to the dissertation research.

The three students who assisted the research kept me sane by helping with the monotonous task of subject testing. Mike Conley and Carolyn Lauer also assisted in the laborious process of color assignments for Experiment 1. Eva Frank designed a set of beautiful color schemes for the second experiment. All three assistants engaged me in discussions that lead to refinements of the research in progress. For clarification of objectives, there is no substitute for instructing another person in how to do what you want accomplished. In the main office of the Department of Geography, Harriet Ashbay organized the scheduling of my experiment volunteers and Marilyn Bria helped me with the mysteries of grant logistics (i.e., how to spend that NSF money).

David DiBiase solved many creative and technical puzzles with me. He endured many hours of the explanation of half-formed ideas, and he was always able to pinpoint the crux of a problem and generate unexpected solutions. He helped with the nitty-gritty of what software to use, how to move graphics between cantankerous programs, how to cure ailing Macintoshes, and generally how to get things to work. He likened this adventure to standing at the mouth of a deep cave shouting directions down to me so I did not get lost.

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INTRODUCTION

Color selection is a critical aspect of visual display and visual analysis of geographic information. Maps concisely summarize large spatial data sets and are produced for wide-ranging purposes: choropleth maps help us understand distributions of socio-economic characteristics; image maps are one component in the evaluation of remotely-sensed data analyses such as land-cover classifications; and geographic information system maps are an avenue by which we can synthesize the relationships between data layers within complex data sets. In each of these contexts, an easily interpreted color scheme may aid in solving problems or gaining new insights from spatial data. A poor scheme may mask relationships and dilute efforts to convince colleagues of the importance of the work.

As cartographers we strive to choose easily distinguished colors that allow accurate recognition of map symbols. We also try to design color schemes that will communicate the logical relationships between mapped data categories or features so that the general form of the mapped distribution is readily apparent. Colors of a carefully designed scheme, however, can be rendered unexpectedly ambiguous by changes in appearance induced by contrast with surrounding map colors.

The overall objective of my research is to develop a quantitative model of induction to aid selection of sets of easily identified map colors. Modelling induction allows use of the smaller color differences needed to design perceptually logical color combinations while avoiding surround-induced misinterpretations. Understanding color interaction allows map schemes to be designed with confidence. Developing objective guidance for color selection is important because color is no longer an expensive luxury for the computer-graphics tools geographers use. Color display is now unavoidable, and most people who work with geographic data in a digital environment grapple with the problem of choosing colors for the graphic display of their work.

The research reported in this dissertation was designed to address the following questions for the entire range of colors on graphic displays:

Do colors shift in the direction of the opponent complement of the surround, as suggested by review of previous literature?

Are smaller color areas shifted in appearance by greater amounts?

What are the magnitudes of induced shifts in a map-reading context?

Two secondary questions were also examined in the first experiment:

What is the effect of breaking the inducing surround into a heterogeneous combination of colors?

How do polygon outlines affect the magnitude of induced changes in appearance?

The above questions were shaped into specific hypotheses that are listed along with the results tables in Chapter 3. The results of the first experiment were used to develop a model for prediction of induced changes in the appearance of map colors. A second experiment tested these predictions in a map-reading context.

This dissertation is structured into six major divisions. I begin with a chapter reviewing color terminology and the simultaneous contrast literature. The first experiment is reported in Chapters 2 and 3 and the second is reported in Chapter 4. The concluding chapter is followed by references and a set of five appendices. These appendices provide listings of experimental procedures, test-color specifications, response data, and the program code for the model of color appearance upon which my research is based.

CHAPTER 1

Review of Terminology and Literature

Simultaneous contrast or surround-induced change has long been recognized as affecting the perception of map colors, and I will review these discussions from the cartographic literature. Little research on simultaneous contrast has been conducted with map stimuli, but both applied and theory-oriented work on induction by color-science, psychology, physiology, photography, and engineering researchers has been conducted. The collection of literature from diverse disciplines, dated over a forty-year time span, reveals a startling array of color terms used with varying precision. Thus, this review chapter begins with definitions and comparisons of color terms. The terminology issues resurface in the review of simultaneous contrast literature because differences in the use of terms complicate the comparison of results and their application within map reading contexts.

Past attempts to model induction effects are reviewed with the intent of identifying a fruitful modelling approach on which to build. The first step in predicting simultaneous contrast is the use of numbers to describe perceived colors, and numerous color specification systems exist from which to choose a promising system. Thus, I complete this chapter by discussing the selection of an appearance-based color metric for quantifying color perception.

Terminology

Generally, simultaneous contrast is the induced enhancement of differences between a given color and surrounding colors; it is the effect of the surround on the color one perceives. Contrast effects are commonly defined with a standard demonstration: a medium gray with a black surround looks lighter than the same gray with a white surround. Peculiar definitions, promulgated through the cartographic literature, designate 'induction' only for changes immediately along edges (Mach bands) or for brightness contrast effects but not for chromatic effects. The definitions also suggest 'simultaneous contrast' should be used only for chromatic effects (Castner 1980 p. 374, Dent 1990 p. 385, Peterson 1979 p. 30). These distinctions may have arisen from Robinson's specific uses of the terms early in the cartographic color literature (Robinson 1952 pp. 93-94, Robinson 1967 p. 54). In current use, however, it is best to avoid this over-specificity that is not common to other disciplines.

I will use the terms 'simultaneous contrast' and 'induction' as synonyms (largely because 'induction,' 'induced,' 'inducing,' are more flexible for communication). *Induction* is a general term that encompasses other effects that alter perceptions such as assimilation, by which adjacent small color areas appear more similar (Fach and Sharpe 1986). However, almost every combination of the terms 'simultaneous,' 'induction,' and 'contrast,' appear in the research literature to label simultaneous contrast effects: chromatic induction, brightness induction, simultaneous color induction, simultaneous brightness induction, simultaneous contrast, simultaneous color contrast, chromatic contrast, and brightness contrast.

As one tries to make sense of the wide range in terminology that appears in communications about color, one must evaluate the rigor with which terms are used. Terms used as synonyms in lay contexts, such as lightness and brightness, have specific differences in meaning in scientific contexts, and these differences may not be clarified by (or even recognized by) authors. Hue, brightness, and saturation are generally an adequate set of terms to describe perceived color, though there are many more choices in terminology available for color description.

Both Hunt (1987a pp. 69-72) and Agoston (1987 p. 12-14) provide good summaries of subjective color terminology, and differences between their definitions are indicative of the lingering lack of consistency among color scientists. Perceptual terms describe subjective color appearance which is affected by the characteristics of both the observer and the object. Psychophysical color specifications are unaffected by changes in the observer. The objective terms of psychophysics are based on color measurements coupled with *standardized* observer characteristics. Perceptual color terms and their psychophysical correlates are listed in Table 1.1.

Hue, brightness, lightness (or value), chroma, and saturation are common perceptual color terms. *Hue* is the dimension described by color names such as blue and orange. *Brightness* is dependent either on illumination, for reflecting surfaces, or on emitted light and describes the amount of light that a color exhibits (ranging from dim to dazzling). *Lightness* is relative brightness; the brightness of an area *relative* to the brightness of a similarly illuminated area that appears white or brightness relative to a reference emitted light that appears white. *Chroma* and *saturation* are both related to the amount of hue in a color or its colorfulness as compared to neutral (white or gray). Saturation by strict definition is colorfulness relative to the brightness of the color, though at a constant brightness level saturation and chroma scales describe the same range of sensations (from pale or grayish to strong or vivid).

Table 1.1 Perceptual and Related Psychophysical Color Terminology

Perceptual Terms	Psychophysical Terms
hue	dominant wavelength
	CIE hue-angle
	Munsell Hue
brightness (luminosity)	luminance
lightness (value)	luminance factor
	CIE lightness
	Munsell Value
chroma	CIE chroma
	Munsell Chroma
saturation	purity
	CIE saturation
hue and saturation	chromaticity

Adapted from Hunt (1987a) p. 71.

The psychophysical terms prefaced with 'CIE' (Commission Internationale de l'Eclairage) may be derived using either the CIELUV or CIELAB systems and the Munsell terms are for dimensions in the Munsell color order system (Hunt 1987a pp. 117-122).

Cartographic Literature

Many summaries of color use in cartography have described surround-induced changes in perceived color (Campbell 1991 p. 131, Dent 1990 pp. 384-385, Imhof 1982 pp. 59-60, Keates 1982 p. 44, Robinson 1952 pp. 93-95, Robinson 1967 pp. 53-54, Robinson and others 1984 pp. 180, 182, Wood 1968 p. 56). These descriptions are used to warn that differences between map colors should be large enough that map readers will be able to differentiate the colors regardless of variations in surrounding map colors. Limiting the required number of colors by limiting the number of map categories has been recommended to aid the designer in making robust color selections that are easily differentiated. Most authors also assured that outlines separating colors reduce induced changes.

In addition to general descriptions of induction in the cartographic literature, induction on maps has concerned researchers of specific cartographic design problems. Literature on color charts, effective computer-displayed maps, continuous-tone choropleth maps, and equal-step color scales have provided discussions of the effect.

Brown (1982 p. 111) and Castner (1980 p. 374) both recommended that cartographic color charts be designed with spaces between the colors to reduce induced enhancement of differences between adjacent colors on charts. Interviews on color chart use with cartographic designers (Brewer 1989-90 p. 6) supported the Brown and Castner recommendations. Four of the interviewees mentioned that difficulties with induced changes in color appearance occurred when using their charts, and two described their use of masks to isolate colors to reduce contrast effects. Castner (p. 377) also urged that color charts be designed to show only sets of colors that will remain distinctly different with changes in appearance caused by varied map surrounds.

Spiker and others (1986) selected a set of point, line, and area colors for effective display of computer generated topographic maps and considered contrast effects a major variable affecting their recommendations. They used color naming to identify frequent confusions for symbol and background color combinations. They then used symbol search tasks to refine their color selections and arrived at a set of color assignments that incorporated large contrasts to promote accurate identification.

In contrast to the approach of Spiker and others (1986), in which identifiability is maximized, Ware (1988) recognized that form information (revealing the overall distribution pattern) may be as important as accurate color identification on thematic computer maps. His subjects matched continuous-tone map colors with legend colors, and he found that lightness and saturation scales were more susceptible to matching errors attributed to induced changes in appearance. Map-to-legend color matches with spectral progressions that show a full range of hues were less error prone. Ware recommended use of a color sequence that increases in lightness to reveal form and also includes hue differences to reduce induced confusions.

Color differences are small and particularly susceptible to induced misinterpretation on continuous-tone choropleth maps. Peterson (1979) and Muller (1979) described the effect of contrast on their results in continuous-tone research. Muller presented subjects with the task of outlining regions of low, medium, and high population density on a continuous-tone map. He ranked counties using mean categorizations calculated from subject responses of 1, 2, or 3 for low, medium, or high (visual ranks). He also ranked the counties by their population densities (density ranks), which was equivalent to ranking by lightness. Muller related discrepancies between visual and density ranks to changes in appearance induced by the relative lightness of surrounding counties. Table 1.2 shows ranks and discrepancies for example counties for one of Muller's test groups ('non-geographers'). These mean displacements of counties within the range of densities on Muller's test map provide objective evidence of induction effects on map perception and evidence of induction as a confounding variable in cartographic research.

Table 1.2 Rank Discrepancies in Muller's Continuous-Tone Results

Lightness of counties ranged from white at 1 (lowest rural population density) to black at 120. Equal rank differences did not imply perceptually equal steps between grays.

Counties that appeared darker; surrounded by lighter, lower density counties:

Visual Rank	73	92	95	100	110
Density Rank	69	87	91	94	107
Discrepancy	+4	+5	+4	+6	+3

Counties that appeared lighter; surrounded by darker, higher density counties:

Visual Rank	4	24	29	5	36	6	37
Density Rank	29	34	38	46	49	50	65
Discrepancy	-25	-10	-9	-41	-13	-44	-28

(Muller 1979 p. 244)

Cartographers working on equal-step scales have qualified their results with recognition of the problem of induction. Kimerling (1975 p. 126) states that background reflectance was the only factor significantly affecting the *form* of lightness-versus-reflectance curves in his research on gray scales. Cox (1980) attempted a systematic treatment of this problem, but he found a complex pattern of response with changes in background. He concluded that only perceptual differences between the lighter grays were affected by changes in background (p. 68). Robertson and O'Callaghan (1986 p. 30-31) observed that the equal-step color sequences they developed need not be precisely uniform because induction substantially alters color perceptions. Kimerling (p. 126) suggested that equal-step gray scales can provide only general lightness-selection guidelines for the same reason. Similarly, Monmonier (1980 p. 36) and Castner (1980 p. 375) both cautioned cartographers to expect imprecision in map reading partly because of induced changes in the appearances of map colors. A cartographic induction model would reveal the magnitude of imprecision that cartographers should accommodate in their design of map color combinations.

Simultaneous Contrast Literature

M.E. Chevreul is the 'father' of simultaneous contrast research and made numerous controlled observations of the effect. Modern research results are consistent with his generalizations from 1839:

> (16.) ... All the phenomena I have observed seem to me to depend upon a very simple law ... *In the case where the eye sees at the same time two contiguous colours, they will appear as dissimilar as possible, both in their optical composition* [hue] *and in the height of their tone* [lightness and/or purity]. We have then, *at the same time,* simultaneous contrast of colour properly so called, and contrast of tone.
> (17.) For two contiguous colours, *o* and *p*, will differ as much as possible from each other when the complementary of *o* is added to *p*, and the complement of *p* is added to *o*...
> (19.) ... when the colours are not of the same degree of intensity, that which is deep appears deeper, and that which is light, lighter;
> (Chevreul 1839/1981 pp. 50-51, italics are Chevreul's)

Chevreul specified the complementary color pairs as red-green, orange-blue, and yellow-violet, and he also considered black and white to function as a complementary pair. Birren noted that Chevreul's complements are afterimage complements (Chevreul 1839/1981 p. 52).

Brightness and Lightness Induction

Since Chevreul's time, a massive body of research on induced changes in brightness has grown and the topic continues to be reworked. Early research is well summarized by Heinemann (1972), revealing a wide variety of functions describing results for different stimulus configurations and different luminance levels. Generally the original description remains acceptable: brightness induction causes a color to look darker with a bright surround and brighter with a dark surround. However, distinctions between brightness and lightness percepts are now better recognized and theoretical links between explanations of lightness *constancy* and brightness *contrast* have been suggested. These developments have lead to criticism of ambiguities in both test stimuli and instructions used in the study of brightness induction.

Constancy, almost the obverse of contrast, is the ability of the visual system to maintain approximately unchanged perceptions with differences in both the level and hue of illumination (for example, the same piece of paper is perceived as white whether it is seen in bright daylight or the dimmer yellow of an incandescent lamp). A common component of constancy research conclusions is that equal ratios of surround and center luminance lead to equal perceptions of *lightness*, regardless of overall luminance levels. Contrast effects, on the other hand, are typically measured as discrepancies between absolute-luminance (brightness) matches rather than the relative-luminance (lightness) matches that may be judged by subjects. Therefore, the uncontrolled mix of lightness and brightness perceptions in induction-experiment designs contributes ratio-derived deviations in perceived brightness measures.

Gilchrist (1988) designed an elegant demonstration of the effect of perceptual structuring on simultaneous contrast by using the same luminance arrangement within two contexts (Figure 1.1). A gray square (Munsell Value 2.1) was seen on the physically shadowed half of a white ground. An array of grays, from which subjects were instructed to make a *lightness* match, was seen on the adjacent lighted half. In the constancy case, the shadow-casting structure was obvious to subjects and the darker surround was perceived as a change in illumination. Alternatively, subject views were masked and only simple dark and light backgrounds for the same array of gray samples were perceived. With the dark surround understood as a shadow, the median value match was 7.5 (much lighter than a 2.1 luminance match) and close to a correct match of paper samples irrespective of differences in illumination. Masking the view produced a median match of 3.0, which is a minor lightness increase compared to the constancy effect and is closer to matching the measured luminances under the different illumination conditions. Thus, with the same instructions, very different grays were matched with the shadowed test gray and the difference depended on interpretation of the display.

Additional contrast and constancy research has focussed on the lightness-brightness distinction. Arend and Goldstein (1987) found large differences in selected matches with differences in instructions that specifically evoked evaluations of lightness or brightness with both simple and complex test stimulus arrangements. Evans, writing in 1948 (p. 166), had also found very different perceptions of simple center-surround stimuli with differences in instructions (these insights are therefore not confined to recent research). Jacobsen and Gilchrist (1988) replicate and adjust classic work on brightness contrast by Hess and Pretori from 1894. They found accurate *brightness* matches for stimuli brighter than their surround and fairly accurate *lightness* matches for stimuli darker than their surround. Thus, a gray with a surround of higher luminance tends to be judged relative to its surround and thus its lightness is evaluated more readily than brightness. The same gray

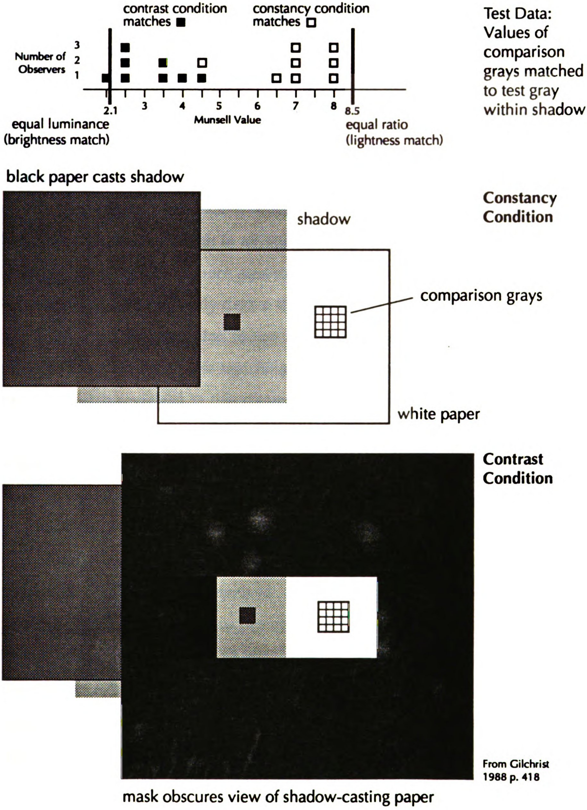


Figure 1.1 **Gilchrist's Experiment Investigating Lightness Constancy and Contrast**

seen on a dark surround will be perceived as luminous and its brightness is evaluated more readily than lightness.

The experimental ambiguity of whether to judge lightness or brightness possibly explains Cox's (1980) interpretation difficulties with his gray-scale results from the cartographic literature. He may have found "complex" differences and increased variation in the perception of only light grays with different background luminances because these light grays were compared by brightness, lightness, or both in an uncontrolled manner. The darker grays, however, may have been more consistently compared by lightness alone because they were frequently darker than their surrounds.

The intent of the preceding review is not to imply that contrast effects do not occur (perfect brightness matching was uncommon in the controlled recent research reviewed in this chapter) but that test instructions and unconscious perceptual structuring of the display can radically affect results. It is unlikely that illumination would be interpreted as varying across a map sheet or across a complex map filling a computer screen. Therefore, the whites of the map may function as references for an assumed constant illumination and large shifts associated with local lightness *constancy* adjustments would not be perceived. In comparison, simple center-surround displays produce an ambiguous perceptual structure that may lead to inappropriate interpretations of test luminances. Therefore, research designed to solve problems of cartographic simultaneous contrast must test induction on maps, or complex map-like displays, and must include test instructions that evoke responses resulting from map-reading tasks. This insight renders much of the early research, based on ambiguous mixtures of lightness and brightness evaluations, of little relevance to prediction of brightness contrast effects in the cartographic context.

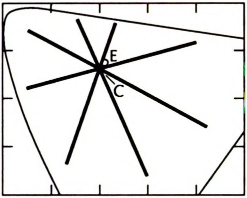
Hue Induction and Complementarity

The research literature generally supports the traditional view that the appearance of a central hue is shifted toward the complement of the surround color (Jameson and Hurvich 1964, Kinney 1962, Krauskopf and others 1986, Troscianko 1977, Valberg 1974). With the exception of Jameson and Hurvich, these authors measured induced changes in chromaticity (hue and saturation) of neutral-appearing centers, which provides little information on how perceptions of more saturated hues are affected by chromatic surrounds. A consistent deviation from complementarity was found by a number of researchers (Eichengreen 1976 tested a yellow center, Takahashi and Ejima 1983 tested a neutral center, Ware and Cowan 1982 tested 15 hues). Their results included a shift toward red with a blue surround rather than an increase in yellow, which is the expected complementary shift with a blue surround. These deviations suggest that induction effects between hues may be more complex than the simple complementary-shift summary implies. Another difficulty with the common generalization of complementary chromatic induction is that researchers work with many different systems of color specification and each system incorporates differing definitions of complementarity.

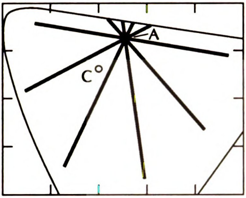
Psychophysical complements are defined on the CIE-(x,y) chromaticity diagram as colors that can be additively mixed, or averaged, to produce a neutral (Agoston 1987 pp. 68-70). Mixture lines are straight when plotted on the chromaticity diagram and this convenient property places complements on opposite ends of *any* straight line through the neutral point (complements along straight mixture lines are also maintained on the CIE-(u',v') chromaticity diagram used in Figure 1.2). Neutrality may be defined as the chromaticity of the equal-energy light source (E) for luminous-appearing colors with dark surrounds or at a standard daylight chromaticity for surface colors (CIE Illuminant C for example, Figure 1.2a). Takasaki (1969) worked with Munsell color samples, for which neutral has the chromaticity of Illuminant C, and his results show hue shifts parallel to Illuminant C complements.

A viewer's perception of neutrality is shifted when the visual system adjusts to the illumination of a scene (Agoston 1987 p. 188, Bartleson 1979). Adaptation is intertwined with simultaneous contrast but, in order to limit the scope of this work, I focus on studies that deal with changes in perception that are due primarily to simultaneous contrast, which is a phenomenon that occurs immediately on viewing stimuli. I have eliminated from discussion most of the research on changes in appearance with adaptation to various illuminants or stimuli (lengthy adaptation to a red surround for example). Perceptual complements on the CIE chromaticity diagrams (x,y or u',v'), however, are best defined using neutral as the chromaticity of the adaptation illuminant. For example, Kinney's subjects were adapted to incandescent light and her induced complementary shifts were well described by mixture lines drawn through the chromaticity point for Illuminant A (Kinney 1962 p. 512 and Figure 1.2b). Valberg's (1974) work produces complements centered on a neutral point that is bluer than typical daylight chromaticities.

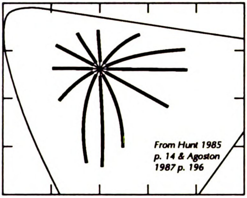
Complement definitions may also be based on systems other than the CIE chromaticity diagram. Complements may be defined as the *afterimage* colors that appear after looking away from a color on which the eyes have been fixed (Agoston 1987 pp. 195-199 and Figure 1.2c). More loosely, complements are colors opposite on the color wheel, which depends on the chosen



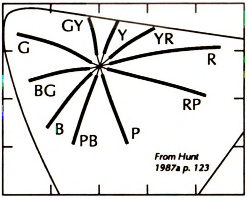
1.2a Additive Complements through Daylight Chromaticity (Illuminant C)



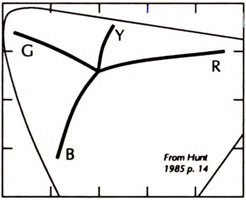
1.2b Additive Complements through Chromaticity of Incandescent Lighting



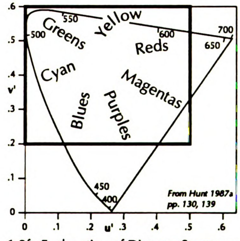
1.2c Afterimage Complements



1.2d Munsell Complements



1.2e NCS Complemetary Unique Hues



1.2f Explanation of Diagram Structures

Figures 1.2a to 1.2e show the boldly outlined portion of the above CIE 1976 (u',v') chromaticity diagram (1.2f). General hue-name regions are shown on this locator, and the curve plots chromaticities of the pure spectrum colors (wavelengths are in nanometers). The CIE (u',v') diagram is chosen as a common base for comparison of complements because it approximates perceptual scaling better than the CIE 1931 (x,y) chromaticity diagram but retains the property of straight-line additive mixtures.

Figure 1.2 Comparison of Complementary Color Definitions

arrangement of hues. For example, the Goethe color circle sets the additive primaries red, green, and blue opposite their respective complements cyan, magenta, and yellow, which are the subtractive primaries (Agoston pp. 45-46). The Munsell color order system also provides a standardized hue circle used to define complements (Figure 1.2d).

Unique red, green, blue, and yellow (also called psychological primaries or unitary hues) provide an additional set of complements. The hue circle of the Swedish Natural Color System (NCS) is one example of an opponent color system structured with unique red opposite unique green and unique yellow opposite unique blue (Hunt 1985 and Figure 1.2e). Hurvich (1981) provides a summary explanation of the opponent theory of color vision that he and Jameson have long worked to develop. A common characteristic of proposed opponent color mechanisms is that the pertinent dimensions used to explain hue perception are red-green and yellow-blue. Color opponency is not new to cartographers. Potential applications of opponent color theory have been examined in previous research by Eastman (1986) and Moellering and Kimerling (1990). I will discuss opponency further in the later section on quantitative models of induction.

Saturation or Chroma Induction

The most direct way of modelling induced changes in colorfulness is to couple chroma with hue in an attribute of chromaticity that is subject to complementary induction effects. For example, a red of moderate chroma with a complementary green surround will appear to be a red of greater chroma, and the same moderate red with a strong red surround will appear to be lower in chroma, or grayed, because of mixture with the green complement induced by the surround. Thus, when the surround and affected colors are similar in hue, the induced complement will reduce the chroma of the center color, rather than cause a shift toward a different hue. Likewise, a color with a complementary surround will have a like hue induced and will therefore increase in chroma. Modelling chroma change by linking it only with hue induction assumes that changes in the brightness of the surround do not induce changes in chroma.

Research relevant to *brightness*-induced changes in colorfulness has focused on saturation, which is defined relative to brightness, and the work has produced contradictory results. Classic rules of induced saturation, found in Kirschman's 'laws' from 1890 (Kinney 1962 p. 503), state that saturation of the induced color increases with increasing saturation of the surround and as brightness contrast with the surround decreases. Alternatively, Pitt and Winter (1974) and Kinney concluded that perceived saturation was greater with a contrasting bright surround than with a dark surround. Troscianko (1982) used color naming to measure induced changes (he defined saturation as "the apparent amount of colour appearing to be emitted from the stimulus" p. 90), and he concluded that perceived saturation was greatest with a neutral surround of near-equal brightness. He maintained that perceived saturation was decreased by induced whiteness or blackness from surrounds of contrasting brightness. Breneman (1977) and Valberg (1974) concluded that perceived saturation was independent of the brightness of the surround, though Breneman's conclusions were for non-adjacent overall surrounds and Valberg worked only with a range of surrounds with brightness equal to or greater than that of his test colors. The range of conclusions about saturation changes induced by changes in brightness has ambiguous cartographic applications and further testing in map reading contexts would best clarify the relevant links between saturation and brightness.

Test Methods

Three general categories of method are used to quantify the magnitude of induced changes in perceived color: matching a comparison field, adjusting to match a unitary hue or white, and color naming. Matching tasks were most common in the research I reviewed. The typical induction experiment presents a central test color with a surround, or other inducing field, and a comparison color without the inducing field. Any one of the fields (test, comparison, or surround) may be adjusted to accomplish a perceived match between the test and comparison colors. Alternatively, a selection of comparison fields are offered from which to select a match. Use of a comparison field may be avoided by having subjects adjust the test color to maintain a white or to maintain a unitary hue (unique red, yellow, blue, or green). Color naming is a less popular method in which subjects are trained to identify, for example, the lightness, saturation, and hue of affected colors without comparison to another color sample. Response analyses in the three categories of method involve comparing differences between colors selected as matches, comparing amounts of adjustment needed to produce a match, or comparing differences in descriptive names when colors are seen with different surrounds.

Further variation in experimental method is found in modes of viewing test stimuli. Some researchers use haploscopic viewing in which one eye sees the test and the other eye sees the comparison color simultaneously. Haploscopic viewing is used in an attempt to prevent induction from affecting the perception of the comparison color, with the comparison color and surround-affected test color positioned adjacent to each other. Binocular viewing (in which both eyes see the same stimuli) is also used in induction research and is a method more applicable to map reading. The subject either looks back and forth between colors or colors are alternated while the subject selects a match.

Spatial Aspects of Induction

Spatial variables affect the magnitude of induced changes in color appearance. Induced change increases as the affected color decreases in size and as the inducing stimulus increases in size and decreases in separation distance. These generalizations are supported in almost all of the work in which spatial variables are tested.

Conclusions vary on the spatial extent to which induction operates. In Heinemann's (1972 p. 160) summary of early work, he reports that a separation of 1.5 to 2 degrees visual angle will prevent induced changes (1° visual angle is 1 cm at an arm's-length viewing distance of 57 cm). More recent work of Blackwell and Buchsbaum (1988) produced a similar conclusion; minimal induced change occured with separations greater than 2° from a 0.6° test color. Leibowitz and others (1953) found that increasing the separation of 0.5°-square test and inducing colors by distances up to 0.5° progressively reduced induced changes in perception. With their separations between 0.5° and 9°, induced perceptions were relatively unchanged. Whipple and others (1988) arrived at the same 0.5° separation cut-off for changing induction amounts with larger concentric-circle stimuli (centers ranged from 1.7° to 4.3°). Ejima and Takahashi (1983) found no further decrease in induction past approximately 0.3° separation from a small test color less than 0.1° wide. These results suggest that only the surround colors within between 0.5° to 2° separation have a substantial effect on perceptions. Note that the separation cut-off of 0.5° is much wider than an outline width, which cartographic texts suggest will eliminate or reduce simultaneous contrast effects that interfere with map color comparisons.

Research work on surrounds contiguous with the central test color suggest there are induced contributions from more distant portions of the surround. Valberg (1974) found maximum induction effects on a 1°-by-2° test color with a 6° surround. Yund and Armington (1975) tested 40 size combinations of concentric centers and surrounds. They found continuously increasing induced change for increasing surround sizes (3° to 20.5° diameters) with constant center sizes (1.5° to 19°). They also found greater induced changes with decreases in center size. On the other hand, De Valois and others (1986) found no change in induction magnitudes with central stimuli ranging from 0.2° to 3° square with a constant surround size. They provide the only results contradicting the general expectations for size and induction relationships (their results may be peculiar to their stimulus that alternated between opponent complements). Again the results are contradictory.

The spatial characteristics of induction should be considered in the prediction of map color appearances because map polygons can vary in number, size, shape, and color in infinite combinations. Cartographic applications require a model of induction that is not dependent on a particular center-surround configuration. The most general induction model incorporating spatial variables is provided by Yund and Armington (1975). Their model predicts the color at a point using distances to edges (boundaries between different colors) for each opponent channel (red-green, yellow-blue, and white-black). Other authors propose less-developed models for complex surrounds that average distance-weighted colors in the surround (Ejima and Takahashi 1983, Marsden 1969). The general formula presented by Yund and Armington has the advantage of elegantly treating both center and surround sizes and shapes simultaneously. Their "edge-distance" approach performed better than area and width measures in Yund and Armington's analysis, though their tests were conducted with relatively large and simple concentric-circle stimuli.

The emphasis of the Yund and Armington model on edges is consistent with psychophysical evidence that edges are important for perception and with physiological evidence that cortical cells respond to specific edge configurations (Livingstone and Hubel 1988). Color differences at edges are also critical elements of Land's (1986) retinex theory that offers an explanation of color constancy. Edge processing issues in contrast and constancy explanations are well summarized by Gilchrist (1988).

Quantitative Generalization about Induction

Induction is often studied with the purpose of testing color vision theories. Early competition was primarily between retinal processing and opponent processing arguments. Application of results from this theory-motivated research in the map context is usually precluded because the theoretical formulations are too general, color measures are vague, formulae include parameters valid for only restricted ranges of stimuli, or test stimuli and viewing conditions are very different from map-reading contexts. Past tests of different models, however, do guide the way to successful approaches to induction prediction. Broad categories of induction models, which individual researchers have refined and combined, are summarized in the following paragraphs.

Trichromatic theory relates color perception to the responses of three types of receptors: long-, middle-, and short-wavelength sensitive cones in the retina of the eye. Retinal treatments of induction are based on the von Kries coefficient law (from 1905) and explain induction using multiplicative constants that adjust the responses of the three receptors: $C = f[(k_1R), (k_2G), (k_3B)]$ where C is the perceived color; R, G, and B are the long-, middle-, and short-wavelength sensitive cone responses to the test color; and k_1, k_2, and k_3 are constants that adjust for induction effects from the surround. Takasaki's (1969) research, for example, supported a von Kries approach to the prediction of induced changes in color.

Opponent theory was put forth by Hering in the 1800's and began as a competing alternative to trichromacy. Opponency mechanisms are now generally accepted as a second stage in the visual processing of color.

Opponent theory finds strong physiological support in the existence of red-green and yellow-blue opponent color cells in the lateral geniculate nucleus, the portion of the brain that initially processes short-, medium-, and long-wavelength responses from receptors in the retina (Livingstone and Hubel 1988).

Opponent-process treatments of induction were pioneered by Jameson and Hurvich (1964) and have been supported in additional induction research (De Valois and others 1986, Ejima and Takahashi 1983, Kinney 1962, Shevell and Wesner 1989, Takahashi and Ejima 1983, Valberg 1974, Yund and Armington 1975). The basic opponent model hypothesizes that induced color changes are additive: $\mathbf{C} = f[(\mathbf{RG_t} + \mathbf{k_1 RG_s}), (\mathbf{YB_t} + \mathbf{k_2 YB_s}), (\mathbf{WK_t} + \mathbf{k_3 WK_s})]$ where **C** is the perceived color; **RG** and **YB** are the red-green and yellow-blue opponent responses; **WK** is the white-black luminance response; **t** and **s** subscripts designate the portion of the response attributed to the test color (**t**) and to the surround color (s) inducing the perceived change; and $\mathbf{k_1}$, $\mathbf{k_2}$, and $\mathbf{k_3}$ are constants that adjust the magnitude of induced change.

A solely retinal explanation of induction has been effectively discounted in the research literature. The operation of induction effects over distances larger than retinal models predict and the effectiveness of dichoptic presentations (the surround is seen by one eye and the superimposed central test color is seen by the other eye) suggest that induced color interactions are produced at levels higher in the visual system than the retina (Whipple and others 1988). The lack of induced change in stimuli that alternated faster than approximately twice-a-second between black and white or between opponent colors also precludes a retinal-process explanation for induction effects (De Valois and others 1986).

Deviations from opponent-process model predictions have lead some researchers to suggest that adjustments at both the retinal and opponent stages of a two-stage color vision model better explain patterns of induced color change (Eichengreen 1976, Takahashi and Ejima 1983, Ware and Cowan 1982). Alternatively, Krauskopf and others (1986) rejected both retinal and opponent approaches and concluded that induction is a producet of interactions at still higher levels of processing in the visual cortex. Adopting an opponent approach, however, seems the most promising first step in the practical and fairly broad-brush approach necessitated by the varied conditions in which a cartographic model of induction would later be applied.

Modelling Color Appearance

The form and tractability of formulae used in attempting to model induced changes in appearance are sensitive to the units of measure used to specify color. The variety of available notation systems complicates the comparison of results and evaluation of function forms and parameters. The internationally accepted CIE-(x,y,Y) system was established in 1931 and is commonly used in the study of color induction, despite its lack of perceptual scaling. Some researchers have chosen to work with perceptually scaled transformations of CIE-(x,y,Y) that are named CIELUV and CIELAB and were standardized in 1976. Krauskopf and others (1986), for example, worked with color metrics defined by retinal receptor sensitivities. Others chose perceptual color order systems, such as Munsell, to provide precise color samples for use in their investigations.

The importance of the chosen color metric has been recognized in induction research. In early work, Heinemann (1972) noted that failures of hypothesized additivity were not surprising given the arbitrary definitions of induction magnitudes (p. 156). In work with induction and opponent theory, Jameson and Hurvich (1964) recommended use of units scaled by *perceptual* response (p. 151). For example, CIE L* lightness is a well-tested perceptually scaled measure that is a cube-root function of luminance (the latter is not perceptually scaled; a unit step at high luminance is perceived as a smaller change than at low luminance). Kinney (1962) expressed the difficulty of modelling induction before perceptually scaled color systems were becoming standardized: "When ... functional relations break down, it is impossible to say whether this is due to a real phenomenon or an inadequacy of the system" (p. 518).

Modelling color appearance is a more involved process than simply describing connections between the retinal and opponent mechanisms discussed up to this point. Nayatani and a group of other lighting and vision researchers have regularly documented the development of their color appearance model that focuses primarily on predicting appearances for varied states of adaptation (Nayatani and others' 1990 paper includes a list of references for recent work on the model). Hunt's extensive work on color reproduction has evolved into an appearance model as well (Hunt 1982, Hunt 1987b Chapter 8). Vision researchers are also working on models of the color vision system. The vision model under development by Guth and others (1980), for example, focused on threshold perceptions (color differences on maps are well above thresholds of perception). The purposes of models specifically focused on subjective color appearance, particularly the more general and applied Hunt model, are most likely to be successful frameworks within which to predict induction in the map context.

The Hunt model is constructed in a physiologically plausible manner as a two-stage model. Chromaticity and luminance measures are first converted to retinal receptor responses. Differences in these red-, green-, and blue-labelled magnitudes are then combined to produce opponent responses along red-green, yellow-blue, and luminance dimensions. The calculation output distinguishes lightness from brightness and saturation from chroma, and it accounts for adaptation given the chromaticity and luminance for a reference white (Hunt 1987b). The Hunt model produces perceptually-scaled appearance dimensions (lightness, redness-greenness, yellowness-blueness along with a number of other measures) that are good candidates for additional adjustment to account for induction from surround colors.

The red-green and yellow-blue dimensions of the Hunt model become non-standard opponent dimensions once other attributes that affect appearance, such as adaptation, are accounted for. The adjusted opponent dimensions may be approximate but provide the following advantages: opponent complements aligned along continuous axes (unlike the NCS unique hue axes; compare Figures 1.3 and 1.2e), perceptually scaled color dimensions, and adaptation adjustments. Perceptual spacing is well recognized as a positive attribute for cartographic applications of color systems (Kimerling 1985, Robertson and O'Callaghan 1986). Adaptation of the map reader to a particular illumination is unavoidable and needs to be accommodated if results are to be generalized to varied map reading conditions. Adaptation to the bluish white in a series of CRT maps or to the incandescent lighting on a paper map, for example, make expectation of induced complementary shifts with respect to only Illuminants E or C over-restrictive of a potential induction model.

The Hunt model is still undergoing revision as other researchers begin to test it in varied applications. Therefore it has the disadvantage of not being a standardized system such as CIE-(x,y,Y) or CIELUV. On the other hand, simultaneous contrast is a subjective effect that has not been well modelled in the objective realm of psychophysics and is better dealt with in the realm of subjective color appearance.

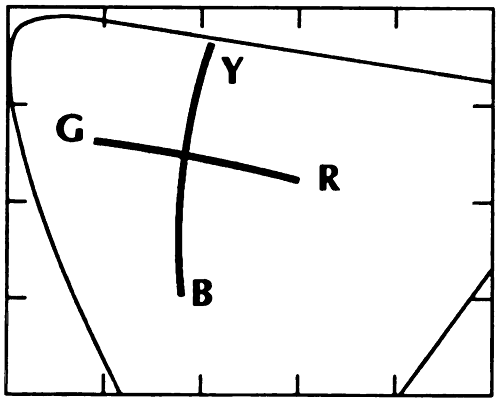


Figure 1.3 Hunt Opponent Axes

Hunt RG and YB axes plotted on CIE-(u',v') chromaticity diagram.

Summary

Review of the simultaneous contrast literature reveals conflicting conclusions based on varied stimuli configurations that do not approximate the complexity of a map. Investigation of ambiguities in the treatment of lightness and brightness, as well as saturation and chroma, further support the importance of quantifying induction effects in a context approximating that in which the model will be applied. To establish a perceptual structure relevant to the map reading context, induction must be judged under realistic illumination conditions and test colors must be embedded in a matrix of other colors that includes reference whites. In addition, a test method that simulates color comparison during map reading requires binocular viewing and the rapid selection of appearance matches, rather than having subjects adjust a comparison color or be trained to name perceived colors.

Review of past attempts to explain induced changes in color reveals that the opponent-process approach is the most common and promising avenue for modelling induction. The many perceptual influences on color perception beyond induced change suggest that previous research on other aspects of color perception should not be ignored in the pursuit of a successful model specific to simultaneous contrast. Thus, I have selected a color appearance model by Hunt that offers an appropriate and extensible quantitative framework for the induction prediction formulae that I proposed to develop. The model output is well suited to induction prediction in the map context: it is designed for application in a wide range of viewing conditions, is adjusted for adaptation, is perceptually scaled, and is opponent

based.

Opponency is the basis of both the Hunt color appearance model and the Yund and Armington "edge-distance" model that attempts to predict induction for spatially varied stimuli. Therefore, the two models may be linked by applying the opponent-based edge-distance formulae to the Hunt opponent color descriptions. Incorporating an opponent link between these two models within a final induction model is a promising way to accommodate spatial aspects of the inducing surround. Such accommodation is important to the prediction of induction effects with the varied spatial configurations of colors that appear on maps.

CHAPTER 2

Experiment 1: Methods

People were asked to match induction-affected colors to choices embedded in patchworks of gray hexagons for Experiment 1. This testing with complex but controlled displays produced data appropriate for modelling simultaneous contrast on computer-displayed maps. In this chapter, I describe and illustrate the test methods and sampling of color space used for the first experiment. In the next chapter, I will summarize and discuss the results of Experiment 1. In both Chapters 2 and 3, figures and tables follow the corresponding *section* of text in which they are referenced, rather than having figure and table pages interrupt paragraphs at arbitrary page breaks.

Test Procedure

Data collection for Experiment 1 was automated with *SuperCard* (Appleton 1990) programming running on an Apple Macintosh SE/30 computer with a 19-inch E-Machines color monitor. Subjects were tested individually with the test administrator seated left of and behind subjects throughout the session. Viewing was standardized using a chin rest that positioned subjects' eyes approximately 57 cm from the display. Testing was conducted in a dim viewing area surrounded by a black curtain (ambient light reflected from a white calibration plate measured 1.5 cd/m^2 with the monitor off). The black curtain and black cloth over the table and chin rest were used to eliminate reflections on the monitor glass that could alter color perceptions in an uncontrolled fashion.

A pilot test of 11 unpaid volunteers was conducted before final testing to practice instructing subjects and to watch for difficulties with the method. The pilot tests revealed that the sessions were too long but otherwise the test was running smoothly. The responses from these 11 subjects provided a preliminary look at data and allowed accurate editing to cut the experiment sessions to the final one-hour length. The pilot responses were not used in the final analysis.

Appendix A provides the script for conducting an experimental session. Before testing began, an Ishihara test for color vision deficiencies was administered and the experimental task was explained using a series of ten practice displays. The practice sessions lasted between 3.2 and 10.6 minutes (mean 6.1), and during this time subject vision adapted to the general brightness of the computer display and illumination of the viewing area. Following practice, subjects responded to 100 different displays (out of 200 total) that were presented in a unique random order for each subject. Sixty subjects participated; thus 30 responses were collected for each display. A brief rest was incorporated in the testing session after every 25 responses. During this rest, subjects turned their attention to the test administrator and responded to background information questions (Appendix A).

Subjects

The responses of 30 men and 30 women with normal color vision were obtained in the experiment. An additional four subjects had been tested but were omitted from the sample (two had deficient color vision, the program malfunctioned for one subject, and one was omitted because of excessive drowsiness). Subjects were recruited through posted advertising on campus and ads in the campus newspaper, and all subjects were paid ten dollars. I advertised for non-students and then accepted all who called (rather than encourage provision of false background information). Twenty-six subjects were students with the remainder from the wider Michigan State University community. Subjects ranged in age from 19 to 61 with a mean age of 26 years.

Test Displays

All test color combinations in Experiment 1 were embedded in a hexagonal grid (Figure 2.1). The center test color was surrounded by an inducing color, and there were six comparison colors in the outer display. These six comparison colors were arrayed in a random order for each display to avoid a positional bias in subject matching criteria. A patchwork of ten neutrals (listed in Appendix B) filled the remainder of the display. The first (white), second, fourth, sixth, eighth and tenth (black) of the neutrals were arranged immediately adjacent to the comparison colors to provide a surround that was varied and of medium lightness overall. The patchwork, out to approximately 4 cm around each comparison color, was constructed such that the surround of each comparison color was a rotated version of the same random pattern of grays, producing a constant comparison surround of medium overall lightness.

One centimeter subtended one degree of visual angle on the test displays. The overall dimensions of the test displays were 25.1 by 25.7 cm. Three different densities of hexagonal grids were used with cells measuring 11, 6.5, and 4.5 mm between parallel edges (Figures 2.1, 2.2, and 2.3). The inducing surrounds ranged between 7.2 and 8.3 cm in diameter among the three grid densities, and distances between the edges of the center and comparison colors ranged between 7.0 and 8.4 cm.

With the test administrator pointing to the comparison colors on a practice display, subjects were asked to "choose one of these six choices that looks most similar in appearance to the center color." Center and comparison colors were marked by small arrows to make their positions clear. Subjects used a mouse to move the cursor to their choice and clicked the mouse button to record their selection. The measured color difference between the center color and the chosen match provided a measure of the induced change in perception of the center color caused by its surround. The click of the mouse button also cleared the screen and initiated presentation of the next display. The interval between displays was approximately 5 seconds as the next display was prepared, and during this interval a homogeneous medium-gray (30.5 cd/m^2) display was presented to maintain subject adaptation.

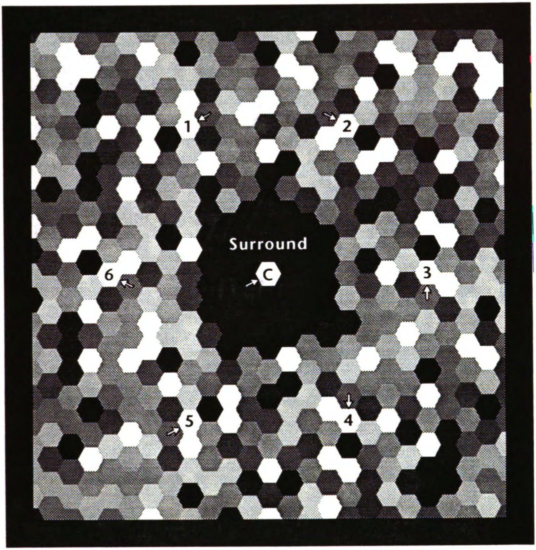


Figure 2.1 Experiment 1 Test Display Format

Hexagons of the largest size (11 mm) are shown at 50% reduction. Cell C is the test color subjects match to comparison colors positioned in cells numbered 1 to 6. The **Surround**, shown in black, induced changes in the perception of C. (Number and letter designations were not present on the experiment displays.)

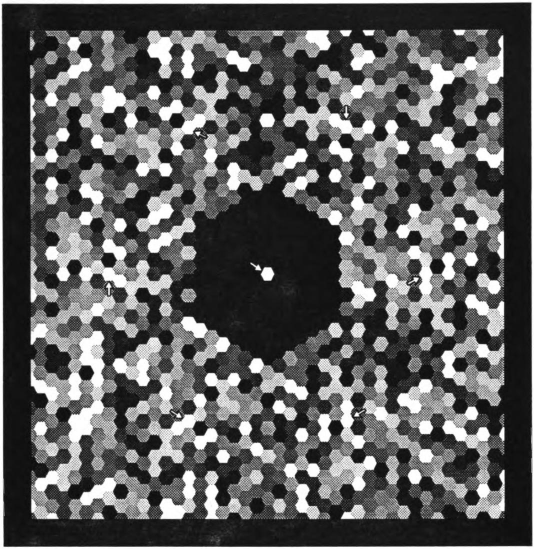


Figure 2.2 Test Display of Medium-Sized Hexagons

6.5 mm hexagons reduced 50%

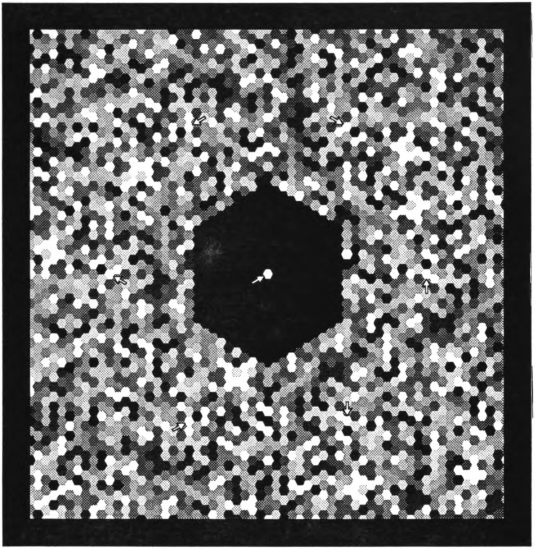


Figure 2.3 Test Display of Small-Sized Hexagons

4.5 mm hexagons reduced 50%

Most displays presented homogeneous inducing surrounds, but two deviations from this configuration were tested: surrounding all hexagons with outlines and breaking up the inducing central surround. As discussed in Chapter 1, cartographic texts have suggested that outlines will reduce induction effects on maps. Both black and white outlines were used with a subset of color combinations to investigate the differences in color perceptions that occurred (Figures 2.4 and 2.5). An additional subset of color combinations was tested with the inducing surround broken into random hexagons of a surround hue and mid-lightness gray, into black and gray hexagons, and into white and gray hexagons (Figure 2.6). These variations were tested to check whether or not induction was a significant influence on perception only in the rather artificial situation (with respect to maps) of a completely homogeneous inducing surround.

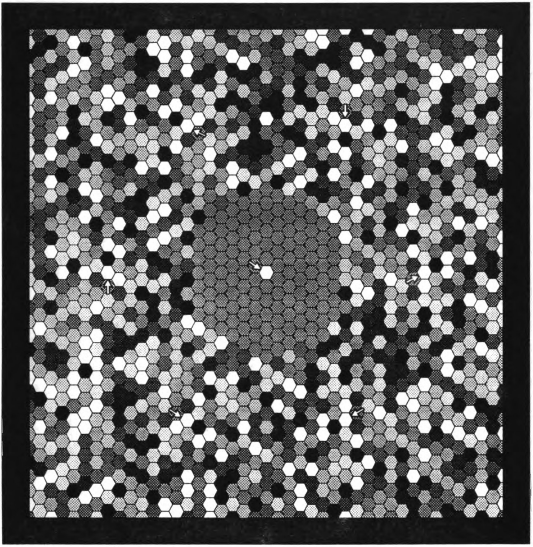


Figure 2.4 Test Display with Black-Outlined Hexagons

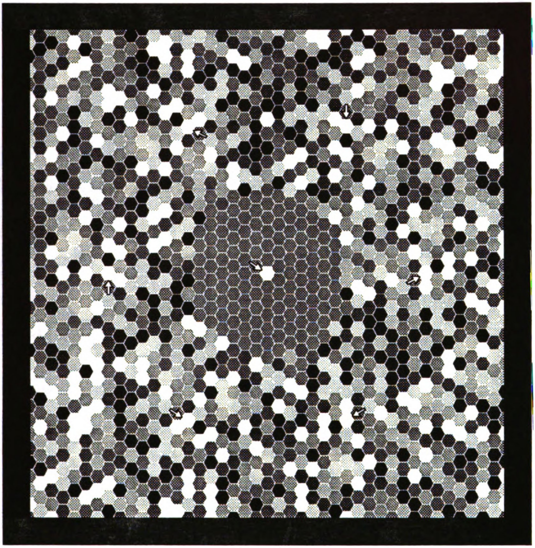


Figure 2.5 Test Display with White-Outlined Hexagons

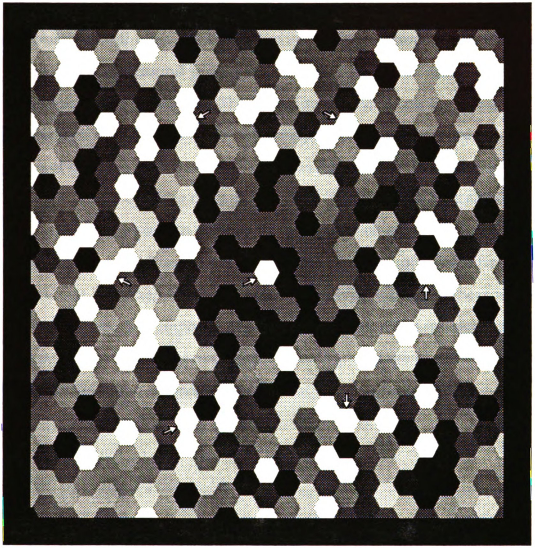


Figure 2.6 Test Display with Example Heterogeneous Inducing Surround

Experiment 1 was designed to simulate conditions of computer-displayed thematic map reading. The use of a full-screen array of colors provided a complex choropleth-like context for the test colors. The comparison of colors within this complex graphic context was better representative of the comparison of colors within the body of a map than the simple center-surround stimuli often used in induction testing. The whites embedded in the patchwork surround provided reference whites that were important to the perception of lightness. The task of matching the center to a given set of comparison colors was similar to the map-reading task because a limited range of colors is used on a map and thus there is a limited set of colors among which the reader must distinguish. I felt that the alternatives of adjusting the comparison color to produce a match or of training subjects in color naming would sensitize subjects to the nuances of color difference to a degree that is not representative of the sensitivity brought to bear when reading a map. The importance of approximating the map-reading task in the design of the experiment outweighed the disadvantage of reduced precision with the limitation of preset selections of comparison colors.

Test Colors

Color combinations were chosen to determine the shift both in distance and direction induced by a surround color. These shifts were measured in Hunt color space. An exhaustive sampling of color combinations from throughout color space would be prohibitively time consuming, and therefore combinations restricted to the opponent color axes were used. To quantify the magnitude or *distance* of color shift, reds were paired with greens in center-surround combinations, yellows and blues were paired, and a set of five grays were paired to sample the lightness dimension (Figures 2.7a and 2.7b). Off-axis combinations were included in testing the *direction* of change to ensure that the expected opponent directions of the shifts held with a wider range of hue combinations. A sample of eight colors, equidistant in color space from each center hue in a circular arrangement, were used for comparison colors for the direction trials (Figure 2.7c). Appendix B lists complete specifications for test colors: luminance and CIE 1931 chromaticity (**L,x,y**); Hunt red-green, yellow-blue, and lightness (**RG,YB,J**); and red-green-blue (**R,G,B**) for monitor display.

The four center hues, at 1.0 unit along each opponent hue axis, were chosen to permit comparison colors of both higher and lower saturation and to permit distinction of the center from surrounds of like hue without an intervening outline or difference in lightness. The steps between the comparison choices were chosen to be equal in Hunt units and just noticeably different to my eye (I have normal color vision) once embedded in the patchwork of grays and at a distance from one another. For the distance trials, the six choices offered with each center-surround combination always included a center match and the remaining five choices were colors to either side of the physical match with one or two more colors offered from the expected direction of shift. For the direction trials, six of the eight choices for each center-surround combination were offered with the two omissions from the direction of the surround with respect to the center, the least likely direction of shift. The direction trial comparisons were forced choice comparisons, since the physical match was not among the choices. Ten of the 200 displays were omitted from the analysis because of errors in color-table assignments that left crucial gaps in the sequence of comparison colors offered. The colors offered as comparisons for each center-surround combination are indicated with the data tables of Appendix C.

The lightness of colors chosen to represent the red-green and yellow-blue axes was held constant (approximately 31.5 cd/m^2 to produce a Hunt lightness of approximately 72.2). This level was chosen because it was midway between the lightness of the most saturated yellows and darkness of the most saturated blues that could be displayed on the color monitor. The mean luminance (31.3 cd/m^2) of the gray patchwork surrounding the comparison colors was set to be approximately the same as the lightness of the test hues. Lightness was held constant for hue comparisons in order to facilitate generalization about induction along the opponent hue dimensions without the complication of lightness induction affecting perceptions simultaneously. Likewise, lightness testing was carried out with neutral stimuli to separate lightness induction magnitudes from hue effects.

A potential disadvantage of the control exercised over the chromatic and lightness dimensions was that the medium-lightness hues featured in the primary testing were not of extreme saturation. The maximum saturation of these medium lightness hues was limited by the gamut of colors available at that lightness on the monitor. Therefore, additional test displays were included that presented ranges of darker red, darker blue, lighter yellow, and lighter green that were more typical of saturated monitor colors (Figure 2.7d, Appendix B). These dark and light center hues were paired with surrounds of medium lightness that were the same lightness as the mean of grays surrounding the darker and lighter comparison colors. The medium-lightness surrounds were used in an attempt to make the lightness induction effects on the center and comparison colors equivalent while studying hue induction in these lighter and darker colors. Differences between comparison choices for the dark reds and dark blues were extended to 1.0 unit because differences of 0.5 were not discernable on the test displays (indicative of deficiencies in the perceptual structuring of the Hunt color appearance space).

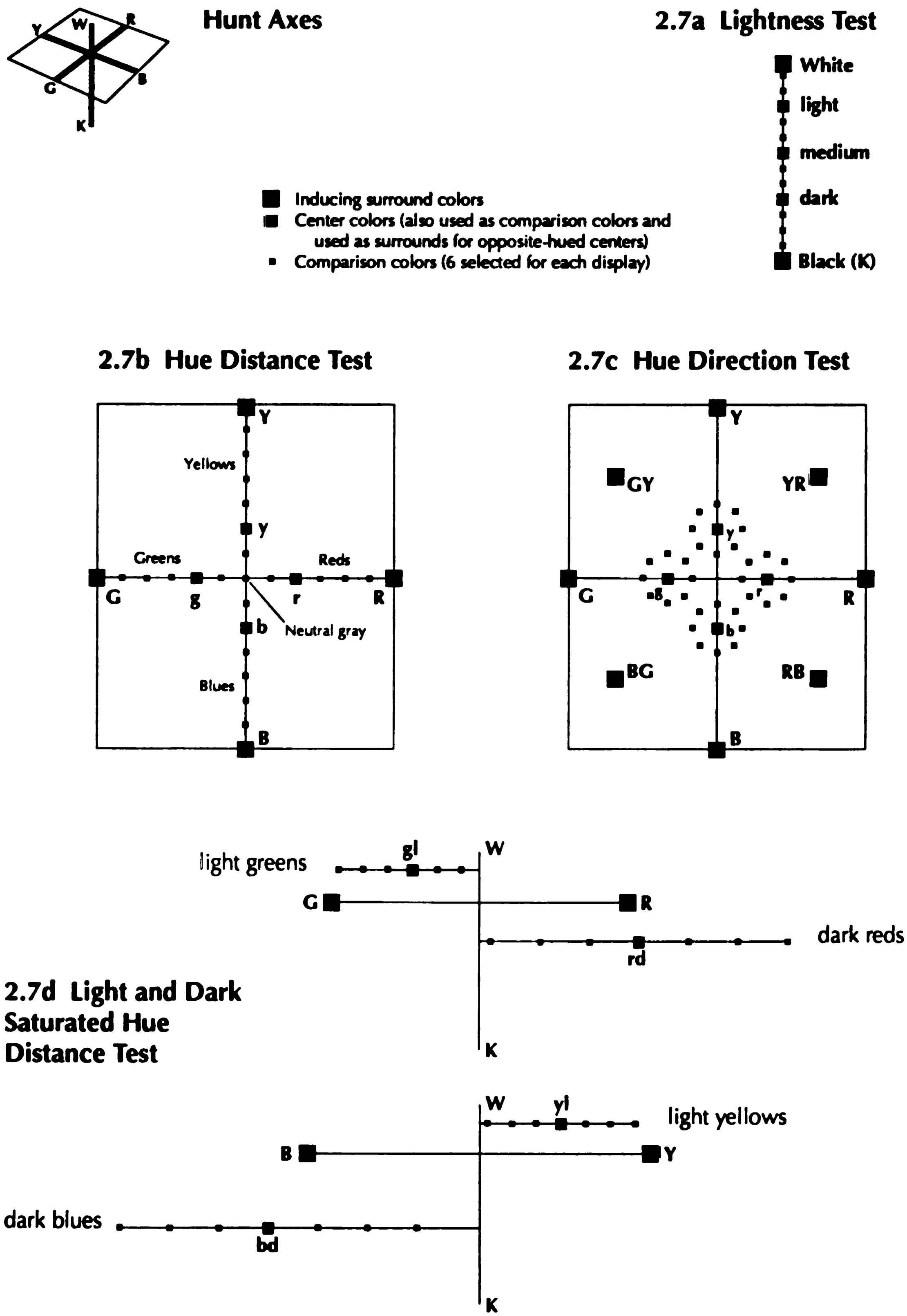


Figure 2.7 Experiment 1 Sampling of Hunt Color Space

Production of Test Colors

Production of monitor colors with specific Hunt coordinates (**RG,YB,J**) was a multi-step process. The luminance and chromaticity (L,x,y) of the aim colors were determined by repeatedly adjusting **L,x,y** used in the Hunt model calculations to produce the desired **RG,YB,J** (the Hunt model was not inverted). Once the **L,x,y** of aim colors were known, the **R,G,B** specifications of the monitor colors were adjusted to approximate the **L,x,y** aim as closely as possible. During this approximation process, colors were measured at five positions on the screen (**C, 1, 2, 4,** and **5** in Figure 2.1) with the gray patchwork filling the remainder of the screen as on the test displays. Colors were measured with a Minolta Chroma Meter CS-100, which is a hand-held colorimeter with through-the-lens viewing. I performed these color measurements positioned as a subject using the chin rest and seated in the test-subject location. The room was also set up with the same curtain and lighting as used for the test sessions to yield measurements of the colors as test subjects saw them.

The Hunt model was run with a set of input constants derived for the particular viewing conditions of displays seen in the experiment. To specify color *appearance*, more information is needed than simply the **L,x,y** measurement of the color of interest. The input constant for the luminance of the reference white was 76 cd/m^2, which was the highest luminance of whites measured on the monitor and was used so that calculated luminance *factors* (upper-case **Y** of the CIE 1931 system) did not exceed 100. The **x,y** chromaticity of the reference white (.270, .296) was set at the mean of measurements of all whites within the patchwork of neutrals for the largest-celled hexagonal grid. The luminance of the adapting background was set at

31.3, the mean luminance of the patchwork grays filling the screen. The conversion factor for calculation of the scotopic luminance of the adapting background was set at 1.2. This constant was derived using the color temperature of the x,y mean of the gray patchwork and extrapolating a value from example factors Hunt provided for 12 other color temperatures. The Hunt model was programmed in HyperTalk and explanatory documentation accompanies the code in Appendix D.

Limitations on Color Precision

Physical factors that may have affected monitor colors were location on the screen, other colors simultaneously displayed, fluctuations in power supply, aging of phosphors, amount of time the monitor had been on, and the previous color displayed at the same location. Commercial monitors are not precision display instruments and quantifying their vagaries was beyond my objectives. Steps were taken, however, to minimize these physical effects on the test colors. The monitor was turned on at least twenty minutes before testing began. The gray screen between displays was present long enough that the trace of the previous display had faded, and thus the same gray preceded each new set of test colors.

Measurements of the colors on all test displays were made over the course of the period of testing to characterize the physical variability of the colors. Figures 2.8, 2.9, and 2.10 show graphs of measurements of the *center* test colors for all surround combinations and hexagonal grid sizes seen in the experiment. The variation in measurements is small compared to differences between comparison choices and is small given the generalized nature of my final guidelines for induction predictions. Thus, the coordinates of the aim colors were used in analysis of subject responses.

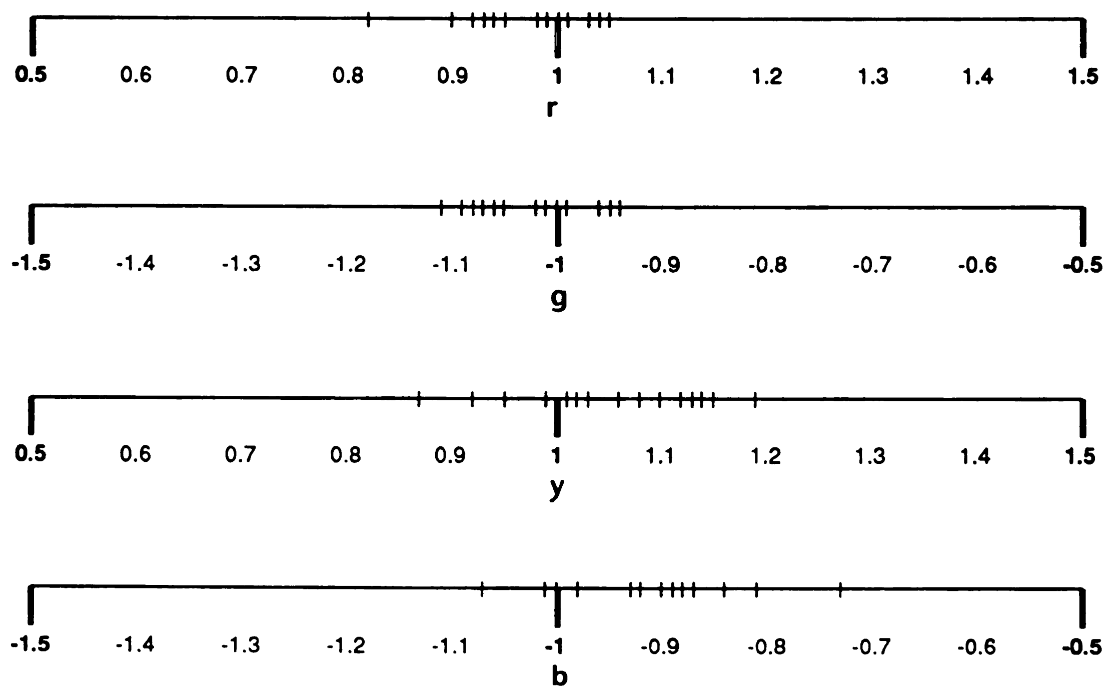


Figure 2.8 Center Measurement Variations for Medium-Lightness Hues

Thin lines mark measurements of centers along segments of the opponent hue axes. Thick lines dropping below the axes mark aim centers at +/- 1.0. Adjacent comparison aim colors are marked by thick lines at +/- 0.5 and 1.5.

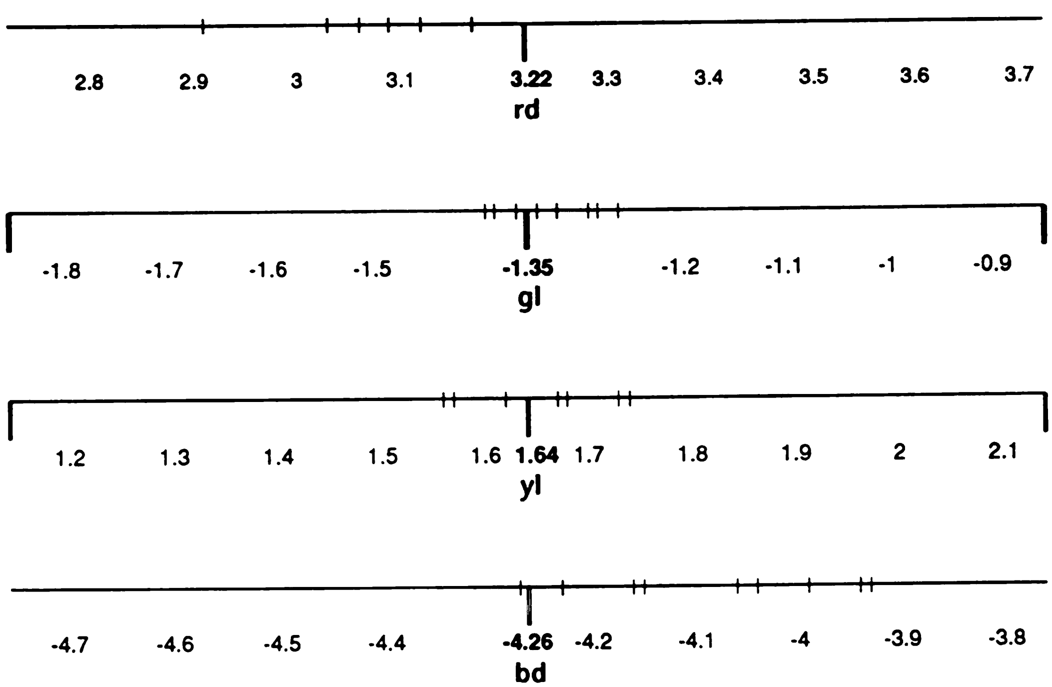


Figure 2.9 **Center Measurement Variations for Light and Dark Saturated Hues**

Thin lines mark measurements of centers along segments of the opponent hue axes. Thick lines dropping below the axes mark aim centers. Adjacent comparison aim colors on the green and yellow axes are marked by thick lines 0.5 units from the aim centers. For the two dark hues (**rd**, **bd**), comparison colors are 1.0 unit from centers, beyond the axis segments shown.

The sequences of colors at light and dark levels were chosen by finding the lightest and darkest saturated opponent color that the monitor could produce. The even-stepped differences between choices were then calculated in toward neutral from these maximum saturation positions. Thus, the positions of the test hues do not fall at 'nice' number positions such as 0.5, 1.0, and 1.5 as with the medium lightness test hues.

Thin lines plot measurements of the lightness of centers only (light, medium, dark) along the J axis.

Thick bars mark center- and comparison-lightness aim positions along the lightness scale.

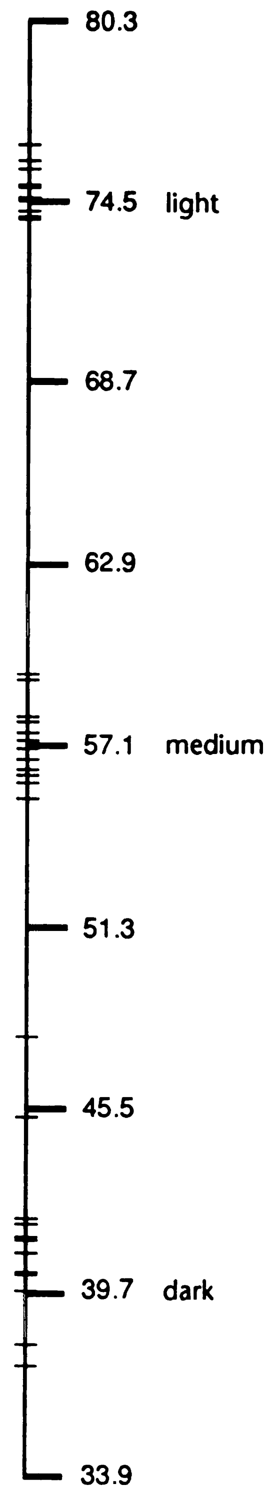


Figure 2.10 **Measurement Variations for Center Lightness**

The impact of physical color variation on subject matches was characterized along with subject variability. All colors were judged within control displays that presented the same patchwork of grays around the center color as the patchwork around the comparison colors (Figure 2.11). These controls for three sizes of hexagons produced data on the accuracy of matches that subjects made given the inherent variability of monitor colors without the effect of induction from the central surround.

Color variations that were small relative to differences between comparison colors were not considered of importance to the final conclusions. Expectation of tight control of computer displayed colors for application of the model developed would render the work of limited use as a design aid to other cartographers also working on commercial monitors. Thus, I preferred incorporation of this physical variability into my analysis, just as variation within the group of 60 diverse subjects provided an approximation of the variability of map readers' perceptions.

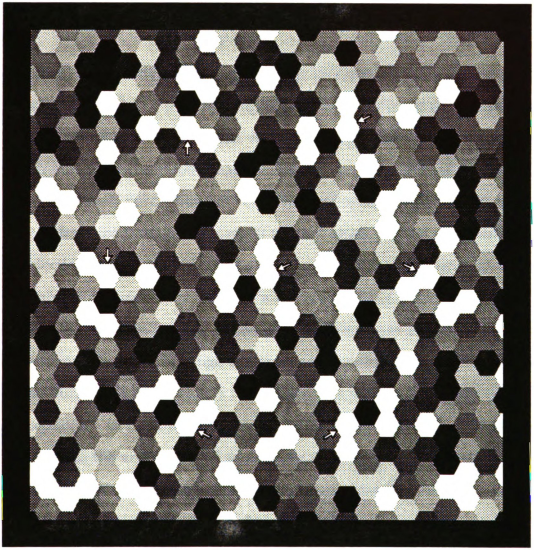


Figure 2.11 Experiment 1 Control Display Format

CHAPTER 3

Experiment 1: Results and Discussion

Recall that the overall objective of my research was development of a *quantitative* model of induction to aid selection of sets of easily identified map colors. Rather than predict *average* color perceptions for particular center-surround color combinations, I acknowledged the inherent variability in map readers' perceptions of color by developing generalized *perception buffers* that accounted for at least 90 percent of test subject responses. The task of selecting colors that will not be confused once they appear with numerous surrounds on a map thus becomes a task of selecting colors that do not have buffers that overlap in color space. Application of the model requires calculation of induced-change buffers for all combinations of colors on a map. These buffers describe regions that encompass most map readers' potential perceptions. In this third chapter, I will describe the results of Experiment 1 and discuss the analyses used to develop the induced-change buffers.

Experiment 1 data were compiled as frequencies of choices for each comparison color matched with the center colors (Appendix C contains a complete listing of the response-frequency data). Distributions of frequencies were compared using both chi-square and Somers's d_{YX} non-parametric statistics. In addition, ordinary least-squares regression of center-surround contrasts against mean induced perceptions was used in model construction. The hypotheses driving the use of these statistics will be detailed as results are described in the sections of this chapter. Because multiple questions are addressed with this data set, I chose to place discussion with the results summaries within each section, rather than in a section remote from the relevant tables and figures.

The Somers's d_{yx} statistic measures association for two ordered discrete variables. The calculated value of the statistic ranges between positive and negative one, and these extremes indicate perfect prediction of the dependent variable by the independent variable. Zero indicates no relationship (i.e., no dependence of the row variable on the column variable). In the Experiment 1 data, subject choices (rows in all tables) are hypothesized to be dependent on differences in surrounds (independent column variables). The asymmetry of d_{yx} is suited to the questions I ask of the data: to what extent does knowledge of the surround help predict subject matches? Asymmetry in a test means that the independence and dependence affects the calculation procedures. Asymmetry distinguishes d_{yx} from other nonparametric measures of association (such as gamma and tau) that are symmetric. The asymptotic standard error for the statistic is used to evaluate whether the calculated d_{yx} departs significantly from zero. Somers's d_{yx} is a PRE (proportionate reduction of error) type of measure requiring systematic comparison of every pair of responses. The statistic is described in Somers 1962 and 1980, Agresti 1981, and Bohrnstedt and Knoke 1982.

The chi-square test of independence was also used to evaluate whether frequency-response distributions for pairs of color-combinations were significantly different. Chi square was included in the analysis to provide confirmation of results from the less familiar d_{yx}. Chi square, however, is not sensitive to the ordering of categories and has the disadvantage of minimum expected-frequency requirements necessitating the collapse of row categories.

Size

With the exception of De Valois and others (1986), previous researchers found that induction produces greater changes in appearance for smaller color areas (Chapter 1). To investigate variation in the strength of induction with size, I tested center hexagons of three sizes: 11, 6.5 and 4.5 mm in diameter (1.1, 0.65, and 0.45 degrees visual angle). The most pronounced differences in induced change were predicted to be between the 11 and 4.5 mm hexagons. Table 3.1 shows the Somers's d_{yx} for 19 hue and lightness distance tests, indicating the extent to which size allows prediction of response frequencies. Appendix C lists the response frequencies for individual hexagon sizes.

In size comparisons for 15 of 19 color combinations, the smallest hexagon size was *not* associated with significantly greater frequencies of shift than the larger hexagon size as had been predicted (Table 3.1). Chi-square tests produced the same pattern of significance for differences in frequency distributions. Though not significant, a *greater* shift in appearance was associated with the *larger* size for the **y B** and **b B** combinations and for grays with dark and black surrounds (these are shifts opposite of expected results). For four red-green combinations, the smaller hexagon colors underwent significantly greater change in appearance than larger hexagons with the same surround. Given the lack of significant size effects for the remaining 15 comparisons, however, data for the three sizes were aggregated for the remaining analyses. Conclusions will be applied to the overall range of sizes represented in the testing. Thus, the promising "edge-distance" model of Yund and Armington (1975) that was described in the Chapter 1 review will not be used.

Table 3.1 Somers's d_{yx} Comparison of Change Induced in Small and Large Test Centers

Each N=60

Hue Distance Test Colors:

		Centers						
		r		g		y		b
Surrounds								
adjacent	R	-.06	G	-.38 **	Y	-.12	B	+.20
opposite	g	+.59 **	r	+.27 *	b	+.13	y	+.15
	G	+.33 *	R	+.18	B	-.05	Y	+.21

Null Hypothesis: small hexagon sizes are not associated with a significantly greater induced shift in perception

** Reject H_0 at .01 confidence level, one-tailed
* Reject H_0 at .05 confidence level, one-tailed

positive d_{yx}: small size associated with greater saturation than large size
negative d_{yx}: small size associated with greater neutrality than large size

Lightness Distance Test Colors:

		Centers				
		l		m		d
Surrounds			W	-.03	W	-.03
	d	-.14	l	-.20		
	K	-.07	K	-.18	K	-.11

Null Hypothesis: small hexagon sizes are not associated with a significantly greater induced shift in perception

Fail to reject H_0 at .05 confidence level (one-tailed) for all lightness combinations

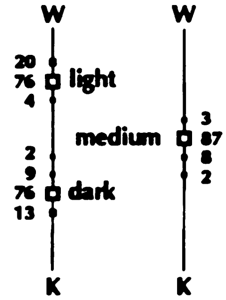
negative d_{yx}: small size associated with greater darkness than large size

Controls

Color matches with the gray-patchwork control surround offered an important baseline for the analysis of Experiment 1 results. The control results were used to determine whether subjects could accurately match centers with comparison choices in the absence of an inducing surround. The frequency-response distributions for the controls also offered an objective distribution with which to compare the perceptions of the colors with inducing surrounds. This comparison is made to answer the question of whether or not shifts in perception were significant. Figure 3.1 provides a summary view of the control responses. Table 3.2 lists the d_{yx} for responses to colors seen with an inducing surround compared to the corresponding control responses (responses for three hexagon sizes were aggregated).

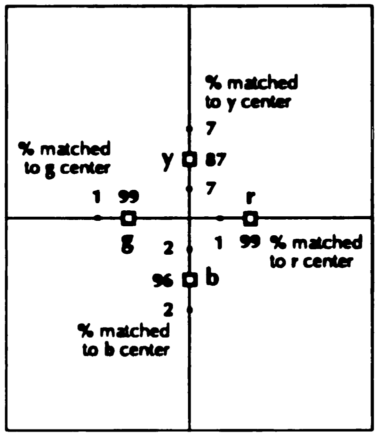
The accuracy of the control matches was surprisingly good given the separation between the center and comparison colors of approximately 7.7 cm and the small color differences between choices. The minor physical variation evident in measurements of the colors (Figures 2.8 and 2.9 in previous methods chapter) did not hinder subjects' abilities to match colors accurately to the comparison choices. Steps between lightness choices, however, were smaller perceptually than differences between hue choices (their numerical units are differently scaled), and lightness differences are generally more difficult to distinguish than hue differences over a distance (Hunt 1987a p. 118). These difficulties manifest as reduced accuracy in matching the control grays; 79 percent of matches were accurate for the lightness control displays (N=270), whereas 95 percent of hue control comparisons were accurate (N=360). Establishing a buffer of one step (5.8 J units along the lightness axis) to either side of the center lightness accounted for 98 percent of the control matches. This matching tolerance was used to evaluate induced shifts in lightness perception that are discussed in the next section.

Most of the 32 color combinations listed in Table 3.2 were associated with significantly more choices of comparison matches from the predicted directions of perceived change than for the corresponding control cases. The exceptions are seven of the lightness and saturated-hue combinations. The centers for three of the four lightness combinations with light (**l**) and medium (**m**) surrounds were not perceived as different than the same gray center with the control surround. The differences in lightness between **l**, **m**, and the control surround are interpreted to be small enough that no significant differences in perceptions were induced (lightnesses are 74.5 for the **l** surround, 57.1 for the **m** surround, and a mean of 61 for the control surround of six grays immediately adjacent to centers). The four light and dark saturated-hue centers with opposite surrounds show induced shifts in the reverse of the predicted direction. I discuss these deviations in the later section on the saturated hues. Chi-square analyses yield the same pattern of significance for the controls with the exception that the four saturated-hue 'opposite' combinations had significantly different distributions of frequencies. The frequency data for the controls are listed with the relevant frequencies for induction sets in Tables 3.3, 3.4, and 3.5 that appear in later sections.

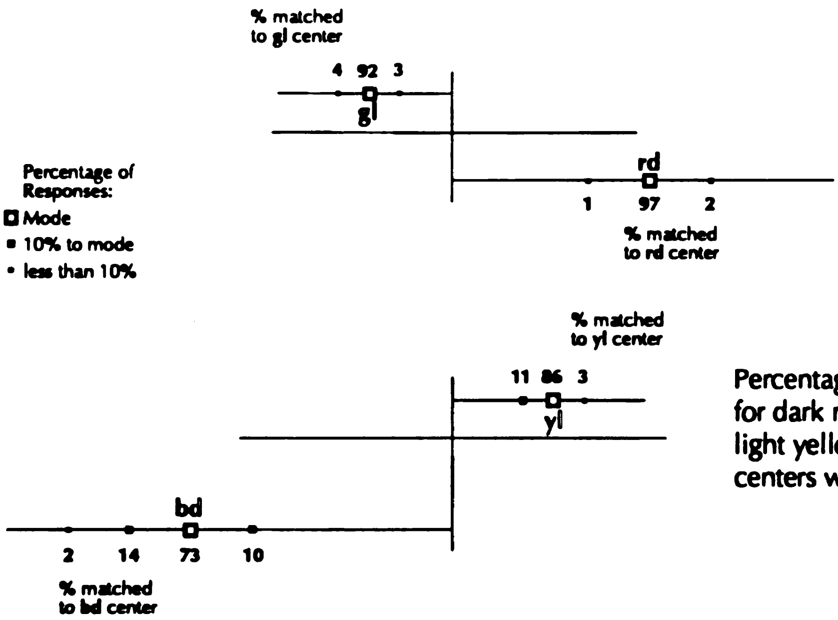


Percentage of responses for light, medium, and dark centers with control surround

Figure 2.7 shows labels for color-space axes.



Percentage of responses for medium-lightness red, green, yellow, and blue centers with control surround



Percentage of responses for dark red, light green, light yellow, and dark blue centers with control surround

Figure 3.1 **Comparison-Color Choices Plotted in Hunt Color Space for Control Surround Test**

Table 3.2 **d_{yx} Comparison of Change Induced by Control and Inducing Surrounds**

Each N=180 or 150

Hue Distance Test Colors

	Centers							
		r		g		y		b
Surrounds								
adjacent	R	-.93 **	G	-.97 **	Y	-.94 **	B	-.99 **
opposite	g	+.48 **	r	+.33 **	b	+.26 **	y	+.39 **
	G	+.56 **	R	+.19 **	B	+.29 **	Y	+.33 **

Lightness Distance Test Colors

	Centers		
	l	m	d
Surrounds			
W	-.74 **	-.24 **	-.27 **
l		+.04	-.19 *
m	+.09		+.13
d	+.16 *	+.71 **	
K	+.61 **	+.75 **	+.60 **

Light and Dark Saturated Hue Distance Test Colors

	Centers							
		rd		gl		yl		bd
Surrounds								
adjacent	R	-.80 **	G	-.77 **	Y	-.83 **	B	-.51 **
opposite	G	-.08	R	-.26	B	-.13	Y	-.25

Null Hypothesis: In comparison to control surround matches, contrasting surround matches are not associated with a significantly greater induced shift in perception in the predicted direction.

** Reject H_0 at .01 confidence level, one-tailed
* Reject H_0 at .05 confidence level, one-tailed

positive d_{yx}: inducing surround associated with greater saturation or greater lightness than control
negative d_{yx}: inducing surround associated with greater neutrality or greater darkness than control

Lightness Test

Induced lightness change is more difficult to measure than induced hue change because the comparison grays that are offered must also have surrounds with some lightness component (with hue induction, a comparison hue can have a neutral surround with no hue component). A black surround cannot be considered as 'no' surround because it does induce a change in perception. For analysis of the research results, both the center grays and comparison grays were considered to have inducing surrounds (the comparison surround was a constant of 61 J, the mean of the patchwork of grays immediately adjacent to the comparisons). Table 3.3 provides lightness response data.

Yund and Armington (1975) found center-surround contrast to be a strong predictor of surround induction, and opponent-theory approaches to induction generally postulate an *additive* effect (i.e., the induced effect is added to the perception). Therefore, to model the induced lightness perceptions, a proportion (**k**) of the lightness contrast between the gray test center (**t**) and its inducing surround (**s**) was *added* to the center gray (**t**). The same proportion (**k**) of the contrast between the lightness of the perceived match (**p**) and the mean of the gray patchwork (**c**) around the comparisons was added to the perceived match (**p**). This contrast relationship was consistent with previous research and produced the following equation:

$$\mathbf{t + k(t - s) = p + k(p - c)} \qquad (1)$$

The proportionality factor (**k**) was estimated as 0.135 with ordinary least-squares regression. Rearrangement of Equation 1 clarifies the appropriateness of estimating **k** using regression with a forced intercept of zero:

$$\mathbf{t - p = k[(p - c) - (t - s)]} \qquad (2)$$

The independent variable on the right of Equation 2 represents the difference in center-surround contrasts for the test color (**t**) and its perceived match (**p**). The variable dependent on this contrast difference is the induced change in perception, on the left of Equation 2. The mean of all matches to the test center was used as a surrogate for the perception of the induction-affected test color (**p**). Figure 3.2 presents a scatterplot of the data with dependent and independent variable axes. The line on the scatterplot shows predicted perceptions. It has a slope of 0.135, the **k** estimate, and passes through the origin. The r^2 for this relationship is .86, a satisfactorily high percentage of explained variance. The slope coefficient is significant at the .001 confidence level (an intercept that is not significant is produced if the line is not forced through the origin).

Once **k** was estimated, Equation 1 was solved for **p**, the predicted perception:

$$\mathbf{p = [t + k(t - s + c)] / (1 + k)} \qquad (3)$$

(**t** is test center lightness, **s** is inducing surround lightness, and **c** is comparison surround lightness). Figure 3.3 shows 12-unit buffers (needed with the control comparisons) centered on the predicted perceptions of lightness. The overall number of responses that these shifted buffers encapsulate accounted for 90 percent of subject lightness matches (N=870, control matches were not included). The only substantial outliers in this process were 14 subjects (22 percent, see Table 3.3) who perceived the light center with a white surround as darker than predicted. Each predicted match corresponds to at least 13 percent of responses for the individual color combination (those response frequencies that fall within buffers). This rate indicates a lean model that does not rely on extravagantly large buffers for its high percentage of successful prediction.

Table 3.3 **Percentage of Matches to Comparison Choices for Lightness Distance Test**

Matches to **l**, light center

Surrounds:	W	c	m	d	K
Choices:					
+16.2		(control)			3
+11.6				2	18
lighter					
+5.8	2	20	32	37	58
match l	**25**	**76**	**62**	**55**	**18**
-5.8	50	4	7	5	3
darker					
-11.6	22			2	
-17.4	2				

Matches to **m**, medium center

Surrounds:	W	l	c	d	K
Choices:					
+17.4			(control)		1
+11.6				3	13
lighter					
+5.8	7	13	3	70	63
match m	**56**	**72**	**87**	**25**	**20**
-5.8	32	13	8	2	2
darker					
-11.6	6	2	2		

Matches to **d**, dark center

Surrounds:	W	l	c	m	K
Choices:					
+23.2			(control)	2	
+17.4					3
lighter					
+11.6	2	2	2		23
+5.8	9	7	9	20	41
match d	**46**	**60**	**76**	**70**	**29**
-5.8	39	28	13	8	3
darker					
-11.5	4	3			

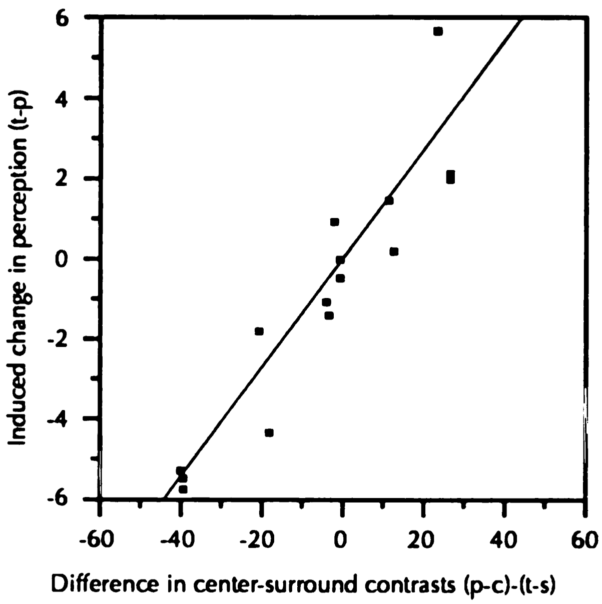


Figure 3.2 Scatterplot for Mean-Response Lightness Data

Line has slope 0.135 and intercept at the origin.

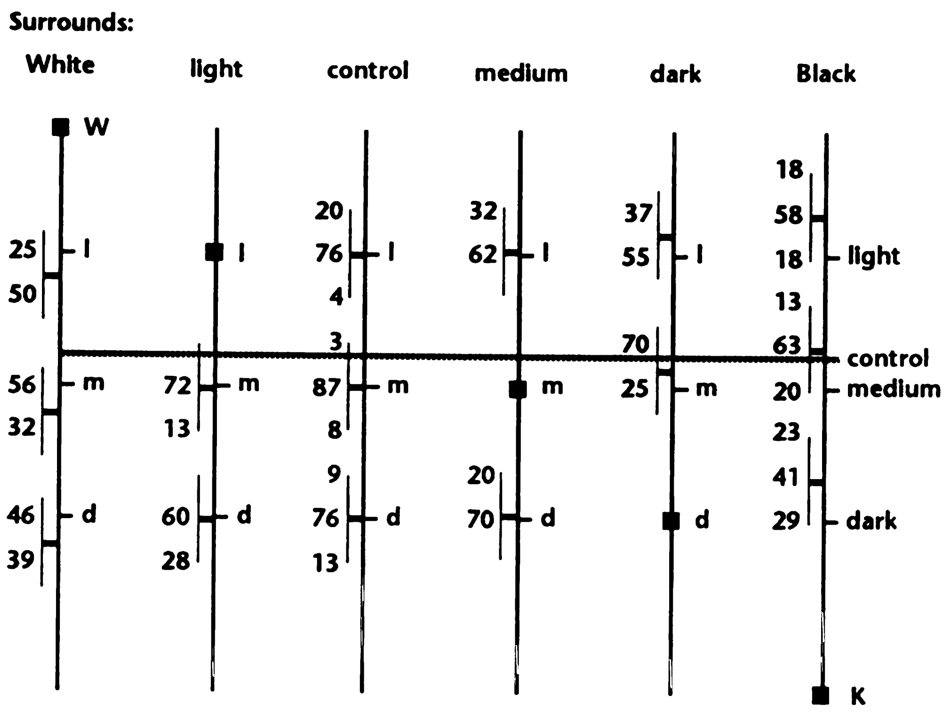


Figure 3.3 Lightness Induction Prediction Buffers

Each of the six bold vertical lines represent the lightness axis. Tick marks to the right of each axis mark center lightness positions and black squares mark surround positions. The numbers along the left of each axis are percent responses for comparison choices (compare to Table 3.3). Bold ticks to the left of axes show predicted mean perceptions, and thin vertical bars represent buffers needed to account for 90 percent of perceptions overall. The percentage of perceptions an individual buffer encapsulates is the sum of the adjacent percentage figures. For example, at the lower left, dark gray with a white surround is perceived as darker and the 12-unit buffer includes choices selected by 46 and 39 percent of subjects.

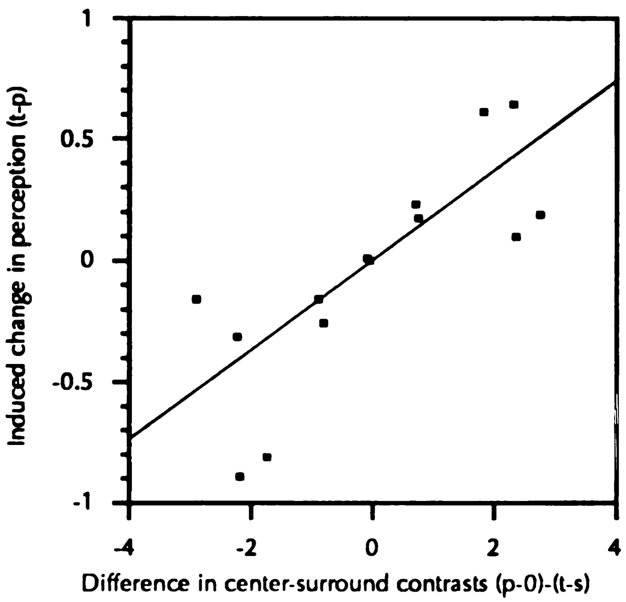
Hue Distance Test

Patterns in the medium-lightness hue response data mandated rethinking plans to treat the red-green and yellow-blue axes as continua with functions similar to that developed for lightness. Estimation of **k** from Equation 2 with center-surround *hue* contrasts and mean perceptions offered explanation of only 61 percent of variation in the data. Figure 3.4a shows a scatterplot for hue of the same form as Figure 3.3 for lightness. Examination of departures from the best-fit line revealed systematic errors (Figure 3.4b shows each point named). Note that perceived change for some of the extreme values of the independent contrast variable collapse back toward zero induced change. These extremes were mean perceptions of centers with surrounds from the opposite ends of the opponent-hue axes.

The magnitudes of induced shift were closely linked to whether the surround hue was *opposite* or *adjacent* the center hue in color space. Examples clarify the *adjacent* and *opposite* terminology I use: yellow surrounded by blue (**y B** or **y b**) is described as an opposite hue combination, and blue surrounded by a more saturated blue (**b B**) is described as an adjacent combination. On the scatterplot, the eight points hovering between 0.1 and 0.3 above and below the zero-change line all plot perceived changes for opposite center-surround combinations. The colors undergoing mean shifts greater than 0.6 each had adjacent surrounds of like hue. These patterns of perceived change are seen in Figure 3.5, in which percent responses for each comparison color are plotted in color space (Table 3.4 lists these percentages). Comparison of frequency distributions using d_{YX} revealed that the number of shifts in perception induced by the more- and less-saturated opposite surrounds were not significantly different (.10 d_{yx} for **r g** compared to **r G** responses; .02 for **g r** to **g R**; -.13 for **y b** to **y B**; -.06 for **b y** to **b Y**).

My sampling of color space was not sufficient to model each neutral-to-hue range as a continuum, so additive constant shifts for opposite and adjacent center-surround cases were derived. A one-step buffer that extends to one step (0.5 units) of greater saturation from the color accounted for 95 percent of subject matches with opposite surrounds (N=690). A one-step buffer to neutral that extends from one step toward neutral accommodated 97 percent of subject matches for adjacent surrounds (N=360). Note that the greater magnitude of the shifts induced by the adjacent surround compared to effects of either opposite surround is evident in the d_{yx} values in Table 3.2. Adjacent combinations produce stronger d_{yx} than opposites (more than $|0.9|$ versus less than $|0.6|$) when responses are compared to frequencies on the control tests.

3.4a



3.4b

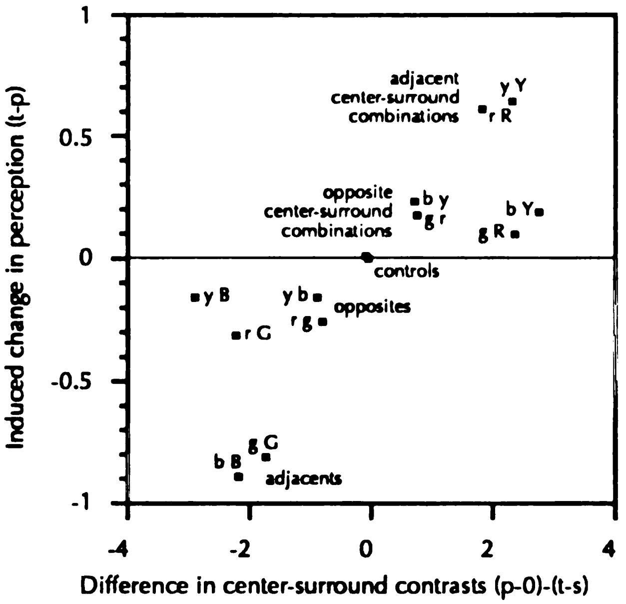


Figure 3.4 Scatterplots of Mean-Response Hue Data

Table 3.4 Percent of Matches to Comparison Choices for Hue Distance Test

Matches to r, the red center

Choices:	Surrounds: control	adjacent R	opposite g	opposite G
more red +1			3	8
+.5			44	49
match r	99	7	52	42
grayer -.5	1	66		1
neutral -1		28		

Matches to y, the yellow center

Choices:	Surrounds: control	adjacent Y	opposite b	opposite B
more yellow +1			4	1
+.5	7		27	32
match y	87	1	66	64
grayer -.5	7	69	3	2
neutral -1		30		

Matches to g, the green center

Choices:	Surrounds: control	adjacent G	opposite r	opposite R
more green -.5	1		34	23
match g	99	3	66	73
gray-green +.5		32		3
neutral +1		63		
gray-red +1.5		1		

Matches to b, the blue center

Choices:	Surrounds: control	adjacent B	opposite y	opposite Y
more blue -1			6	3
-.5	2		36	33
match b	96	1	58	60
grayer +.5	2	19	1	3
neutral +1		80		

Red- and green-surround induced shifts in color space

Yellow- and blue-surround induced shifts in color space

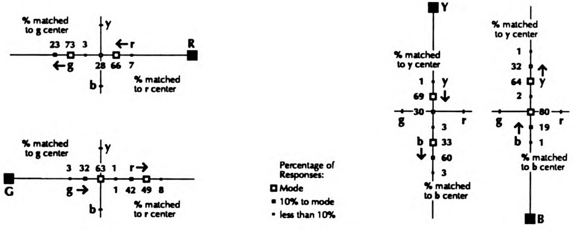


Figure 3.5 Comparison-Color Choices Plotted in Hunt Color Space for Hue Distance Test

Hue Direction Test

The direction test of hue shifts offered comparisons 0.5 units in hue difference in six directions in color space from each center color. Expected perceptions, based on opponent theory, were toward the opponent complement of the surround, and Table 3.5 is organized such that the number of matches to the expected perception are arranged across the middle row of each table. Matches counter-clockwise and clockwise to either side of the expected response are arranged above and below this central row. More extreme responses were aggregated and are listed in the top and bottom rows of the tables (Appendix C contains full data listings). The direction data are plotted in color space in Figure 3.6. Looking across this set of diagrams shows that shifts were generally away from the surround color positions.

The analysis of lightness and medium-hue distance data made successful use of modest buffers that encapsulated high percentages of subject perceptions. In keeping with this approach, a fan-shaped buffer spanning 90 degrees in the opponent-complement direction from the surround was used to account for 90 percent of subject matches (N=930). Figure 3.6 shows the perception buffers for all center-surround combinations. Note that the modal-response frequencies are all contained within these buffers; the application of predicted opponent-complement shifts is well fit to these response data. This success confirms that offering comparison colors along only the opponent axes was appropriate for the hue distance test discussed in the previous section.

The difference in magnitude of shift for opposite and adjacent surrounds for the *distance* test is also revealed in aggregate *direction* data of frequencies for opposite and adjacent surrounds (N=120 for opposites and N=120 for adjacents). For the adjacent surrounds, 83 percent of the matches were the expected opponent complement with *no* responses straying outside the 90-degree buffer. In contrast, only 36 percent of responses were matches in the expected directions for the opposite surrounds with 27 percent of responses scattered outside the buffer. Greater variation in responses occurred for opposite surrounds with no clear alternative to the opponent complement for the direction of shift.

Looking back at the distance-test response frequencies for these opposite surrounds (Table 3.4), 60 percent of subjects perceived an accurate match, unaffected by surround induction. The direction tests were forced choices (no accurate appearance match was offered if no induced change was perceived). Thus, greater variability of responses was consistent with randomness provoked in subject responses when no acceptable match was available. Greater consensus was apparent for adjacent-surround matches in the direction test and, likewise, 97 percent of subjects selected matches at least 0.5 units toward neutral in the corresponding distance tests.

Table 3.5 Frequencies of Matches to Comparison Choices for Hue Direction Test

Each N=30 (note that tables list frequencies, *not* percentages)

Matches to r
red center

Surrounds:	adjacent				opposite			
Choices:	RB	R	YR	Y	GY	G	BG	B
counter-clockwise >+45° from expected	2				4	2	2	
counter-clockwise +45° from expected	1	4	1	1	3	4	4	10
expected	**27**	**26**	**18**	**7**	**16**	**17**	**23**	**17**
clockwise -45° from expected			10	18	5	7	1	2
clockwise <-45° from expected			1	4	2			1

Matches to g
green center

Surrounds:	adjacent				opposite			
Choices:	GY	G	BG	B	RB	R	YR	Y
counter-clockwise >+45° from expected	4					1	5	1
counter-clockwise +45° from expected	8			1	5	3	16	2
expected	**16**	**25**	**10**	**14**	**14**	**9**	**5**	**22**
clockwise -45° from expected	2	5	16	15	7	4	4	5
clockwise <-45° from expected			4		4	13		

Matches to y
yellow center

Surrounds:	adjacent				opposite			
Choices:	YR	Y	GY	G	BG	B	RB	R
counter-clockwise >+45° from expected				2			(no data)	
counter-clockwise +45° from expected	4		5	19	9			
expected	**15**	**22**	**23**	**9**	**16**	**10**		**9**
clockwise -45° from expected	9	8	2		3	15		20
clockwise <-45° from expected	2				2	5		1

Matches to b
blue center

Surrounds:	adjacent				opposite			
Choices:	BG	B	RB	R	YR	Y	GY	G
counter-clockwise >+45° from expected			1		1	1	7	
counter-clockwise +45° from expected	9	2	2	5	1	1	10	13
expected	**19**	**26**	**19**	**14**	**20**	**7**	**13**	**14**
clockwise -45° from expected	1	2	8	8	4	11		3
clockwise <-45° from expected	1			3	4	10		

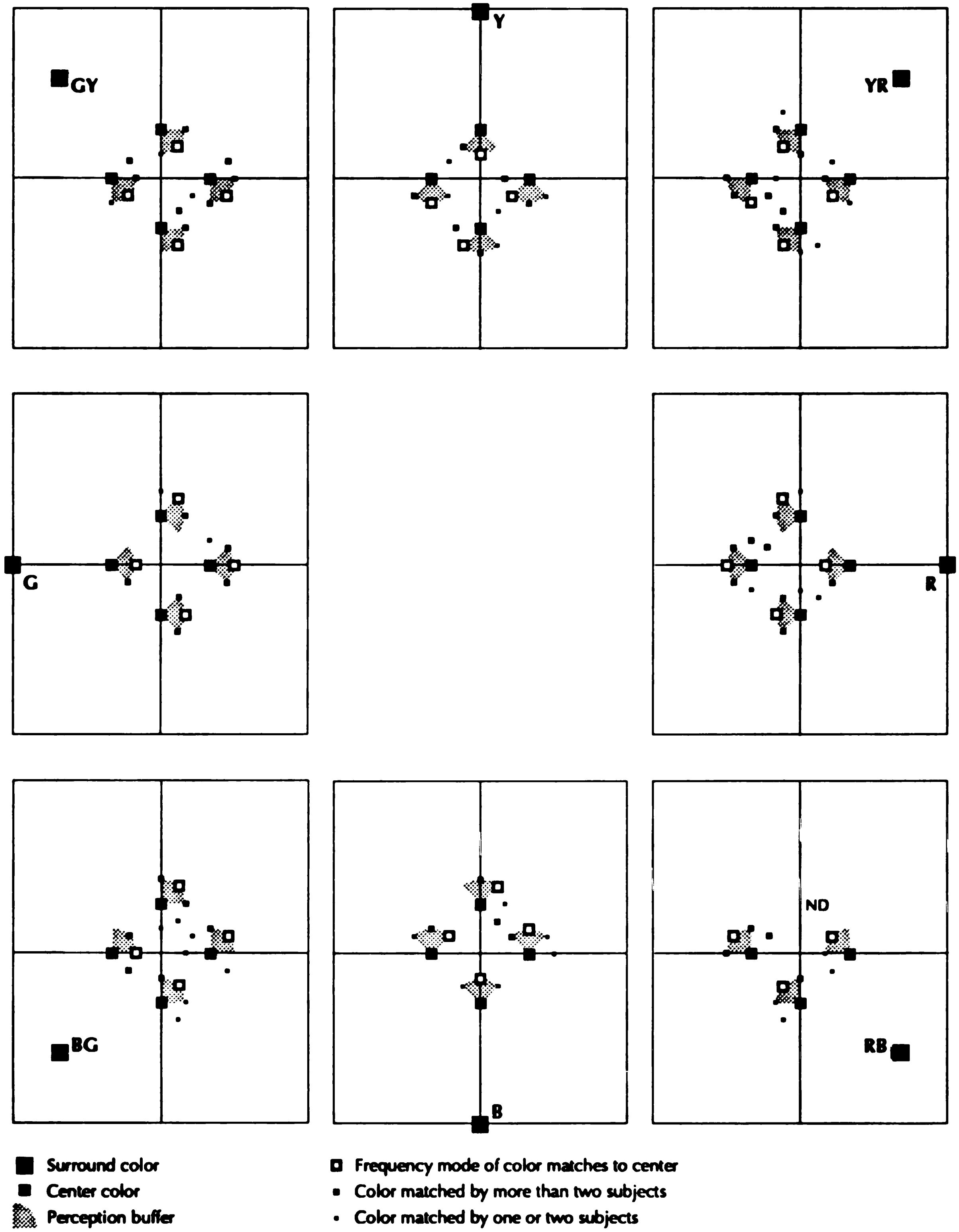


Figure 3.6 Comparison-Color Choices Plotted in Hunt Color Space for Hue Direction Test

Light and Dark Hue Distance Test

The light and dark saturated-hue test produced puzzling results. As with the medium-lightness hues, the shifts in perception were stronger for adjacent than for opposite hue combinations (note values of d_{yx} in Table 3.2 and percent responses in Table 3.6). The opposite-surround shifts were all toward reduced colorfulness (the direction opposite to that predicted) though only two (**gl R**, **bd Y**) were significant in comparison with control frequencies (if the alternate tail for one-tailed significance was used to evaluate d_{yx}).

Adjacent-surround shifts occurred in the expected direction of reduced colorfulness. The saturation of the dark hues (**bd** and **rd** centers) was slightly *greater* than the saturation of their medium-lightness adjacent surrounds (Figure 3.7). This relationship points out a contradictory case for the two commonly made generalizations about induction: the complement of the surround is induced and greater difference between the center and surround is induced. Accord with the second generalization requires these dark hues to shift in appearance away from their surrounds, not toward them with addition of their surround's opponent complement. These **bd** and **rd** centers also point out an omission in my sampling of center-surround combinations. I did not test the effect of surrounds that were the same hue as the center and *less* saturated than the center.

An alternative interpretation of the responses for these two dark hues does not produce a contradiction of the generalization that induced shifts increase the perceptual difference between the center and surround hues. The hue axes may be disproportionately expanded at low lightness in the Hunt color space. The suspicion that the axes were perceptually stretched for darker hues followed from the decision to select comparison hues 1 unit in color difference to allow discernability (rather than maintaining the 0.5 unit difference used for selection of medium and light comparison hues). This interpretation suggests the interesting possibility of using induction to aid the difficult evaluation of relative saturation at different lightness levels.

Lightness differences between center and surround colors reduced induction magnitudes overall. At medium-lightness, a similar effect may have been the greater strength of induction by adjacent (like-hued) surrounds compared to induction by opposite-hued surrounds. The lessened induced change in saturation with additional qualitative differences (differences in hue, differences in lightness) suggested that distinctions by saturation alone may be particularly susceptible to induced shifts in appearance.

Because of the lessened induction effect with lightness differences, the overall prediction guidelines in the Chapter 3 summary recommend that perception buffers for adjacent hue combinations extend 1 unit from the original center color. The hue-distance analysis supported a narrower prediction that did not include the center color.

Table 3.6 Percent of Matches to Comparison Choices for Saturated Hue Distance Test

Matches to **rd**, dark red center

Surrounds:		control	adj. R	opp. G
Choices: more red	+1	2		4
match	rd	97	19	84
	-1	1	79	11
grayer	-2		2	

Matches to **gl**, light green center

Surrounds:		control	adj. G	opp. R
Choices: more green	-.5	4	1	1
match	gl	92	19	72
	+.5	3	79	27
grayer	+1		1	

Matches to **yl**, light yellow center

Surrounds:		control	adj. Y	opp. B
Choices: more yellow	+.5	3		10
match	yl	86	8	60
	-.5	11	70	29
grayer	-1		22	1

Matches to **bd**, dark blue center

	control	adj. B	opp. Y
-2	2		1
-1	14	6	9
bd	73	37	58
+1	10	51	30
+2		7	2

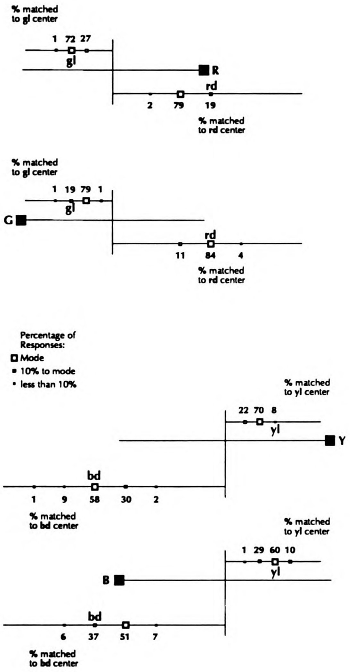


Figure 3.7 Comparison-Color Choices Plotted in Hunt Color Space for Saturated Hue Distance Test

Variations on Displays

A subset of displays in Experiment 1 were varied to test secondary hypotheses about center-surround interactions at *single* grid densities. As described in the previous methods chapter, both black and white outlines were drawn around all cells in the hexagonal grids used to build the test displays (Figures 2.4 and 2.5). The heterogeneous display variation described in Chapter 2 involved imposition of a pattern of gray hexagons within the inducing-surround colors (Figure 2.6). For example, the heterogeneous version of **r R** presented saturated red and neutral (**N**) of the same lightness around the lower-saturation red center. To examine the effects on perception of these varied displays, response data were compared with responses to the standard versions of the displays (contiguous and homogeneous inducing surrounds with the same hexagonal grid densities). Responses were also compared to corresponding control responses. Each comparison involved 60 responses.

The data for three outline comparisons and six heterogeneous combinations were omitted from the analysis. For these combinations, the distinction of inducing versus control surrounds did not produce a significant difference in response prediction for the single hexagon density (recall that responses for color combinations seen with two or three hexagonal grid densities were aggregated for the primary control comparisons). The omissions were made because this discussion of results focuses on whether responses to the display variant were more like the control *or* more like the induced responses. If there was only a weak difference between the control *and* induced response patterns, then additional variants of that display combination had nothing to contribute to the discussion.

Hexagon Outlines

Table 3.7 presents d_{yx} statistics for comparisons of outlined-hexagon responses to the contiguous inducing-surround responses and to the control-surround responses. Among 17 comparison pairs, there are only three for which outlines caused the responses to be not significantly different from the control responses and significantly different from responses to the standard inducing display (black outlines for **r g** and white outlines for **rd R** and **bd Y**). For an additional two comparisons (white outlines for **g G** and **m K**), outline versions produced responses that were significantly different from both the control and inducing cases. The intermediate nature of the responses for **gl R** (white outlines) rendered them not significantly different from either the inducing or control responses. These last three comparisons revealed an intermediate reduction of induction effects by the hexagon outlines. The remaining eleven d_{yx} comparisons show that knowledge of whether hexagons were outlined or contiguous provided no significant improvement in prediction of the subject responses.

For the majority of comparisons, the addition of outlines did not reduce the amount of change induced by the surround. Of 17 comparisons, the six discussed in the previous paragraph (for which outlines either reduced or removed the induced change) provided only weak support for the commonly held notion that outlines on maps counteract simultaneous contrast. Within this small sample, black outlines were less effective than white outlines, with only one instance of black removing induced change.

Table 3.7 **d_{yx} Comparison of Change Induced by Outlined Surrounds Relative to Contiguous and Control Surrounds**

Each N=60

	hex. size	white outlines induce:		white outlines control:		black outlines induce:		black outlines control:	
r g	(6)	-.17		+.23	*	-.34	**	+.03	
g G	(4.5)	+.52	**	-.87	**	(no data)			
y Y	(4.5)	+.11		-.95	**	+.20		-.92	**
b B	(6)	-.03		-.99	**	+.04		-.96	**
l W	(6)	-.03		-.80	**	+.16		-.77	**
m K	(4.5)	-.36	**	+.33	*	+.13		+.80	**
rd R	(11)	+.57	**	-.20		+.10		-.70	**
gl R	(4.5)	+.21		-.18		+.07		-.34	**
bd Y	(6)	+.38	**	+.03		+.14		-.29	*

Null Hypothesis for 'induce' columns: The center test color with a contiguous inducing surround does not undergo a significantly greater shift in perception than with outlines separating the center and surround hexagons.

Null Hypothesis for 'control' columns: The center test color with outlined hexagons in the inducing surround does not undergo a significantly greater shift in perception than with the control surround.

** Reject H_0 at .01 confidence level, one-tailed
* Reject H_0 at .05 confidence level, one-tailed

Heterogeneous Surrounds

Table 3.8 lists d_{yx} for comparisons of heterogeneous-surround responses to the homogeneous-surround responses and to the control responses. Of the ten comparison pairs in Table 3.8, responses for five of the heterogeneous surrounds are significantly different from both responses for the corresponding homogeneous surround and for the control. These d_{yx} are opposite in sign, indicating reduced changes in the center perception. Two (both **l K** combinations) of the heterogeneous surrounds induced the same amount of change as the corresponding homogeneous versions. Responses for three of the heterogeneous surrounds (**m K, d K, rd R**) were not significantly different from the control responses, indicating that breaking up the surround removed the induction effect.

The results show that heterogeneous surrounds induce changes in perception. Consistent with the research literature, the induced change was most frequently intermediate between the effect of the homogeneous surround and the control surround. Results from this small sample of heterogeneous surrounds were not intended for prediction of the magnitude of these intermediate perceptions but to confirm that induction is not peculiar to the simple case of homogeneous surrounds.

Table 3.8 **d_{yx} Comparison of Change Induced by Heterogeneous Surrounds Relative to Homogeneous and Control Surrounds**

Each N=60

	hex. size	homog. surround	control patchwork
r R	(11)	+.50 **	-.60 **
g G	(4.5)	+.72 **	-.87 **
y Y	(11)	+.48 **	-.38 **
l W	(6.5)	+.53 **	-.39 **
l K	(4.5)	-.14	+.51 **
l K	(11)	-.09	+.77 **
m K	(6.5)	-.47 **	+.12
d K	(4.5)	-.41 **	-.09
rd R	(4.5)	+.61 **	-.19
yl Y	(4.5)	+.58 **	-.25 *

Null Hypothesis for 'homogeneous surround' column: The center test color with a homogeneous surround does not undergo a significantly greater induced shift in perception than with a heterogeneous surround of the same surround color and neutral.

Null Hypothesis for 'control patchwork' column: The center test color with a heterogeneous surround (composed of an inducing color and neutral) does not undergo a significantly greater induced shift in perception than with the control patchwork surround.

** Reject H_0 at .01 confidence level, one-tailed
* Reject H_0 at .05 confidence level, one-tailed

Summary

The analysis of results from Experiment 1 boils down to a simple set of broad guidelines for predicting changes in perception induced by surrounding colors. The rules build on the **RG, YB,** and **J** specifications of color appearance from the Hunt model.

To predict *lightness* perceptions, use the **J** designations of lightness from the Hunt model:

Calculate the difference between the lightnesses of the center and surround colors (center **J** - surround **J**).

Mutiply the difference by 0.135 and add the product to the lightness of the center (if the surround is lighter than the center the difference is negative and therefore the center lightness is reduced).

To predict *hue* perceptions, work on a graph showing the colors plotted in Hunt color space:

Decide whether the surround hue is opposite or adjacent the center hue (they are adjacent if they are on the same side of neutral along an axis or are in the same quadrant).

Draw a 90° buffer (a quadrant of a circle) extending from the center color toward the opponent complement of the surround color (extending equally to either side of this opponent direction).

If the colors are adjacent, draw this buffer with a radius of 1.0 unit. If they are opposites, draw the buffer with a smaller radius of 0.5 units. (The 'units' are the same units in which the relative redness-greenness and relative yellowness-blueness axes of the graph are scaled.)

Viewers will have difficulty distinguishing two colors if *both* of the following are true:

The induction-affected lightness of the center color is within 12 lightness units of the perceived lightness of another color.

The other color falls within the center's hue buffer or the other color's buffer intersects that of the center color.

This model for the prediction of induced misinterpretations of colors is intended for application to centers ranging in size from one-half to one degree of visual angle. The rules should hold whether colors are contiguous or finely outlined. Example applications of the model to specific map schemes are provided in Chapter 4, in which the success of predictions is analysed.

CHAPTER 4

Experiment 2 : Methods, Results, and Discussion

Experiment 2 tested predictions made by the model developed with Experiment 1. Subjects compared colors for three versions of each of 20 computer-displayed maps. They were asked to decide whether or not specific color pairs represented the same or different map categories. The comparison colors were presented with different inducing surrounds predicted to produce either incorrect responses or longer response times. These center colors were also compared with control surrounds of the same color. For the third version, map colors were adjusted such that the model predicted previously inducing surrounds would no longer cause an incorrect or slowed response. This chapter presents the test methods and results for the confirmatory second experiment. Discussion follows methods and results in a separate section.

Methods

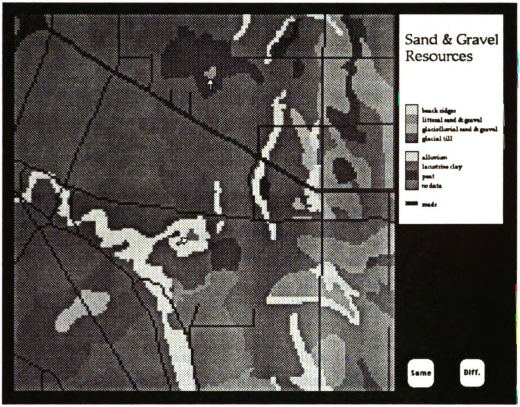
Subjects

As in Experiment 1, subjects were recruited with posters and newspaper advertising, tested individually, and paid ten dollars. Altogether, the responses of 30 subjects with normal color vision were obtained for Experiment 2. An equal number of males and females were tested and their ages ranged from 18 to 53 with a mean of 27. Seventeen subjects were non-students and 13 were students. The responses of an additional 5 subjects were omitted from the final sample because of an interrupted test session, irregular response strategies, and drowsiness. Six paid pilot subjects were tested to clarify test instructions and establish a test time of approximately 50 minutes.

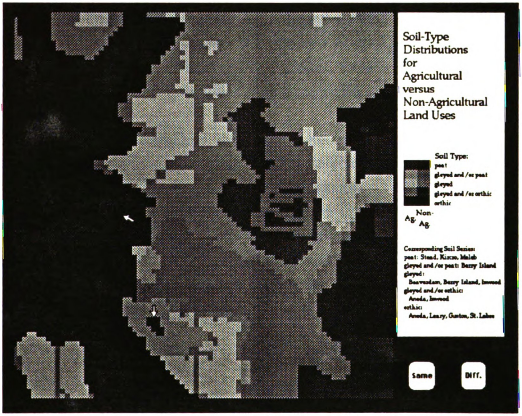
Test Displays

Figure 4.1 shows black and white versions of two test maps. The ten maps for Experiment 2 were produced with *Map II* (Pazner and others 1989). They were "recoded," "combined," "maximized," "overlayed," "spread," and otherwise manipulated variations on a set of seven geographic data layers for North St. Anne in Manitoba. These data were compiled in *Map II* format by landscape architecture students under the supervision of Richard Perron at the University of Manitoba. The North St. Anne data were made available by Dr. Pazner. Square subsections of the *Map II* maps were imported to *SuperCard*, and titles and legends were then added. Thus, all test maps were generated from real data and included accurate titles and legends.

Each map was presented with two different color schemes to produce 20 test maps. A variety of color scheme types were appropriate for the test maps. Qualitative schemes, for which nominally different categories were represented primarily with differences in hue, were used for eight maps (denoted by QL in Table 4.1). The two single-sequence (SS) schemes ranged from light to dark for single variables. Four are double-ended (DE) schemes for which darker colors of different hues emphasized both extremes of the distributions. Six bivariate schemes were included: two schemes combined quantitative (SS or DE) and qualitative (N for nominal: 'Ag.' or 'Non-Ag.' in this case) variables (SS/N and DE/N); two schemes combined qualitative categories with a nominal ('Inside' or 'Outside') variable (QL/N); and two schemes were two-variable quantitative schemes (SS/SS).



Map 18



Map 3

Figure 4.1 **Black-and-White Versions of Example Test Maps** (reduced 48%)

Table 4.1 **Experiment 2 Map Titles and Scheme Types**

Map Number	Map Title and Color Scheme Number	Scheme Type
9	Land Cover 1	QL
16	Land Cover 2	QL
11	Land Use 1	QL
2	Land Use 2	QL
18	Sand & Gravel Resources 1	QL
13	Sand & Gravel Resources 2	QL
6	Soil Series 1	QL
15	Soil Series 2	QL
14	Soil-Drainage Classes for Agricultural Land 2	SS
10	Soil-Drainage Classes for Forested Areas 2	SS
4	Soil-Drainage Classes for Agricultural Land 1	DE
1	Soil-Drainage Classes for Forested Areas 1	DE
19	Evaluation of Potential Campground Sites 1	DE
20	Evaluation of Potential Campground Sites 2	DE
7	Agricultural Land Uses and Aquifer Recharge 1	QL/N
8	Agricultural Land Uses and Aquifer Recharge 2	QL/N
17	Soil-Type Distributions for Agricultural versus Non-Agricultural Land Uses 1	SS/N
3	Soil-Type Distributions for Agricultural versus Non-Agricultural Land Uses 2	DE/N
12	Soil Drainage and Distance to Surface Water 1	SS/SS
5	Soil Drainage and Distance to Surface Water 2	SS/SS

In all cases the map colors were chosen such that the perceptual organization of hue, value, and saturation provided a logical parallel to the organization of the mapped data. The schemes were designed by Eva Frank, a geography senior who had completed a Map Design course under my direction. Colors were not chosen with the purpose of encouraging induced misinterpretation or with restriction to particular positions relative to the axes of Hunt color space. A wide variety of colors were sought in the design of the set of maps.

Once the schemes were completed, the luminance and chromaticity (**L,x,y**) of map colors were measured and converted to redness-greenness, yellowness-blueness, and lightness notations (**RG,YB,J**) using the Hunt model. I used the same parameter settings with the Hunt model as used in the first experiment (Chapter 2). The color schemes for each map were plotted in Hunt color space after the conversion to Hunt notation.

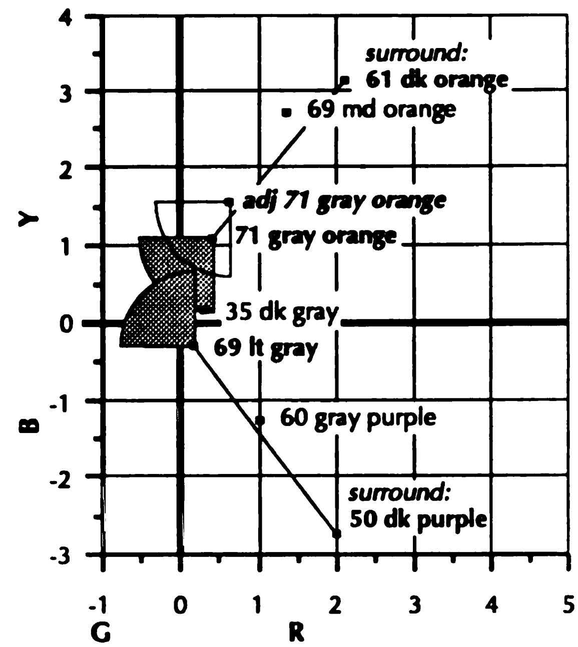
One color pair predicted to fall victim to induced confusions was chosen from each of these graphs. To make these color-pair choices, I compared induced lightness changes and the overlap of hue buffers as recommended at the close of Chapter 3. For half of the test maps, two examples of the same color were predicted to look like representatives of different categories with surround induction. For the other ten maps, selected colors that were different were predicted to look the same with induction. Thus, ten color pairs for each case, **Same** or **Different**, were chosen from the graphs. Figure 4.2 provides a demonstration of the color selection process. The **L x y**, **RG YB J**, and **R G B** specifications for the colors of each of the 20 map schemes are listed in Appendix E.

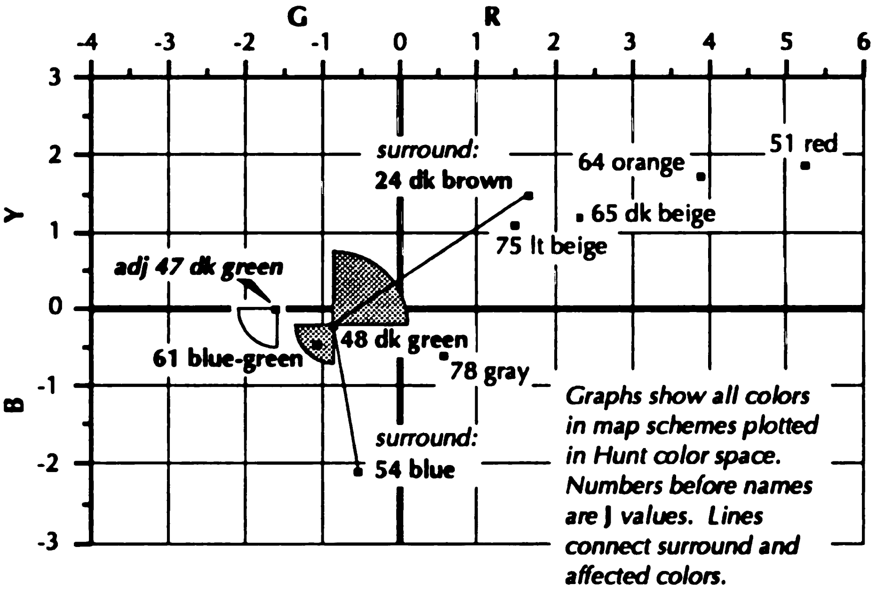
Map 4: Soil-Drainage Classes for Agricultural Land 1

Effect of adjacent dark-orange surround on gray-orange center:
draw hue buffer 1.0 in blue-green direction;
add 1 unit to gray-orange lightness for 72 J
72 = 71 + [0.135 x (center 71 - surround 61)]

Effect of adjacent dark-purple surround on light-gray center:
draw hue buffer 1.0 in green-yellow direction;
add 3 units to light-gray lightness for 72 J
72 = 69 + [0.135 x (center 69 - surround 50)]

Potential induced confusion is in overlap of induction buffers of gray orange and light gray, which both have lightnesses of 72.
These two **different** colors may look the same.
I adjusted by increasing the saturation of gray orange to prevent the buffers from overlapping.





Effect of adjacent blue surround on dark-green center:
draw hue buffer 1.0 in yellow-red direction;
subtract 1 unit from dark-green lightness for 47 J
47 = 48 + [0.135 x (center 48 - surround 54)]

Effect of opposite dark-brown surround on dark-green center:
draw hue buffer 0.5 in blue-green direction;
add 3 units to dark-green lightness for 51 J
51 = 48 + [0.135 x (center 48 - surround 24)]

Map 13: Sand and Gravel Resources 2

Potential induced confusion is in overlap of dark-green induction buffer (tinted wedge) with blue-green that has a lightness of 61 (within 12 units of dark green's induced lightness of 51).

Thus, identical dark greens may look different because one surround shifts the color perception to overlap blue-green.

I adjusted by increasing the greenness of dark green so its buffer no longer overlaps with blue green (open wedge).

Figure 4.2 Example Color-Pair Selections from Experiment 2 Map Schemes

Three versions of each map were prepared once color confusions were identified: one had surrounds predicted to induce misinterpretation of color categories, one had matching control surrounds for both colors, and one had the scheme adjusted to remove induced difficulties. The test-color patches and surrounds were superimposed on the maps. This artifice was introduced in order to control the experiment more carefully than selection from the existing distributions would allow. The two colors that were compared on the three map versions were thus the exact same shape, size, and distance apart. The surrounds for induced, controlled, and adjusted cases were also equal in shape and size between maps.

The color patches added to the maps were drawn with the characteristic stair-step edges imposed on the maps by the resolution of the original data. Arrows, of the same style used in Experiment 1, were positioned to point to the colors that subjects compared. Once the patches and arrows were positioned, the square maps were rotated or inverted differently for each of the map versions to reduce potential learning with repeated evaluations of colors in the same positions. Patches were positioned and rotations made such that the test colors were not located immediately adjacent to the map legends.

Altogether, 150 color pairs were evaluated by each subject. The practice session at the beginning of the experiment comprised the ten base maps with different schemes than those of the test. Three versions for each of 20 color schemes were evaluated twice by each subject for 120 trials. In addition, one of each map with the adjusted scheme was included in the test with easily evaluated comparison colors. These comparisons were used to provide variety that could partly obscure the structure of the test and to provide more presentations of the adjusted schemes. The test maps were presented in a unique random order to each subject.

Test Procedure

The first and second experiments were the same in overall structure. The second experiment was conducted using the same color monitor, curtained viewing area, and viewing distance used for Experiment 1. The same introductory protocol, background information questions, and color vision test were also used (Appendix A).

For each map in the test, subjects were first presented with a gray screen showing two arrows and an **OK** button. They were instructed to be sure of the arrow positions and then click on **OK** using the mouse. The gray mask was then removed to reveal the map, legend, and two oblong buttons at the lower right labelled **Same** and **Diff.** The two arrows were pointing to two map colors and subjects were instructed to "decide whether these two colors are from the same map category or different map categories." During the practice session, the test administrator explained that the legend provided a key to the map colors and that each color represented a map category. These instructions were repeated for both a qualitative scheme with ten legend colors and a quantitative/qualitative scheme with a two-by-five legend arrangement. Subjects were also told that their responses were timed and that they should work quickly but accurately. The time between pressing **OK** and pressing **Same** or **Diff.** was recorded as the response time for each trial.

The test instructions were detailed to ensure that subjects made comparisons of the map colors based on whether induced changes caused map colors to look like they belonged to a different category and not simply whether induction caused general differences in the colors. The latter effect on map colors would not hinder a directed map reader as much as the first, more relevant, concern. The complete wording of the instructions is listed in Appendix A. Subjects were asked at the end of the test to describe how they made their decisions to check that they had followed these instructions.

Once subjects clicked on the **Same** or **Diff.** button to make their response, the map was replaced with a homogeneous gray screen for approximately two seconds. The two arrows for the next map and **OK** were then superimposed on the gray, awaiting the click that initiated display of the next map. Display of the two arrows before each map allowed subjects to find them easily once they were overlayed on the map. This strategy was successful in removing search times (required to find the arrows) from the response-time data (Figure 4.3 pairs an arrow display with its map). The gray screen between maps was the same gray used between hexagonal displays in Experiment 1.

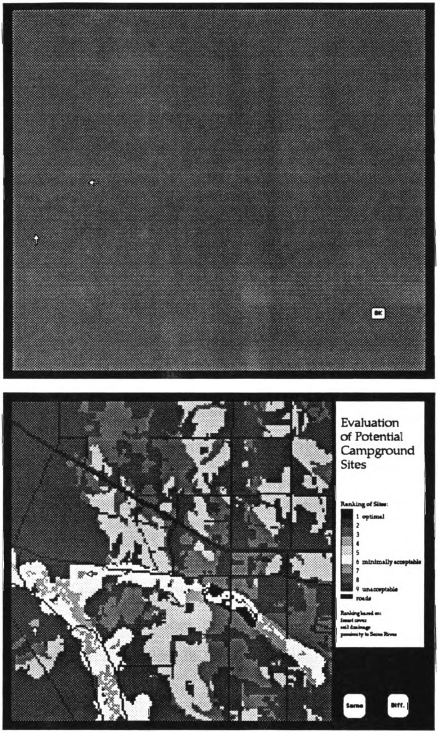


Figure 4.3 Example Arrow Display and Corresponding Map

The top display shows positions of test arrows before the induced version of Map 20 is displayed. The bottom display shows the arrows on the test map after the subject clicked on **OK**. (The map was displayed in full color.)

Hypotheses

Times for subjects to decide whether colors represented the same or different map categories were analysed to answer the questions that follow:

Does the model predict induced difficulty in color interpretation?

C < I	Response times with same-color control surrounds (C) are less than those with different inducing surrounds (I).

Does the predicted color adjustment reduce the induced difficulty?

I > A	Response times for the original colors with inducing surrounds (I) are greater than for adjusted colors with inducing surrounds (A).

Does the adjustment remove the induced difficulty?

A = C	Response times for the adjusted colors with inducing surrounds (A) are the same as those for the original colors with control surrounds (C).

The assumption underlying these hypotheses is that the longer a subject hesitated before making a response, the more difficult the decision, even though the response was correct. In the context of comparing map colors, this additional cognitive processing time may be a result of pausing to look at other map colors, looking at the legend, and looking back and forth to confirm a decision in addition to looking carefully at the colors in question.

Results

Response Time Data Processing

Tables 4.2 and 4.3 present results from Experiment 2. Table 4.2 lists the number of *incorrect* responses for each version of the map-color comparisons: induced (I), adjusted (A), and controlled (C). Recall that each subject saw each version of each map twice. If they answered correctly (**Same** or **Diff.**) on both trials then their two response times were averaged. If they answered correctly for only one of the two trials, this single response time was used in the analysis. Incorrect responses on both trials for any of the three versions resulted in removing that subject from the analysis of response times for that particular map scheme. The second column (N) of Table 4.3 lists the number of response-time triplets (I, A, and C times for one subject) that were used for analysis of each map scheme. The samples ranged from all 30 to a minimum of 13 subjects for the response-time analyses.

A missing response time (both trials incorrect) required omission of the subject because the experiment was structured for the sensitive *one-way repeated-measures analysis of variance* (ANOVA). The repeated-measures approach removes the variability between subjects from the analysis of group differences in mean response times (differences between subjects was expected but would be relevant to discussion of a question separate from generalization about the model performance). The I, A, and C versions of the maps were the fixed effect under study. Phrasing equivalent to a *repeated measures* design for one-way ANOVA is a *randomized block* design (Wilkinson 1989 p. 219) with subjects as blocks responding to the maps in a random order.

Table 4.2 Experiment 2 Maps and Number of Incorrect Responses

Each N=60

Map Number	Map Title and Color Scheme Number	Responses Incorrect I	A	C
1	Soil-Drainage Classes for Forested Areas 1	18	3	6
2	Land Use 2	3	1	2
3	Soil-Type Distributions for Agricultural versus Non-Agricultural Land Uses 2	18	2	3
4	Soil-Drainage Classes for Agricultural Land 1	3	0	0
5	Soil Drainage and Distance to Surface Water 2	7	6	2
6	Soil Series 1	5	0	0
7	Agricultural Land Uses and Aquifer Recharge 1	30	3	2
8	Agricultural Land Uses and Aquifer Recharge 2	3	2	2
9	Land Cover 1	29	8	10
10	Soil-Drainage Classes for Forested Areas 2	5	4	2
11	Land Use 1	2	1	0
12	Soil Drainage and Distance to Surface Water 1	13	14	0
13	Sand & Gravel Resources 2	24	11	0
14	Soil-Drainage Classes for Agricultural Land 2	26	22	0
15	Soil Series 2	26	27	0
16	Land Cover 2	3	4	1
17	Soil-Type Distributions for Agricultural versus Non-Agricultural Land Uses 1	24	28	3
18	Sand & Gravel Resources 1	21	22	1
19	Evaluation of Potential Campground Sites 1	37	22	1
20	Evaluation of Potential Campground Sites 2	21	19	0

Table 4.3 Experiment 2 ANOVA of Logged Response Times

The probability (p) values shown in bold are those small enough that the null version of the associated hypothesis may be rejected. The hypotheses are listed in the previous section of this chapter.

						critical probability values:			
						.050	.017	.017	.017
							(Bonferroni levels)		
	N	all	1 df contrasts						
	subj	F	F	F	F	p	p	p	p
Map		IAC	IA	AC	CI	IAC	IA	AC	CI
1	24	1.21	1.99	1.61	0.02	.309	.165	.211	.887
2	30	22.37	44.65	9.53	12.92	**.000**	**.000**	**.003**	**.001**
3	23	9.01	15.09	0.21	11.73	**.001**	**.000**	.648	**.001**
4[†]	29	12.55	20.86	0.25	16.52	**.000**	**.000**	.617	**.000**
5[†]	26	11.19	11.67	1.27	20.63	**.000**	**.001**	.265	**.000**
6	29	10.52	19.96	1.78	9.82	**.000**	**.000**	.187	**.003**
7	20	10.25	19.66	2.03	9.07	**.000**	**.000**	.163	**.005**
8	29	5.68	8.39	0.00	8.64	**.006**	**.005**	.966	**.005**
9	19	5.00	8.07	0.05	6.87	**.012**	**.007**	.827	**.013**
10[†]	28	8.23	4.86	3.41	16.42	**.001**	.032	.070	**.000**
11[††]	30	5.76	4.15	1.77	11.35	**.005**	.046	.188	**.001**
12	26	13.83	5.86	8.03	27.61	**.000**	.019	**.007**	**.000**
13	21	15.40	3.05	13.61	29.55	**.000**	.088	**.001**	**.000**
14	20	8.87	0.31	11.12	15.17	**.001**	.578	**.002**	**.000**
15[†††]	16	10.06	0.40	17.32	12.47	**.000**	.533	**.000**	**.001**
16	29	17.69	0.33	23.41	29.34	**.000**	.565	**.000**	**.000**
17[†]	15	14.83	0.08	20.91	23.51	**.000**	.785	**.000**	**.000**
18	21	8.95	0.07	14.37	12.41	**.001**	.790	**.000**	**.001**
19	13	11.35	0.00	17.06	16.98	**.000**	.992	**.000**	**.000**
20[†]	20	14.30	4.10	28.08	10.72	**.000**	.050	**.000**	**.002**

[†] removed subject with extreme residual to improve normality or variance
[††] two response-time groups not normal (gap in histogram)
[†††] variances not equal with natural logarithm (LN) transformation

Fulfillment of ANOVA Assumptions

The assumptions of ANOVA required that groups of response times for each map version were normally distributed with equal variance. The response-time groups displayed an expected skew toward shorter times with a tail of subjects taking time to think before making their decisions. Likewise, variances were greater with the longer response times for the more difficult comparisons. Of the 60 response-time groups (I, A, and C groups for 20 maps), 23 were not normal (the nonparametric Lilliefors test was used to evaluate normality). Heteroscedasticity plagued the response variances for all but four of the maps (Bartlett's test was used to compare variances).

Two techniques were used to transform these groups of response times to normality and homoscedasticity. The natural logarithms of response times for all maps were used for the ANOVA. For five maps, omission of single subjects with extreme residuals was necessary to meet the assumptions (these are marked † in Table 4.3). The log transformation and the removal of outliers produced groups that were all normally distributed with the exception of the adjusted and control groups for Map 11 (†† in Table 4.3). Examination of these histograms revealed a gap in the frequency distributions that was resistant to transformation to normality. In addition, differences in response variance for Map 15 did not yield to removal of obvious outliers or alternative transformations.

Wilcoxan signed-rank testing, a nonparametric treatment of the data, was used to confirm the ANOVA results for all of the maps with a particular eye toward discrepancies with the results for Maps 11 and 15. The Wilcoxan test was used to compare pairs of response-time groups (I to A, A to C, and C to I). The test required calculation of differences in response times for each subject and ranking the absolute values of the differences. The sum of ranks for positive and for negative time differences were compared by calculating a probability that there is no difference between the two groups of matched times.

Overall, the Wilcoxan test produced only three, out of 60, hypothesis evaluations that were different than the ANOVA results. None of these discrepancies occurred for the results for Maps 11 or 15. Because ANOVA is considered relatively robust and because of agreement with the Wilcoxan results, the ANOVA results for these two maps that do not meet the normality and homoscedasticity assumptions are reported along with results for the other maps in Table 4.3. The specifics of the supporting Wilcoxan analysis are not listed, though the three discrepancies with the ANOVA are noted in Figure 4.4 that appears in the next section.

ANOVA Results

In Table 4.3, the F ratios and associated probabilities resulting from the ANOVA are reported. The F statistic indicates the ratio of the variance of mean response times *between* groups to the variance *within* groups. The probability (p) values show the likelihood that this difference occurred by chance. For the overall comparisons of the three groups of times for each map, a probability of more than .05 occurred for only one map (listed as Map 1 in Table 4.3).

The hypotheses listed in the previous section detail *a priori* contrasts planned between the I, A, and C groups of response times. These one-degree-of-freedom contrasts are made within the ANOVA procedure (Dowdy and Wearden 1983 p. 278, Wilkinson 1989 p. 197-201). The results of the contrasts between each pair of response-time groups are listed in Table 4.3. The

Bonferroni procedure was used to establish a critical probability level of .017 for each contrast. This level is one third of the overall critical value of .05. The .017 level was used to maintain *overall* protection against a Type 1 error at .05 for the three interdependent contrasts (Wilkinson 1989 p. 201). The contrasts for which the associated null hypothesis may be rejected are shown in bold type in Table 4.3.

The maps in Table 4.3 are arranged in a systematic order. The first map was the single example for which there was not a significant difference between the I and C response-time means. The second group of eight maps (2 through 9) were those for which the I means were significantly slower than the A means. The adjusted-scheme mean for Map 2 was also significantly *faster* than the control, but the remaining seven A and C means were not significantly different. For Maps 10 and 11 there was no significant difference between either I and A or A and C means. This lack of difference indicated that the adjusted group means were between those of I and C, which were close but still significantly different (C < I). The last set of maps (12 to 20) were those for which the adjustments did not produce a significant difference between I and A mean times, with I and A both significantly slower than C.

Graphic Data Summary

Figure 4.4 provides a graphic summary of the response time data. Tukey box plots were constructed showing the three distributions for each map. Within each of the 20 frames, the left box shows the logged response times for the induction-affected colors (I), the middle box shows the A response times, and the right box shows the C times (I, A, and C labels appear below the boxes). The bold line across each box marks the median of the group times and the box encloses the interquartile range. The top and bottom edges of the box are referred to as upper and lower 'hinges.' The maximum range encompassed by the box whiskers is four times the interquartile range (1.5 of the interquartile range above and below the hinges), but the whiskers extend only to the last data value within this range. Response times beyond the whiskers are plotted with asterisks.

The box plots provide a nonparametric view of the logged data that complements the parametric ANOVA results, which are summarized at the bottom of each frame. The boxes are also shaded to echo the ANOVA results. For boxes with like shading, there was no significant difference between the means of the response times (**I = A, A = C, C = I** below boxes). Note that the *medians* were close when the *means* were not significantly different. Likewise when **I > A, A > C**, or **C < I**, the boxes have different shadings and the differences between medians support the ANOVA results. The instances in which the Wilcoxan analysis produced differing evaluations of hypotheses are indicated in parentheses above the ANOVA summary line (Maps 9, 12, and 20).

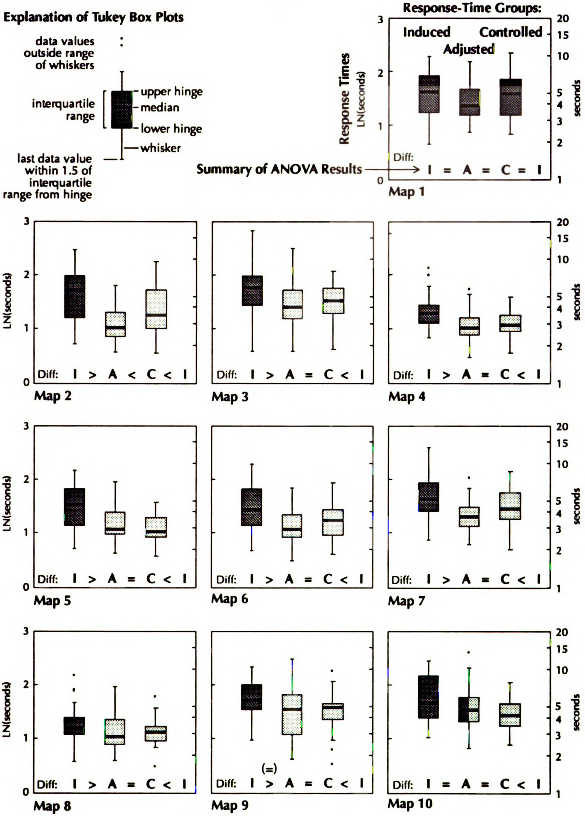


Figure 4.4 Graphic Summary of Experiment 2 Results

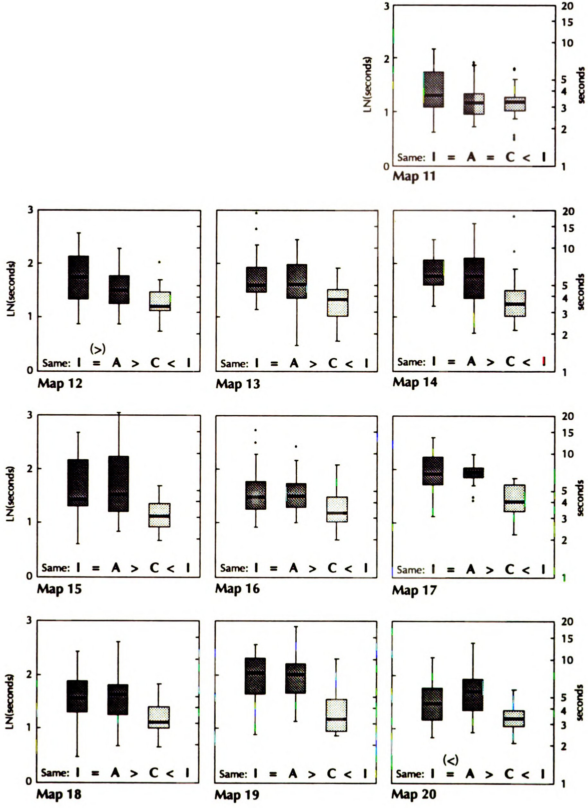


Figure 4.4 (continued)

Discussion

The null version of the first hypothesis (**C = I**) is rejected for 19 of the 20 map schemes. In all but one case (Map 1), use of the model allowed prediction of surround colors that would make comparison of the center colors more difficult (the single failure of the model is discussed later in this section). For eight maps (2 to 9), adjustments to the color schemes removed this induced difficulty. The model performed exceptionally well for these maps. For Maps 10 and 11, the adjustment reduced but did not remove the induced difficulty. For the remaining 9 maps (12 to 20), the adjustments predicted to reduce or remove the induced difficulty were not associated with a significant decrease in the mean response times (**I = A**).

Faulty Adjustments to Schemes

Structuring the 20 maps into sets with similar significance patterns revealed an interesting dichotomy in the data. Adjustments to the schemes were unsuccessful for all of the maps for which the correct response was **Same** (the two colors were representatives of the same map category). The adjustments removed the induced confusion entirely for all but two of the maps for which the correct response was **Different**. The exceptions were Map 1, for which the induced changes did not affect response times, and Map 10, for which the adjusted mean was not different than either the induced or controlled means. Labels for **Same** and **Different** question types are placed in the lower left of each frame of Figure 4.4.

Interpreting the difference between response patterns for the **Same** and **Different** questions necessitates reflection on differences in these two types of matching tasks. When centers were different in color, adjustments to the scheme changed the specific center colors on which subject attention was focussed. When centers were the same color, the notice of potential confusions with other map colors required examination of colors other than those to which the question arrows pointed. This additional attention was required to notice the effect of adjustment to the scheme; it was the difference between the two question centers and another map color that was increased.

The adjustment to all **Same** questions failed to produce a significant difference in response times. This failure indicates that subjects either were not making comparisons with additional map colors or that these comparisons also increased response times such that no improvement was evident. The relative number of incorrect responses (Table 4.2) suggest similar levels of difficulty for **I** and **A** versions of each **Same** question (supporting the first speculation of lack of additional comparisons). The greater frequencies of incorrect responses also suggest that the **Same** responses were more difficult than **Different** responses when the centers in question had different surrounds (**I** and **A**).

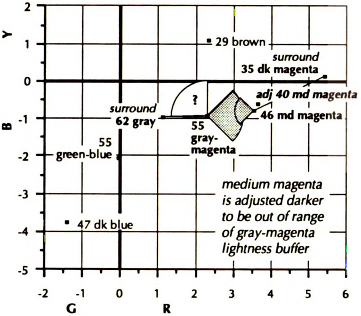
Desaturated Surround Effects

As discussed in Chapter 3, the sampling of the Hunt color space for Experiment 1 omitted center-surround combinations for which the surround was of the same hue as the center *and* was less saturated than the center. Following the model's general predictions, the less saturated surrounds should induce a shift toward the complement of the surround, which is toward the color of the surround since the center is of greater saturation. An alternative generalization, conflicting with the prediction of a complementary shift, is that induction increases the perceived difference between center and surround colors. Thus, the surround should shift the center towards greater saturation, which is not toward its complement.

Six of these situations were included in the Experiment 2 comparisons (Figure 4.5 provides example graphs). Maps 8, 11, and 17 comparisons were constructed to correspond with prediction of induced difficulty with complementary shifts. Maps 1, 15, and 19 comparisons were constructed to correspond with prediction of induced difficulty with a shift of the center color toward greater saturation and not toward the complement of the surround. Conclusions I can draw from the results for these comparisons do not have the strength of those from the more carefully controlled Experiment 1 (all color attributes were varied simultaneously in the Experiment 2 schemes).

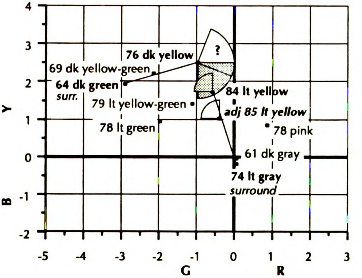
The effect of the answer (**Same** of **Different**) is confounded with variations in this nuance of the predictions for less saturated surrounds. Both types of prediction were substantiated by two **Same** response sets for each. This result reinforced the suggestion that the **Same** responses with different surrounds (**I** or **A**) were more difficult, regardless of the modelled induction effects. Maps 1 and 8 required **Different** responses. Recall that Map 1 yielded the single failure of the model's prediction of slowed response times, and it was the single **Different** case for which the complementary-shift rule was not followed in construction of the comparisons. The Map 8 comparison was constructed with complementary-shift expectations and its significant results were consistent with those for the other **Different** responses. Guidance on whether or not to maintain the complementary-shift direction for less saturated surrounds was, however, garbled by the lack of distinction for the **Same** responses.

Map 1: Soil-Drainage Classes for Forested Areas 1



Comparison constructed to test shift away from the surround (tinted buffer), rather than toward the opponent complement of the surround ('?' buffer)

Map 8: Agricultural Land Uses and Aquifer Recharge 2



Comparison constructed to test shift toward the opponent complement of the surround (tinted buffer), which is more toward the surround color than the '?' buffer

Figure 4.5 **Comparison of Desaturated Surround Predictions for Maps 1 and 8**

Summary

My overall conclusion from the Experiment 2 results is that it is easier to induce matched colors to look different than to induce different colors to look matched. Thus, colors that are already different can be adjusted more readily to repair induced ambiguity. The model accurately predicts these adjustments. When colors are the same and appear with different surrounds it is more difficult to confidently decide that they match. This study was not adequately controlled to be sure of the nature of the failure in the model adjustments for **Same** responses; an additional control presenting center colors with different surrounds that should *not* induce confusion with other map colors was needed (controls I used always had identical surrounds for color pairs).

CHAPTER 5

Conclusions and Recommendations

I have developed a set of guidelines for the prediction of surround-induced changes in color appearance. The specific rules for applying the model to a set of map colors are detailed at the close of Chapter 3. They provide an extension of the Hunt model of color appearance to predict simultaneous contrast effects between colors on complex computer-displayed maps. The model performed well in subsequent testing with a set of 20 maps, although results for **Same** and **Different** responses differed. In the course of developing the model and testing it, additional research questions came to light. I will briefly summarize results and discuss recommendations for further work in this final chapter.

Lightness Induction

Darker surrounds induce perceived lightening of a color and lighter surrounds induce darkening. To predict the effect, the contrast in lightness between a center color and its surround is calculated. A small proportion of this contrast is then added to the color of the center to estimate its perceived lightness. The greater the contrast between center and surround, the greater the lightness shift.

Lightness perceptions were, however, less affected by induction than I had expected. This may be partly because the computer monitor is not capable of creating a great range of lightnesses with which to work. The small shifts in lightness may also be due to testing simultaneous contrast effects in the context of complex displays rather than with isolated center-surround stimuli. The issue of recognizing the interplay of lightness versus brightness evaluations and contrast versus constancy effects was discussed in Chapter 1. Lightness induction was a significant effect on map color perception in this research, and I have modelled it in a manner applicable to map-reading situations.

Chromaticity Induction

The shift in hue and saturation of a color is estimated by constructing a buffer, or zone of potential perceptions, that extends from the color toward the opponent complement of the surrounding hue. If the center and surround are similar in hue, the buffer extends a greater distance than if the center and surround are dissimilar in hue. Yellow surrounds cause a color to shift toward blue and blues cause a shift toward yellow. Red surrounds cause a shift toward green and greens cause a shift toward red. These directions of shift are applied simultaneously for hues that do not fall on these opponent axes (for example, a green-blue causes a shift toward red-yellow). Chromaticity shifts that occur toward neutral are induced desaturations of color, rather than perceived hue changes.

Saturation Importance

Shifts in saturation induced by like hues were the largest shifts witnessed in this research. Saturation is generally a less well understood color attribute and is infrequently used as a primary contrast variable in the construction of map schemes. A thematic scheme that makes use of a progression from a saturated hue to neutral (white, gray, or black) does, however, require systematic saturation differences to produce an orderly scheme, though lightness changes or hue may define the look of the map. In teaching I have found that novice color users will describe the differences in hue and lightness between colors but will not describe differences along the third dimension of saturation (though they would not say that, for example, orange and brown or green and olive match). This often unrecognized variable is apparently particularly susceptible to induced shifts. This unexpected aspect of perception suggests that guidelines to pinpoint specific color interpretation difficulties would aid design because many people will not overtly identify a saturation difference, making it difficult for them to notice that the saturation difference is compromised by induction. This leads me to wonder whether the reason this dimension is readily affected by induction is *because* people pay less overt attention to it.

The result that surrounds of like hue produced greater shifts than more distant hues was also unexpected. The general interpretation of opponent effects with which I began suggested that greater contrasts along a red-green or yellow-blue axis would produce greater shifts, as would greater contrast along the lightness axis. The sampling of color space used in the first experiment did not include a sufficient range of color combinations with which to fully address this aspect of the model (more center-surround contrasts with like hues were needed).

Recommendations for Saturation Research

Additional research would reveal whether increasing saturation contrasts within like-hue combinations produce increasing or decreasing perceived shifts. The reduction of shifts with greater difference may be restricted to the qualitative differences I tested (interaction between different hues, and hue shifts with differences in lightness). A subjective interpretation of what I saw on the displays was that centers with surrounds that were very different in color were affected by induction but the interaction was so obvious that it could be compensated by subjects in their analytical evaluation of the colors.

More work could also be done to determine how desaturated and gray surrounds affect more saturated centers, as discussed in previous chapters. Is the shift still toward the surround's complement or away from the surround toward increased saturation?

Model Applications

The model is readily implemented for evaluation of a set of map colors that are specified in Hunt units of lightness (J) and relative **RG** and **YB**. Potential induced confusions between map colors are found by applying the model to each combination of map colors related as center and surround. Given the set of colors on a map, induction may cause colors to have overlapping hue perception buffers and lightness buffers. These colors will be difficult to distinguish on the map when they appear with the offending surrounds that cause the shifts. This model provides an objective check of a set of colors to warn of potential difficulties for map readers interpreting the mapped data.

The logic of a scheme may also be considered at the stage of evaluating induced shifts within a map scheme. If the potential confusions occur with center-surround combinations that would not appear on the map, the induction relationship is not of concern for that map scheme. For example, the effect of a high-elevation color on a low-elevation color may seem to be a problem, but the logic of the mapped terrain will preclude their occurrence in a contiguous center-surround relationship.

An alternative way to go about the evaluation of a scheme would be to check all center-surround combinations that do appear on the map. Three different sizes of center colors, however, did not produce significant differences in induction magnitudes in this research. This lack of difference casts doubt on the potential advantage of prediction models sensitive to size and spatial relationships between map polygons. Because maps frequently present a limited set of colors, the comparison of *all* color combinations provides a more comprehensive evaluation of the scheme and requires less calculation. Likewise, heterogeneous surrounds will produce the same or a reduced shift in appearance, and in these cases looking at the effects of all potential combinations of centers and surrounds provides a cautious but not inappropriate warning.

Recommendations for Applications Research

Investigating a greater range in color sizes is an obvious extension of this work. The model I have developed is suitable for centers ranging from one-half to one degree visual angle (within this range I found no systematic differences in susceptibility to induction). The surrounds in Experiment 1 were of a uniform large size. In comparison, the inducing surrounds on the maps in the second experiment were quite small in many cases and surround effects were still evident in the response-time analysis. Additional research could clarify the effects of the surround-size parameter on the induction relationship.

Color difference is a companion of induced change in the discrimination of colors. I have not evaluated the importance of the initial differences between map colors in my analysis of the Experiment 2 schemes, relying on careful design to meet that requirement. Basic color-difference guidelines (least practical differences; not just noticeable differences) would be an appropriate starting point in map color selection for the novice and detecting induced shifts that compromise these differences would be added assistance. The calculation of induction magnitudes may be used to establish practical color differences for map design.

Building on the Hunt model may limit use of the guidelines I have set forth. Because the final induction model provides fairly broad recommendations, the advantages of using the Hunt specifications may be outweighed by the advantages of using a simpler perceptually-scaled color system such as CIELUV. The formulae for CIELUV are more readily programmed and they are invertible, which would aid an extended model's ability to specify adjustments to colors to remove induced confusions. Testing a simpler color system against the advantages of accounting for the effect of adaptation on color appearance, for example, would be a useful extension of the research.

Final Comments

An underlying assumption of highly-focussed map design research, such as this induction work, is that cartographers bear responsibility for efficiency in the communication of mapped information. Map readers, however, share this responsibility for success of the two-way communication process. The map reading tasks used in this research were realistic but required only simple color comparisons. The overall perceptual structuring of a map scheme, in addition to the differentiability of colors, should have important effects on the success of map readers motivated to solve more complex spatial problems. The apparent difficulty of deciphering a map color scheme may also affect the perceived usefulness of a map and may affect the amount of effort that a map reader is willing to invest in using the map. Research concerned with the broader issue of color scheme effects on the understanding of spatial patterns is needed.

In developing a model of induction, I have drawn on a large body of color theory. The induction model has a deceptively simple structure because it is based on a comprehensive appearance model which in turn is based on decades of color perception research. Bringing this theory into the applied realm of map color perception offered the challenge of deciding which aspects of the experiments could be controlled and which could vary without corrupting the results. The model is intended to be applied to color combinations from throughout color space, which is an expansive goal. The perception-buffer approach for the prediction of both lightness and chromaticity induction was chosen to accommodate 90 percent of map readers, rather than limiting conclusions to perceptions of an artificial average reader. The goal of my guidelines for predicting induction is to provide a practical tool for the design of successful color schemes for computer-displayed maps.

LIST OF REFERENCES

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Agoston, G.A. 1987. *Color Theory and Its Application in Art and Design*. 2nd ed. New York: Springer-Verlag.

Agresti, A. 1981. Measures of Nominal-Ordinal Association. *Journal of the American Statistical Association* 76(375):524-529.

Appleton, B. 1990. *SuperCard 1.5*. San Diego: Silicon Beach Software Inc.

Arend, L.E., and R. Goldstein. 1987. Simultaneous Constancy, Lightness, and Brightness. *Journal of the Optical Society of America A* 4(12):2281-2285.

Bartleson, C.J. 1979. Changes in Color Appearance with Variations in Chromatic Adaptation. *Color Research and Application* 4(3):119-138.

Blackwell, K.T., and G. Buchsbaum. 1988. The Effect of Spatial and Chromatic Parameters on Chromatic Induction. *Color Research and Application* 13(3):166-173.

Bohrnstedt, G.W., and D. Knoke. 1982. *Statistics for Social Data Analysis.* Itasca, Illinois: F.E. Peacock.

Breneman, E.J. 1977. Perceived Saturation in Complex Stimuli Viewed in Light and Dark Surrounds. *Journal of the Optical Society of America* 67(5):657-662.

Brewer, C.A. 1989-90. Color Chart Use in Map Design. *Cartographic Perspectives* 4:3-10.

Brown, A. 1982. A New ITC Colour Chart Based on the Ostwald Colour System. *The ITC Journal* 2:109-118.

Campbell, J. 1991. *Introductory Cartography*. 2nd ed. Dubuque, Iowa: Wm. C. Brown.

Castner, H.W. 1980. Printed Color Charts: Some Thoughts on Their Construction and Use in Map Design. *ACSM-ASP Technical Papers, 40th Annual Meeting*:370-378.

Chevreul, M.E. 1839/1981. *The Principles of Harmony and Contrast of Colors and Their Applications to the Arts (Introduction and Notes by F. Birren).* Translated by C. Martel in 1854 from 1839 French edition. New York: Van Nostrand Reinhold.

Cox, C.W. 1980. The Effects of Background on the Equal Value Gray Scale. *Cartographica* 17(1):53-71.

De Valois, R.L., M.A. Webster, K.K. De Valois, and B. Lingelbach. 1986. Temporal Properties of Brightness and Color Induction. *Vision Research* 26(6):887-897.

Dent, B.D. 1990. *Cartography: Thematic Map Design*. 2nd ed. Dubuque, Iowa: Wm. C. Brown.

Dowdy, S., and S. Wearden. 1983. *Statistics for Research*. New York: John Wiley and Sons.

Eastman, R.J. 1986. Opponent Process Theory and Syntax for Qualitative Relationships in Quantitative Series. *The American Cartographer* 13(4):324-333.

Eichengreen, J.M. 1976. Unique Hue Loci: Induced Shifts with Complementary Surrounds. *Vision Research* 16:199-203.

Ejima, Y., and S. Takahashi. 1983. Relationship Between Chromatic Induction and Spatial Variables: An Integrated Explanation in Terms of Element-Contribution Function. *Journal of the Optical Society of America* 73(2):203-207.

Evans, R.M. 1948. *An Introduction to Color*. New York: John Wiley & Sons.

Fach, C., and L.T. Sharpe. 1986. Assimilative Hue Shifts in Color Gratings Depend on Bar Width. *Perception and Psychophysics* 40(6):412-418.

Gilchrist, A.L. 1988. Lightness Contrast and Failures of Constancy: A Common Explanation. *Perception and Psychophysics* 43(5):415-424.

Guth, S.L., R.W. Massof, and T. Benzschawel. 1980. Vector Model for Normal and Dichromatic Color Vision. *Journal of the Optical Society of America* 70(2):197-212.

Heinemann, E.G. 1972. Simultaneous Brightness Induction. In *Visual Psychophysics*. pp. 146-169. Edited by D. Jameson and L. M. Hurvich. New York: Springer-Verlag.

Hunt, R.W.G. 1982. A Model of Colour Vision for Predicting Colour Appearance. *Color Research and Application* 7(2, pt 1):95-112.

Hunt, R.W.G. 1985. Perceptual Factors Affecting Colour Order Systems. *Color Research and Application* 10(1):12-19.

Hunt, R.W.G. 1987a. *The Reproduction of Colour in Photography, Printing and Television*. 4th ed. Tolworth, England: Fountain Press.

Hunt, R.W.G. 1987b. *Measuring Colour*. Chichester, England: Ellis Horwood.

Hurvich, L.M. 1981. *Color Vision*. Sunderland, Massachusetts: Sinauer Associates.

Imhof, E. 1982. *Cartographic Relief Representation*. Translated by H. J. Steward. New York: Walter de Gruyter.

Jacobsen, A., and A. Gilchrist. 1988. Hess and Pretori Revisited: Resolution of Some Old Contradictions. *Perception and Psychophysics* 43(1):7-14.

Jameson, D., and L.M. Hurvich. 1964. Theory of Brightness and Color Contrast in Human Vision. *Vision Research* 4:135-154.

Keates, J.S. 1982. *Understanding Maps*. New York: Longman Group.

Kimerling, A.J. 1975. A Cartographic Study of Equal Value Gray Scales for Use with Screened Gray Areas. *The American Cartographer* 2(2):119-127.

Kimerling, A.J. 1985. The Comparison of Equal-Value Gray Scales. *The American Cartographer* 12(2):132-142.

Kinney, J.A.S. 1962. Factors Affecting Induced Color. *Vision Research* 2:503-525.

Krauskopf, J., Q. Zaidi, and M.B. Mandler. 1986. Mechanisms of Simultaneous Color Induction. *Journal of the Optical Society of America A* 3(10):1752-1757.

Land, E.H. 1986. Recent Advances in Retinex Theory. *Vision Research* 26(1):7-21.

Leibowitz, H., F.A. Mote, and W.R. Thurlow. 1953. Simultaneous Contrast as a Function of Separation Between Test and Inducing Fields. *Journal of Experimental Psychology* 46(6):453-456.

Livingstone, M., and D. Hubel. 1988. Segregation of Form, Color, Movement, and Depth: Anatomy, Physiology, and Perception. *Science* 240:740-749.

Marsden, A.M. 1969. An Elemental Theory of Induction. *Vision Research* 9:653-663.

Moellering, H., and A.J. Kimerling. 1990. A New Digital Slope-Aspect Display Process. *Cartography and Geographic Information Systems* 17(2):151-159.

Monmonier, M.S. 1980. The Hopeless Pursuit of Purification in Cartographic Communication: A Comparison of Graphic-Arts and Perceptual Distortions of Graytone Symbols. *Cartographica* 17(1):24-39.

Muller, J.C. 1979. Perception of Continuously Shaded Maps. *Annals of the Association of American Geographers* 69(2):240-249.

Pazner, M., K.C. Kirby, and N. Thies. 1989. *Map II Map Processor: A Geographic Information System for the Macintosh.* New York: John Wiley and Sons.

Peterson, M.P. 1979. An Evaluation of Unclassed Crossed-Line Choropleth Mapping. *The American Cartographer* 6(1):21-37.

Pitt, I.T., and L.M. Winter. 1974. Effect of Surround on Perceived Saturation. *Journal of the Optical Society of America* 64(10):1328-1331.

Robertson, P.K., and J.F. O'Callaghan. 1986. The Generation of Color Sequences for Univariate and Bivariate Mapping. *IEEE Computer Graphics and Applications* 6(2):24-32.

Robinson, A.H. 1952. *The Look of Maps: An Examination of Cartographic Design.* Madison: The University of Wisconsin Press.

Robinson, A.H. 1967. Psychological Aspects of Color in Cartography. *International Yearbook of Cartography* 7:50-61.

Robinson, A.H., R.D. Sale, J.L. Morrison, and P.C. Muehrcke. 1984. *Elements of Cartography.* 5th ed. New York: John Wiley & Sons.

Shevell, S.K., and M.F. Wesner. 1989. Color Appearance Under Conditions of Chromatic Adaptation and Contrast. *Color Research and Application* 14(6):309-317.

Somers, R.H. 1962. A New Asymmetric Measure of Association for Ordinal Variables. *American Sociological Review* 27(6):799-811.

Somers, R.H. 1980. Simple Approximations to Null Sampling Variances. *Sociological Methods and Research* 9(1):115-126.

Spiker, A., S.P. Rogers, and J. Cicinelli. 1986. Selecting Colour Codes for a Computer-Generated Topographic Map Based on Perception Experiments and Functional Requirements. *Ergonomics* 29(11):1313-1328.

Takahashi, S., and Y. Ejima. 1983. Chromatic Induction as a Function of Wavelength of Inducing Stimulus. *Journal of the Optical Society of America* 73(2):190-197.

Takasaki, H. 1969. Von Kries Coefficient Law Applied to Subjective Color Change Induced by Background Color. *Journal of the Optical Society of America* 59(10):1370-1376.

Troscianko, T.S. 1977. Effect of Subtense and Surround Luminance on the Perception of a Coloured Field. *Color Research and Application* 2(4):153-159.

Troscianko, T.S. 1982. Saturation as a Function of Test-Field Size and Surround Luminance. *Color Research and Application* 7(2, pt 1):89-94.

Valberg, A. 1974. Color Induction: Dependence on Luminance, Purity, and Dominant or Complementary Wavelength of Inducing Stimuli. *Journal of the Optical Society of America* 64(11):1531-1540.

Ware, C. 1988. Color Sequences for Univariate Maps: Theory, Experiments, and Principles. *IEEE Computer Graphics and Applications* 8(5):41-49.

Ware, C., and W.B. Cowan. 1982. Changes in Perceived Color Due to Chromatic Interactions. *Vision Research* 22:1353-1362.

Whipple, W.R., H. Wallach, and F.J. Marshall. 1988. The Effect of Area, Separation, and Dichoptic Presentation on the Perception of Achromatic Color. *Perception and Psychophysics* 43(4):367-372.

Wilkinson, L. 1989. *SYSTAT: The System for Statistics*. Evanston, Illinois: SYSTAT Inc.

Wood, M. 1968. Visual Perception and Map Design. *The Cartographic Journal* 5(1):54-64.

Yund, E.W., and J.C. Armington. 1975. Color and Brightness Contrast Effects as a Function of Spatial Variables. *Vision Research* 15:917-929.

APPENDICES

APPENDIX A

APPENDIX A

Experiment Procedures

The procedures for Experiments 1 and 2 are described in detail in this appendix. Much of the protocol is common to both experiments, and the shared procedures are designated BOTH in the script that follows. Those instructions unique to the individual experiments are headed by EXP 1 or EXP 2 labels. The four experiment administrators adjusted their phrasing for individual speaking styles, but they were trained with these scripts. All four strove for accuracy and consistency in presentations to subjects.

BOTH
Room Preparation:

Computer on (half-hour warm up)
Chair in hallway (if multiple appointments)
Answering machine to "announce" and volume to "minimum" (EXP 1)
Maps shuffled (each Exp. 2 and first half of Exp. 1)
Lights on
Fan in position and on appropriate speed
Black curtain up
Chin rest in place, with napkin cover
Window blinds open
Prepare clipboard and pencil
  consent form on top
  folded background form with vision test up
  subject number on background form
$10 in pocket

Introduction:

Welcome subject
Flip "experiment in progress" sign

EXP 1

You are participating in research on color perception. We are studying perception to improve computer-map design. I'll first test your color vision. Then you'll look at a series of colors on the computer screen and select colors similar in appearance.

EXP 2

You are participating in research on the perception of map colors. We are studying perception to improve computer-map design. I'll first test your color vision. Then you'll look at a series of maps on the computer screen and decide whether or not specific map colors match.

BOTH

This is a black curtain that will give us controlled surroundings for the computer screen.

Before we start, could you please sign this consent form. It's required by the university for experiments with people.

Hand clipboard and pencil to subject

BOTH

Color Vision Test:

Now we'll do the color vision test. Turn to the next sheet on your clipboard and fill out the questions on the left half of the page.

Turn off both overhead lights
Wait until questions completed

OK, please stand facing me behind the line over by the window. That gives us good daylight for the test. This is a standard test that you may have seen before. It will go quickly. I'll show you sets of dots and you tell me what numbers you see in them.

Open Ishihara book
Stand behind other line (75 cm)
Hold plates perpendicular to subject's line of sight with good lighting

As you look at the pages, say out-loud the numbers you see and also write them down in the right-hand column on the form you have. If you don't see a number on a page, tell me so and put an 'X' on the form.

Go through five plates. They should answer in 3 seconds - quickly. Note hesitations on form. When complete, put away plates and take forms. Write down 'normal' or 'deficient' at bottom of form.

You have normal color vision. Let's go to the experiment now.

If deficient:
According to this test, you have anomalous color vision...
don't dwell on a diagnosis

BOTH
Preparation:

Lower black curtain
Hook string from back of curtain to bookcase
Turn on both overhead lights

I have a chin rest here to position your eyes at a constant distance from the screen. Let's adjust the chair so this will be comfortable for you.

You don't need to prop your head on the chin rest - just position your head so your chin is at the bar.

Adjust chair, tighten well

Is this fan speed good for you? It takes about 45 minutes to go through this test, so it will get stuffy in here. Feel free to adjust the fan or the chair later on.

Adjust fan

Have you used a mouse before? Are you left or right handed? ... How's that?

Adjust mouse pad, center mouse

Close black curtains

EXP 1
Practice Session:

I first have a series of 10 practice images. As we work through these, you can get used to using the mouse and can ask me any questions you may have.

Press 'Start Practice' button

Each display will look something like this.

There's a center color here with an arrow to it *(point)*.

Around the outside there are 6 choices, also with arrows *(point)*.

Choose one of these 6 choices *(point again)* that **looks most similar in appearance** to this center color*(point again)*.

If familiar with mouse:
To make you're selection, click on the chosen color. The computer will record your choice.

If not:
You move the mouse on this pad with your hand and the cursor (the little hand on the screen) will move with it. To make your selection, move the hand over to the color you've chosen and press this button on the mouse *(demonstrate)*. The computer then records your choice. You'll get good at this with just a little practice.

Click to get gray between displays

When you click the mouse, the colors will disappear as they just did. This gray screen will appear between cards. The computer takes some time to put up the displays, since they are large graphics files. It also gives you a chance to rest.

Do a few of these screens to practice.

EXP 1
Practice (continued)

Interrupt at about third display or when appropriate

Be sure to look at all 6 before making your choice, but don't take too long if you're having trouble choosing. Just choose the one that looks closest in appearance to the center color. Try to go through the displays quickly.

Break on fifth

Every twenty-five cards during the real test, this break message will come up. This give you a chance to rest your eyes, shift your position, turn your neck, and such. I'll also ask you a question for our background information. I'll ask you the first background question now: *(Q 1 on form)*

When you are ready to continue with the test, click on that message on the screen.

Do you have any questions?

Continue to end of practice

Do you want to do any more practice before we start?

If not, begin experiment.

EXP 2
Practice Session:

I first have a series of 10 practice maps. As we work through these, you can get used to using the mouse and can ask me any questions you may have.

Press 'Start Practice' button

Before each map, this gray screen is displayed. On it you'll see two arrows. They will be pointing to two map colors. This little hand is the cursor you control with the mouse (*demonstrate if not familiar with mouse*). When you are sure of the positions of the arrows, move the cursor to this **OK** button and click the mouse key.

Click OK to display map

Here is an example map. The arrows point to these two colors *(point).*
I want you to decide **whether the two colors are from the same map category or from different categories.** The legend for the map, over here, provides a key to all of the map colors. On this map there are 10 different map categories.
These two colors look like they are examples from the same yellow category. One may look a bit lighter or otherwise different than the other, but since there is only one yellow in the legend you would choose **Same**. To make your response, move the cursor to the **Same** button and click. If the colors were from different categories, you would click on the **Diff.** button.

Click to get gray between maps

When you click the mouse, the colors will disappear as they just did. This gray screen will appear and then the next set of arrows will come up. Press **OK** when you are ready. After you press **OK**, leave the mouse still so you are right between the two choices. Move to your choice once you make the decision.

EXP 2
Practice (continued)

This map **also has 10 different categories** represented by 10 colors. Though these two map colors are similar, there are **two** yellow-brown colors in the legend, so you would decide that the arrows point to colors from different categories.

If there was only **one** yellow-brown in this legend, you would decide that the colors were from the **Same** category, despite their differences.

Subject makes choice.

When you press the **Same** or **Diff.** button, the computer records your choice. It **also** records the amount of time you took to respond; the time between pressing **OK** and **Same** or **Diff.** I want you to answer as quickly as you can while still being accurate. Don't race through, making sloppy choices. Do click the button, however, **as soon as** you decide whether the map categories for the colors are the same or different.

Continue with these maps to practice.

Sit back and let them go through a few.
Watch for problems and interrupt if needed.

Break on sixth

Every 35 maps during the real test, this break message will come up. This gives you a chance to rest your eyes, shift your position, turn your neck, and such. I'll also ask you a question for our background information. I'll ask you the first background question now: *(Q 1 on form)*

When you are ready to continue with the test, click anywhere on that break message. Right now we are continuing with practice maps.

Continue to end of practice

Do you have any questions?
Click on that **Start Test** button to begin the real test.

BOTH
Exit:

When they get to 'End' card, rejoice

Open curtains

EXP 2

Tell me how you went about making your decisions. What strategies did you use?

BOTH

tell them a little about our objectives

With this experiment, we're studying the perceptual effect called simultaneous contrast. Surrounding colors affect the colors you perceive. Contrast usually increases the difference between colors. If you have a gray, for example, surrounded by light colors, the gray will look darker. We're trying to predict how much color change can occur in the computer displays so we avoid designing confusing computer maps.

Do you have any comments or questions about the test?

Record on form or provide more explanation

One last formality associated with paying you; I need you to sign this form showing you received the 10 dollars.

Give them $10 and have them sign voucher

Thanks
Bye

Back-up data file to disk
Put data file into "Subject Data" folder on hard disk
Fill out log sheet.
Flip sign
Prepare for next subject

The consent form signed by all subjects:

CONSENT

1. I have freely consented to take part in a scientific study being conducted by Cynthia Brewer and her assistants. I will be participating in a study on the design of maps for computer displays.
2. The study has been explained to me, and I understand the explanation that has been given and what my participation will involve.
3. I understand that I am free to discontinue my participation at any time without penalty. I understand that the expected length of my participation is approximately one hour.
4. I understand that the results of my participation in the study will be kept in strict confidence, as will those of all other individuals participating. In other words, all participants will remain anonymous in the reporting of results. Within these restrictions, results of the study will be made available at my request.
5. I understand that my participation in the study does not guarantee any beneficial results to me. My participation will have no influence on my grades in coursework or my rating as an employee.
6. I understand that, at my request, I can receive additional explanation of the study after my participation is completed.

Signed: ___________________________ Date: ______________

This page and the next show the background information form used for both experiments. The dashed breaks on the second page group the questions asked at each of the four test breaks during an individual session. The primary purpose of these breaks was to distract the subject from their somewhat monotonous task and to provide a conversational interlude with the test administrator. I wanted to inspire care in performance of the tasks, but avoid having the subject feel uncomfortable by watching over them without ever saying a word. The response data were astoundingly clean so this strategy may have worked. The data gathered with the background questions is not used in this research, other than to provide a general summary of subject gender, age and student or non-student status.

Subject Number: ________

Background Information

Age: ________

Gender (M/F): ________

Will you be wearing corrective lenses while viewing the computer screen?

Circle one: glasses
contacts
neither

If you wear *tinted* lenses, please describe the tint:

Color Vision Test

Plate	Response
1	---------
2	---------
3	---------
4	---------
5	---------

Subject Number: ______ **Background Information**

---

1. Have you studied color or color perception? _______

(If yes:) Please describe your experience:

2a. In what ways do you commonly use computers?

2b. What types of color computer graphics are you familiar with?

3a. What types of maps do you commonly use?

3b. What types of computer-displayed maps are you familiar with?

4a. What is your occupation (major, if student)?

4b. How did you find out about our experiment? _______________

4c. Have you participated in other research experiments? _________

(If yes:) Briefly describe the experiment(s):

APPENDIX B

APPENDIX B

Experiment 1 Color Information

The extended table in this appendix provides a listing of the **RG YB J, L x y,** and **R G B** specifications for all Experiment 1 test colors.

Table B.1 Experiment 1 Color Specifications

Distance Test
Medium-lightness opponent hues

Label	Hunt: RG	YB	J	cd/m^2 L	CIE: x	y	RGB in 100's (max = 65535): R	G	B
0.0 N	**-0.01**	**0.01**	72.15	32.2	.278	.302	445	420	415
2.5 R	**2.50**	0.00	72.21	29.7	.341	.270	655	315	410
2.0	**1.99**	0.00	72.21	30.2	.329	.276	625	345	420
1.5	**1.50**	0.00	72.13	30.6	.317	.282	595	370	420
1.0 r	**0.99**	-0.01	72.11	31.1	.304	.288	545	390	420
0.5	**0.51**	0.01	72.20	31.7	.292	.295	510	415	430
-2.5 G	**-2.51**	-0.01	72.15	32.4	.217	.331	150	495	410
-2.0	**-2.01**	0.00	72.19	32.4	.230	.325	235	485	415
-1.5	**-1.49**	0.00	72.14	32.3	.243	.319	305	480	420
-1.0 g	**-0.99**	0.00	72.17	32.3	.255	.313	360	465	420
-0.5	**-0.50**	0.02	72.20	32.3	.267	.308	415	450	425
3.0 Y	-0.01	**3.00**	72.20	30.9	.411	.483	510	410	065
2.5	0.01	**2.50**	72.13	31.0	.387	.454	510	425	150
2.0	-0.01	**2.00**	72.13	31.2	.363	.425	495	425	200
1.5	-0.01	**1.50**	72.12	31.4	.341	.395	480	415	245
1.0 y	-0.01	**1.00**	72.18	31.7	.319	.364	475	430	305
0.5	-0.01	**0.50**	72.13	31.9	.298	.333	465	430	360
-3.0 B	0.02	**-3.02**	72.17	30.9	.214	.188	390	360	655
-2.5	0.01	**-2.51**	72.12	31.1	.223	.206	400	385	620
-2.0	0.00	**-1.99**	72.17	31.4	.233	.225	415	400	580
-1.5	0.00	**-1.51**	72.16	31.6	.243	.243	410	395	520
-1.0 b	0.00	**-1.01**	72.15	31.8	.254	.262	420	405	485
-0.5	0.00	**-0.49**	72.14	32.0	.266	.282	440	415	450

Direction Test Surrounds
R, G, Y, B above and secondaries:

YR	**2.12**	**2.12**	72.15	29.7	.426	.376	655	340	205
RB	**2.12**	**-2.11**	72.19	29.7	.266	.196	560	285	580
BG	**-2.12**	**-2.10**	72.14	32.0	.194	.240	150	460	570
GY	**-2.13**	**2.12**	72.17	32.0	.282	.452	260	480	220

Table B.1 (continued)

Direction Test Comparisons	**RG**	**YB**	**J**	**L**	**x**	**y**	**R**	**G**	**B**
							RGB in 100's		
Comparison choices in color directions from **r** center (e.g. r-yr is 1.0 unit in the yellow-red direction of 45° from the red center r)									
r-y	**1.00**	**0.50**	72.13	31.0	.325	.313	570	400	380
r-yr	**1.36**	**0.35**	72.15	30.7	.328	.300	590	380	390
r-r	**1.50**	**0.00**	72.13	30.6	.317	.282	595	370	420
r-rb	**1.36**	**-0.34**	72.17	30.8	.301	.269	570	380	455
r-b	**1.00**	**-0.50**	72.11	31.1	.287	.267	530	390	470
r-bg	**0.66**	**-0.34**	72.15	31.5	.284	.278	510	410	460
r-g	**0.51**	**0.01**	72.20	31.7	.292	.295	510	415	430
r-gy	**0.65**	**0.36**	72.14	31.4	.310	.311	530	405	390
Comparison choices in color directions from **g** center									
g-y	**-1.01**	**0.49**	72.22	32.3	.266	.338	367	467	380
g-yr	**-0.66**	**0.34**	72.23	32.3	.271	.326	400	460	395
g-r	**-0.50**	**0.02**	72.20	32.3	.267	.308	415	450	425
g-rb	**-0.64**	**-0.35**	72.14	32.2	.256	.294	405	452	455
g-b	**-1.00**	**-0.49**	72.21	32.3	.245	.292	360	463	465
g-bg	**-1.36**	**-0.36**	72.16	32.3	.239	.301	325	475	455
g-g	**-1.49**	**0.00**	72.14	32.3	.243	.319	305	480	420
g-gy	**-1.35**	**0.35**	72.17	32.3	.254	.334	335	482	400
Comparison choices in color directions from **y** center									
y-y	**-0.01**	**1.50**	72.12	31.4	.341	.395	480	415	245
y-yr	**0.35**	**1.35**	72.19	31.3	.345	.376	525	427	287
y-r	**0.51**	**1.00**	72.17	31.3	.334	.351	525	415	318
y-rb	**0.35**	**0.64**	72.18	31.6	.314	.333	513	425	370
y-b	**-0.01**	**0.50**	72.13	31.9	.298	.333	465	430	360
y-bg	**-0.36**	**0.66**	72.21	32.1	.290	.343	440	458	372
y-g	**-0.50**	**1.00**	72.12	31.9	.298	.365	430	463	332
y-gy	**-0.36**	**1.35**	72.14	31.7	.318	.387	453	453	290
Comparison choices in color directions from **b** center									
b-y	**0.02**	**-0.47**	69.12	28.7	.266	.282	440	415	450
b-yr	**0.35**	**-0.65**	69.84	29.2	.268	.270	455	403	468
b-r	**0.51**	**-0.99**	69.86	29.0	.263	.255	470	395	500
b-rb	**0.36**	**-1.34**	69.88	29.0	.252	.244	453	400	528
b-b	**0.01**	**-1.50**	70.79	30.1	.243	.243	410	395	520
b-bg	**-0.35**	**-1.36**	69.86	29.3	.240	.253	395	420	520
b-g	**-0.49**	**-0.99**	69.89	29.5	.246	.269	386	425	485
b-gy	**-0.34**	**-0.65**	69.83	29.5	.256	.280	405	430	465

Table B.1 (continued)

Distance Test	RG	YB	J	L	x	y	R	G	B
							RGB in 100's		
Light and dark saturated hues									
Dark reds									
6.22	**6.21**	0.00	57.56	15.3	.415	.229	655	060	320
5.22	**5.20**	0.00	57.53	15.7	.395	.238	620	140	325
4.22	**4.22**	0.01	57.49	16.1	.375	.248	566	185	320
3.22 **rd**	**3.20**	0.01	57.54	16.6	.353	.259	523	225	325
2.22	**2.22**	0.01	57.57	17.1	.330	.270	475	260	325
1.22	**1.22**	0.01	57.56	17.6	.305	.282	420	293	330
0.22	**0.22**	-0.01	57.50	18.1	.278	.294	350	325	330
Light greens									
-2.85	**-2.85**	0.00	83.92	48.0	.210	.339	0	635	510
-2.35	**-2.36**	0.00	83.90	47.9	.223	.332	235	605	500
-1.85	**-1.86**	0.01	83.95	47.9	.236	.326	330	600	513
-1.35 **gl**	**-1.35**	0.01	83.93	47.8	.249	.320	400	575	505
-0.85	**-0.84**	0.00	83.90	47.7	.261	.313	470	564	515
-0.35	**-0.36**	-0.01	83.87	47.6	.272	.307	530	555	520
Light yellows									
3.14	0.01	**3.14**	83.51	44.8	.417	.483	655	515	080
2.64	0.00	**2.63**	83.52	45.1	.394	.458	655	540	175
2.14	-0.01	**2.14**	83.52	45.4	.372	.432	620	530	235
1.64 **yl**	0.01	**1.65**	83.51	45.7	.351	.404	620	545	300
1.14	0.01	**1.14**	83.47	46.0	.329	.374	605	540	365
0.64	0.01	**0.63**	83.54	46.5	.307	.343	600	555	440
0.14	-0.01	**0.14**	83.51	46.9	.286	.312	585	550	510
Dark blues									
-7.26	0.10	**-7.26**	44.52	8.9	.161	.076	190	070	655
-6.26	-0.02	**-6.26**	44.52	9.1	.166	.096	180	145	590
-5.26	0.03	**-5.26**	44.62	9.3	.175	.118	180	175	510
-4.26 **bd**	0.00	**-4.28**	44.52	9.4	.185	.143	190	198	455
-3.26	0.00	**-3.25**	44.65	9.6	.199	.173	200	210	395
-2.26	-0.02	**-2.24**	44.61	9.7	.215	.206	210	225	345
-1.26	-0.01	**-1.26**	44.60	9.8	.234	.241	220	230	295

Table B.1 (continued)

Distance Test

	RG	YB	J	L	x	y	R	G	B
							RGB in 100's		
	RG	**YB**	**J**	**L**	**x**	**y**	**R**	**G**	**B**
Lightness									
90.7 W	0.00	0.00	**90.71**	58.5	.282	.304	655	615	595
86.1	0.01	-0.01	**86.07**	50.9	.281	.303	605	575	560
80.3	0.00	0.00	**80.27**	42.4	.280	.303	530	500	485
74.5 l	0.01	0.00	**74.54**	35.0	.279	.302	485	455	445
68.7	0.00	0.00	**68.68**	28.4	.277	.301	430	410	403
62.9	-0.01	0.01	**62.94**	22.8	.275	.300	380	365	360
57.1 m	0.01	0.01	**57.10**	17.9	.273	.298	325	310	310
51.3	0.01	0.00	**51.30**	13.8	.269	.295	280	270	275
45.5	0.00	0.00	**45.51**	10.4	.264	.292	239	240	253
39.7 d	(0.00	0.01)	**39.66**	7.6	(.258	.288)*	195	195	205
33.9	(0.00	0.00)	**33.90**	5.4	(.250	.282)*	160	160	168
28.2	(0.01	0.01)	**28.17**	3.7	(.239	.274)*	131	131	138
22.4	(0.01	0.01)	**22.36**	2.4	(.223	.262)*	100	100	105
16.9 K	(-0.03	0.00)	**16.87**	1.5	(.199	.245)*	060	060	063

Grays in control-surround patchwork

Grays have a slight blue-green color. They were grays available in the system color table and were used to avoid a distracting flash of colors when color tables between displays were changed. L,x,y is mean of 20 measurements of gray within patchwork. Grays 1, 2, 4, 6, 8, 10 are immediately adjacent to comparison hexagons and center test hexagon with control surround.

	RG	YB	J	L	x	y	R=G=B
1	-0.21	-0.19	**92.93**	62.4	.273	.299	65535
2	-0.24	-0.19	**89.04**	55.7	.272	.299	61166
3	-0.19	-0.16	**84.72**	48.8	.273	.299	56797
4	-0.20	-0.10	**75.30**	35.9	.272	.300	48059
5	-0.21	-0.08	**70.61**	30.5	.271	.300	43690
6	-0.14	0.02	**60.46**	20.6	.271	.301	34952
7	(0.02	0.19)	**42.08**	8.7	(.269	.302)*	21845
8	(0.09	0.30)	**35.54**	5.9	(.268	.303)*	17476
9	(0.50	0.63)	**19.35**	1.8	(.268	.305)*	08738
10	(0.83	0.72)	**12.82**	1.0	(.275	.305)*	0

* Colors too dark for accurate measurement of x,y chromaticity with Minolta Chroma Meter (the low luminance measures (L), however, are within meter's range)

APPENDIX C

APPENDIX C

Experiment 1 Frequency Response Data

The tables of this appendix summarize frequencies of response for all test displays from Experiment 1.

Each row provides numbers of responses for a single comparison color. For each display, six comparison colors were offered, and choices that were not selected by any of the subjects are marked with a dash (-). In a few cases choices were duplicated and these are marked with a repeated dash (--).

The columns list responses for individual test displays (N=30 in each column). The first row of column labels lists the center and inducing surround colors. For example, **l W** is a light center with a white surround and **r G** is a red center with saturated green surround (see Appendix B). The second row of column labels describes the size of the hexagons in the display grid: **11** for 11 mm, **6** for 6.5 mm, and **4** for 4.5 mm. The letter portion of these labels designates the type of test: **d** for the primary distance tests, **c** for control, **w** for white outlines, **k** for black outlines, and **v** for heterogeneous inducing surrounds (see Chapter 2 methods description for explanation of types and supporting figures).

Table C.1 Frequency Response Data for Lightness Distance Test

Lightness Distance Test: Light Center

	l control			l W					l m	
	c4	c6	c11	d4	d6	w6	k6	v6	d4	d6
90.7 W								-		
86.1	-	-	-	-			-	-	-	-
80.3	5	8	5	1	-	1	1	3	7	12
74.5 l	21	22	25	8	7	6	7	18	21	16
68.7	4	-	-	14	16	15	20	8	2	2
62.9	-	-	-	6	7	7	2	1	-	-
57.1 m	-	-	-	1	-	-	-		-	-
51.3					-	1				

(cont'd)	l d		l K				
	d4	d11	d4	d6	d11	v4	v11
90.7 W			1	1	1	1	-
86.1	1	-	5	6	5	3	-
80.3	8	14	17	16	19	16	28
74.5 l	19	14	4	7	5	8	2
68.7	1	2	3	-	-	1	-
62.9	1-	-	-	-	-	1	-
57.1 m		-					
51.3							

Table C.1 (continued)

Lightness Distance Test: Medium Center

	m control			m W				m l				m d	
	d4	d6	d11	d4	d6	d11	v4	d4	d11	w11	k11	d6	d11
86.1												-	
80.3												--	-
74.5 l			-		-								-
68.7	-	-	-	-	-		-	-	-	-		1	1
62.9	1	1	1	3	1	2	1	3	5	1	4	24	18
57.1 m	25	27	26	16	17	17	9	20	23	19	23	5	10
51.3	2	2	3	7	11	11	17	6	2	10	3		1
45.5	2	-	-	4	1	-	3	1	-	-	-		
39.7 d	-	-		-		-	-	-	-	-	-		
33.9						-					-		

(cont'd)	m K					
	d4	d6	d11	w4	k4	v6
86.1						
80.3		-	-	-	-	
74.5 l	1	-	-	-	1	
68.7	3	6	3	1	6	-
62.9	18	13	26	12	17	7
57.1 m	7	10	1	12	6	19
51.3	1	1	-	5	-	4
45.5	-					-
39.7 d						-
33.9						

Table C.1 (continued)

Lightness Distance Test: Dark Center

	d control			d W						d l	
	c4	c6	c11	d4	d6	d11	w11	k11	v11	d4	d6
62.9			-								
57.1 m			-								-
51.3	2	-	-	2		-		2	-	-	1
45.5	5	3	-	3	2	3	2	2	1	3	1
39.7 d	19	25	24	10	18	13	15	20	22	18	18
33.9	4	2	6	12	9	14	13	6	7	8	9
28.2	-	-		3	1	-	-	-	-	1	1
22.4	-	-		-	-	-	-	-	-	-	
16.9 K					-		-				

(cont'd)	d m		d K			
	d6	d11	d4	d6	d11	v4
62.9	1		-		-	
57.1 m	-		2	1	-	
51.3	-	-	7	7	7	1
45.5	5	7	7	15	15	7
39.7 d	22	20	12	6	8	14
33.9	2	3	2	1	-	7
28.2		-		-		1
22.4		-				-
16.9 K						

Table C.2 Frequency Response Data for Hue Direction Test

	r control			r R				r g				
	c4	c6	c11	d4	d6	d11	v11	d4	d6	d11	w6	k6
2.5 R	-		-	-		-	-	-	-	-	-	-
2.0	-	-	-	-	-	-	-	3	-	-	-	-
1.5	-	-	-	-	-	-	-	21	12	7	7	3
1.0 r	29	30	30	4	2	-	12	6	18	23	23	25
0.5	1	-	-	16	18	25	18	-	-	--	-	2
0.0 N	-	-	-	10	10	5	-	-	-		-	-
-0.5		-			-							

(cont'd)	rG		
	d4	d6	d11
2.5 R	-	-	-
2.0	4	3	-
1.5	16	16	12
1.0 r	10	11	17
0.5	-	-	1
0.0 N	-	-	-
-0.5			

	g control			gG					g r		
	c4	c6	c11	d4	d6	d11	w4	v4	d4	d6	d11
-2.5 G	-	-	-				-		-	-	-
-2.0	-	-	-	-	-	-	-	-	-	-	-
-1.5	-	-	1	-	-	-	-	-	13	13	5
-1.0 g	30	30	29	--	-	3	4	4	17	17	25
-0.5	-	-	-	5	11	13	16	22	-	-	-
0.0 N	-	-	-	25	18	14	10	4	-	-	-
0.5					1	-		-			

(cont'd)	g R			
	d4	d6	d11	v6
-2.5 G	-	-	-	
-2.0	-	-	-	-
-1.5	8	9	4	6
-1.0 g	22	20	24	24
-0.5	-	1	2	-
0.0 N	-	-	-	-
0.5				-

Table C.2 (continued)

	y control			y Y						y b		
	c4	c6	c11	d4	d6	d11	w4	k4	v11	d4	d6	d11
3.0 Y	-	-	-							-	-	-
2.5	-	-	-	-	-		-	-		-	-	-
2.0	-	-	-	-	-	-	-	-	-	2	1	1
1.5	6	-	-	-	-	-	-	-	3	8	11	5
1.0 y	24	29	25	-	-	1	2	3	8	19	17	23
0.5	-	1	5	20	20	22	20	21	19	1	1	1
0.0 N				10	10	7	8	6	-			
-0.5						-			-			

(cont'd)	y B			
	d4	d6	d11	v4
3.0 Y	-	-		
2.5	-	-	-	
2.0	1	-	-	1
1.5	6	15	8	11
1.0 y	22	14	22	17
0.5	1	1	-	1
0.0 N			-	-
-0.5				-

	b control			b B					b y			b Y	
	c4	c6	c11	d4	d6	d11	w6	k6	d4	d6	d11	d4	d11
-3.0 B	-	-	-						-	-	-	-	-
-2.5	-	-	-	-	--	-	-	-	-	-	-	-	-
-2.0	-	-	-	-		-	-	-	3	1	1	2	-
-1.5	1	1	-	-	-	-	-	-	9	17	6	12	8
-1.0 b	28	28	30	1	-	-	-	1	17	12	23	15	21
-0.5	1	1	-	7	8	2	7	8	1	-	-	1	1
0.0 N				22	22	28	23	21					

Table C.3 Frequency Response Data for Light and Dark Hue Distance Test

	rd control			rd R						rd G		
	c4	c6	c11	d4	d6	d11	w11	k11	v4	d4	d6	d11
6.22											-	-
5.22	-	-	-	-	-	-	-	-	-	-	-	-
4.22	2	-	-	-	-	-	-	-	-	1	3	-
3.22 rd	27	30	30	7	4	6	24	9	25	29	24	23
2.22	1	-	-	22	25	24	5	21	5	-	3	7
1.22	-	-	-	1-	1	-	1	-	-	-	-	-
0.22	-	-	-		-	-	-	-	-	-		

	gl control			gl G			gl R					
	c4	c6	c11	d4	d6	d11	d4	d6	d11	w4	k4	v11
-2.85	-	-	-	-	-	-	-	-	-	-	-	-
-2.35	-	-	-	-	-	-	-	-	-	-	-	-
-1.85	3	1	-	-	1	-	-	-	1	2	-	1
-1.35 gl	27	28	28	7	6	4	20	23	22	23	22	12
-0.85	-	1	2	23	22	26	10	7	7	5	8	17
-0.35	-	-	-	-	1	-	-	-	-	-	-	-

	yl control			yl Y			yl B				
	c4	c6	c11	d4	d6	v4	d4	d6	d11	w11	k11
3.14	-	-	-				-				-
2.64	-	-	-	-	-	-	-	-	-	-	-
2.14	1	2	-	-	-		1	4	4	3	-
1.64 yl	24	27	26	3	2	18-	13	22	19	25	27
1.14	5	1	4	21	21	12	15	4	7-	2	3
0.64	-	-	-	6	7	-	1	-		-	-
0.14				-	-	-		-	-	-	

	bd control			bd B			bd Y					
	c4	c6	c11	d4	d6	d11	d4	d6	d11	w6	k6	v11
-7.26	-	-	-	-	-		-				-	
-6.26	2	-	-	-	-	-	-	1	-	1	-	-
-5.26	5	1	7	3	1	1	2	-	6	5	1	4
-4.26 bd	20	28	18	12	7	14	15	15	22	19	19	25
-3.26	3	1	5	12	20	14	12	13	2	5	10	1
-2.26	-	-	-	3	2	1	1	1	-	-	-	-
-1.26						-		-	-	-		-

Table C.4 Frequency Response Data for Hue Direction Test

Center: r

Surround:	B	BG	G	GY	Y	YR	R	RB
r-y	17	4	2				-	-
r-yr	2	23	4	4	-		-	-
r-r	1	-	17	3	-	-		
r-rb	-	1	7	16	1	-		
r-b			-	5	7	1	-	-
r-bg			-	2	18	18	4	2
r-g	-	1		-	4	10	26	1
r-gy	10	1				1	-	27

Center: g

Surround:	B	BG	G	GY	Y	YR	R	RB
g-y	14	-	-				8	7
g-yr	15	10	-	4	1		5	4
g-r	-	16	25	8	-	2		-
g-rb	-	4	5	16	2	3		
g-b			-	2	22	16	1	
g-bg			-	-	5	5	3	-
g-g	-	-		-	-	4	9	5
g-gy	1	-				-	4	14

Center: y

Surround:	B	BG	G	GY	Y	YR	R	RB
y-y	10	9	2				1	no
y-yr	15	16	19	-				data
y-r	1	3	9	5	-	-		
y-rb	4	1	-	23	-	-	-	
y-b		1	-	2	22	4	-	
y-bg			-	-	8	15	-	
y-g	-			-	-	9	9	
y-gy	-	-			-	2	20	

Center: b

Surround:	B	BG	G	GY	Y	YR	R	RB
b-y	26	9	-			-	1	8
b-yr	2	19	13	7	1		2	-
b-r	-	1	14	10	-			-
b-rb		1	3	13	1	1		
b-b		-	-	-	7	1	-	
b-bg	-			-	11	20	5	1
b-g	-			-	10	4	14	2
b-gy	2	-	-			4	8	19

APPENDIX D

APPENDIX D

Program Code for Hunt Model of Color Appearance

The Hunt model was programmed in HyperCard and was used interactively. Program code was associated with buttons (graphics that are clicked on with the mouse to run their code or script) and with cards (the individual screens displayed as the program is used). Descriptions were also listed in fields (text blocks that are scrolled to accommodate lengthy discussions). In this appendix, each card is shown and the text and scripts associated with that card are listed in the pages that follow the card. Altogether there are six cards:

1. Hunt's Model of Color Appearance
2. Input Template
3. Calculate RGB Cone Absorption Values
4. Calculate Cone and Rod Responses
5. Intermediate Measures of Appearance
6. Sample Appearance Measures

Hunt's Model of Color Appearance

Programmed by Cynthia Brewer, Winter 1990
Calculations are for related colors only.

References:

New Input Stack

Summary of Variables:

This summary of the variables that are used in this program is organized approximately in order of appearance. Generally, Hunt's variable names are used directly or in a systematically modified form:
W: Variable names ending in "W" are measures for the reference white.
b: Variables local to a handler (subprogram) have names ending in "b" when corresponding values for both the sample and reference white will be passed to the handler with separate calls
f: Names that end in "f" are used for field names that are local to a handler and used to record on cards measures for both the sample and reference white.

Figure D.1 Card 1

Introductory Notes Field

Programmed by Cynthia Brewer, Winter 1990
Calculations are for related colors only (not isolated color patches).

References:

Hunt, R.W.G., 1987, "Measuring Colour," Chichester: Ellis Horwood, Chapter 8 (pages 146 to 173).

Calculations are numbered with the step numbers from the above description of the model. The steps have been reordered to allow a logical program flow, but they retain their original step numbers for ease of reference to the original formulation.
Page numbers in the documentation of this program are for the above primary reference unless otherwise noted.

Page references followed by "CRA'87" are to the following article:
Hunt, R.W.G., 1987, A Model of Colour Vision for Predicting Colour Appearance for Various Viewing Conditions. "Color Research and Application" 12(6): 297-314.

Page references followed by "CRA'82" are to the following article:
Hunt, R.W.G., 1982, A Model of Colour Vision for Predicting Colour Appearance. "Color Research and Application" 7(2): 95-112.

'New Input Stack' Button

```
on mouseUp
  lock screen
  go to card "input template"
  doMenu Copy Card
  doMenu New Stack...
  put the short name of this stack into newStack
  if newStack <> "hunt code" then
    doMenu Paste Card
    go to first card
    doMenu Cut Card
    unlock screen
    tabKey
  else  -- 'New Stack' dialogue box was cancelled
    go to first card
    unlock screen
  end if
end mouseUp
```

Summary of Variables Field

This summary of the variables that are used in this program is organized approximately in order of appearance. Generally, Hunt's variable names are used directly or in a systematically modified form:
W: Variable names ending in "W" are measures for the reference white.
b: Variables local to a handler (subprogram) have names ending in "b" when corresponding values for both the sample and reference white will be passed to the handler with separate calls.
f: Names that end in "f" are used for field names that are local to a handler and used to record on cards measures for both the sample and reference white.

Chromaticity coordinates for sample, reference white, and local use in handler
x y, xW yW, xb yb

Luminance factors: sample, ref W, local
bigY, bigYW, bigYb

Photopic luminance in cd/m^2: sample, ref W, local
L, LW, Lb

Luminance in cd/m^2 of adapting background: photopic, scotopic
LA, LAS

Factor for calculation of LAS
scotop

Chromatic induction factor
Nc

Brightness induction factor
Nb

Name entered on current input card
label

Full card name for current input card
dataCard

XYZ tristimulus values: local
bigXb, bigYb, bigZb

Absorptions of three cone types: sample, ref W, equal-energy illuminant (SE), local, field
R G B, RW GW BW, RE GE BE, Rb Gb Bb, Rf Gf Bf

Stimulus response functions: cones, rods
FNfp, FNfs

Stimulus response function local arguments: cones, rods
fpC, fsC

Luminance-level adaptation factors: photopic, scotopic
FL, FLS

Measures of purity of the adapting illuminant for each cone type
hr hg hb

Retinal-stage chromatic adaptation factors for each cone type
FR FG FB

Cortical-stage chromatic adaptation factors for each cone type
RD GD BD

Responses after adaptation for each cone type: sample, ref W, local, field
Ra Ga Ba, RaW GaW BaW, Rab Gab Bab, Raf Gaf Baf

Color difference signals: sample, ref W, local, field
C1 C2 C3, C1W C2W C3W, C1b C2b C3b, C1f C2f C3f

Rod response after adaptation
Sa

Photopic achromatic response
Aa

Total achromatic response: sample, ref W, local, field
A, AW, Ab, Af

Blue-Yellow response
t

Red-Green response
p

Hue angle (360 degrees): sample and local, ref W, field
hs, hsW, hsf

Hue angles for unique hues (constants)
Rhs Yhs Ghs Bhs

Eccentricity factors for unique hues (constants)
Res Yes Ges Bes

Constants for unique hue with nearest lower hue angle: hue angle, eccentricity factor
h1, e1

Constants for unique hue with nearest higher hue angle: hue angle, eccentricity factor
h2, e2

Eccentricity factor
es

Low-luminance tritanopia factor
Ft

Blueness-yellowness: sample, ref W, local, field
bigMBY, bigMBYW, bigMBYb, bigMBYf

Redness-greenness: sample, ref W, local, field
bigMRG, bigMRGW, bigMRGb, bigMRGf

Colorfulness: sample, ref W, local, field
M, MW, Mb, Mf

Relative blueness-yellowness with more convenient numbers: sample, refW
mBYc, mBYcW

Relative redness-greenness with more convenient numbers: sample, refW
mRGc, mRGcW

Brightness: sample, ref W
Q, QW

Lightness of sample
J

Chroma of sample
C

Intermediate variables used to split calculations (defined immediately before use)
divsum, conesum

Variables used to scale plot of mRG, mBY, and Q for sample:
RGpt BYpt Qpt

Scale circle proportional to Q for plotting
radius

Position circle on plot: bottom-left, top-right (RG, BY coordinates)
RGbl BYbl, RGtr BYtr

Flag to limit measures calculated and output for reference white (contains "yes" or "no")
refW

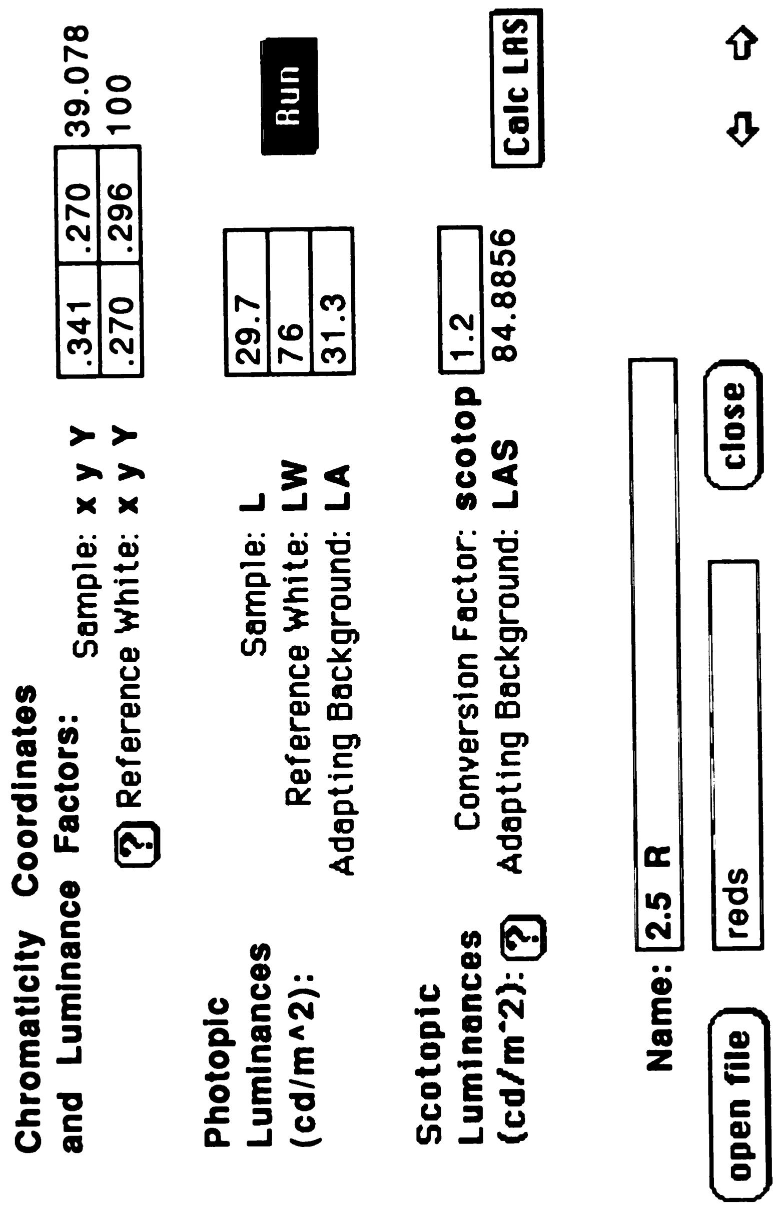

Figure D.2 Card 2

'open file' Button

```
on mouseUp
  global outfile
  put background field "Outfile name" into outfile
  open file outfile
  write outfile && the date to file outfile
  write return to file outfile
  write "xW  yW  LW  LA  scotop" to file outfile
  write return to file outfile
  write background field "xW" & "   " to file outfile
  write background field "yW" & "   " to file outfile
  write background field "LW" & "   " to file outfile
  write background field "LA" & "   " to file outfile
  write background field "scotop" to file outfile
  write return to file outfile
  write "name, RG, YB, J, L, x, y" to file outfile
  write return & return to file outfile
end mouseUp
```

'Run' Button

```
on mouseUp
  global x, y, bigY, xW, yW, bigYW, L, LW, LA, LAS
  global label, dataCard, dataStack
  put field "L" into L
  put field "LW" into LW
  put (L / LW * 100) into bigY
  put bigY into field "bigY"
  put field "x" into x
  put field "y" into y
  put field "xW" into xW
  put field "yW" into yW
  put field "bigYW" into bigYW
  put field "LA" into LA
  put field "LAS" into LAS
  put field "Name of Sample" into label
  set name of this card to "input," && label
  put the long name of this card into dataCard
  put the long name of this stack into dataStack
  set hilite of background button "Run" to true

  go to card "RGB calc" of stack "hunt code"
  CALLS1
end mouseUp
```

'Calc LAS' Button

```
on mouseUp
  -- Disagreement exists in sources on the 2.26 multiplier used to
  -- calculate LAS. 2.46 appears in "Measuring Colour" and 2.26 appears
  -- in the Hunt 1987 CRA reference. Use of 2.26 is consistent with
  -- use of the 2.26 divisor in the FLS equation (Step 15).
  -- Use of 2.26 in this calculation produces correct output for example
  -- calculations in "Measuring Colour," although neither 2.26 or 2.46
multipliers
  -- produce results matching the LAS values reported for those example
colors.

  put field "LA" into LA
  put field "scotop" into scotop
  put (LA * scotop * 2.26) into field "LAS"
  set hilite of background button 2 to true
end mouseUp
```

Calculate RGB Cone Absorption Values

Reference White:	**RW**	**GW**	**BW**
	95.419885	102.590378	134.630905
Equal-Energy Illuminant:	**RE**	**GE**	**BE**
	102.703	98.472	91.822
Sample:	**R**	**G**	**B**
	42.856398	36.943413	51.698202

Continue

RGB values based on the CIE 1931 Standard Colorimetric Observer spectral sensitivity functions.

Figure D.3 Card 3

RGB Calculations (XYZRGB)
This portion of the program is a 'card script' that is called by the 'Run' button.

```
on CALLS1
 global xW, yW, bigYW, x, y, bigY
 -- Calc for reference white
  XYZRGB xW, yW, bigYW, "RW", "GW", "BW"
 -- Calc for equal-energy illuminant (SE)
 XYZRGB 1 / 3, 1 / 3, 100, "RE", "GE", "BE"
 -- Calc for sample
 XYZRGB x, y, bigY, "R", "G", "B"
 send mouseUp to card button "continue"
end CALLS1
```

CALCULATE CONE ABSORPTION VALUES

```
on XYZRGB xb, yb, bigYb, Rf, Gf, Bf

 -- 1. Calc CIE 1931 XYZ tristimulus values (p. 168): bigXb bigYb bigZb

 put ((xb * bigYb) / yb) into bigXb
 put ((1 - xb - yb) * bigYb / yb) into bigZb

 -- 2. Calc cone absorptions: Rb Gb Bb
 -- RGB represent amounts of radiation usefully absorbed per unit area of the
 -- retina by the three cone types in a given state of adaptation.
 -- The calculations are based on the spectral sensitivity functions of
 -- the CIE 1931 Standard Colorimetric Observer. (pp. 147, 148, 168)

 put ((0.40024 * bigXb) + (0.7076 * bigYb) - (0.08081 * bigZb)) into card field Rf
 put ((-0.2263 * bigXb) + (1.16532 * bigYb) + (0.0457 * bigZb)) into card field Gf
 put (0.91822 * bigZb) into card field Bf

end XYZRGB
```

Calculate Cone and Rod Responses

Cone responses to sample after adaptation:	**Ra** 6.838442	**Ga** 6.132184	**Ba** 6.489165	
Photopic achromatic signal and color difference signals for sample:	**A** 42.844919	**C1** 0.706258	**C2** -.356981	**C3** -.349277
Cone responses to reference white after adaptation:	**RaW** 10.339826	**GaW** 10.471	**BaW** 10.86861	
Photopic achromatic signal and color difference signals for ref. white:	**AW** 56.865761	**C1W** -.131174	**C2W** -.39761	**C3W** 0.528784

Continue

Figure D.4 Card 4

Cone and Rod Response Calculations (ADAPT, CONEROD)
This portion of the program is a 'card script' that is called by the preceding 'Continue' button

```
on CALLS2
  global R, G, B, RW, GW, BW, bigY, bigYW
  ADAPT
  CONEROD R, G, B, bigY, "Ra", "Ga", "Ba", "A", "C1", "C2", "C3"
  CONEROD RW, GW, BW, bigYW, "RaW", "GaW", "BaW", "AW", "C1W",
"C2W", "C3W"
  send mouseUp to card button "continue"
end CALLS2

------------------------------------------------------------
-- STIMULUS RESPONSE FUNCTIONS:
-- Physiologic evidence supports the use of hyperbolic functions for
-- these two calculations. (pp. 148, 168 and pp. 297, 298 CRA'87)

-- CONES

function FNfp fpC
  return (40 * ((fpC^0.73) / (fpC^0.73 + 2)) + 1)
end FNfp

-- RODS
-- Lower constants and exponents than in cone function reflect the lower
-- contrast and brightness mediated by rod vision. (pp. 160, 170)

function FNfs fsC
  return (30.5 * (30 / (fsC + 30)) * (fsC^0.56 / (fsC^0.56 + 0.16)) + 0.61)
end FNfs

------------------------------------------------------------
-- CALCULATE ADAPTATION FACTORS USED IN BOTH REFERENCE
WHITE AND
-- SAMPLE CALCULATIONS

on ADAPT
  global LA, LAS, RW, GW, BW, RE, GE, BE, FL, FLS, FR, FG, FB, RD, GD, BD

  -- 4. Calc luminance-level adaptation at a retinal processing stage: FL
  -- (5LA is approximation of luminance of reference white) (pp. 149, 150, 168)
  -- The cube-root relationship used for FL is common in research relating
  -- visual response and intensity (p. 288 CRA'87).

  put (((100 * (5 * LA)) / ((5 * LA) + 10^5))^(1 / 3) + 0.001) into FL
```

```
-- 5. Calc measures of purity of the adapting illuminant: hr hg hb
-- Calc chromatic adaptation factors for retinal-stage processing: FR FG FB
-- FR, FG, and FB represent the effects that adaptation to colors of
-- lights becomes less complete as illuminant purity increases and
-- more complete as luminance increases. (pp. 149, 152, 168)
-- RE, GE, BE are the RGB values for the equal-energy stimulus (SE).
-- SE is used as an anchor in the calculation of FR, FG, FB because
-- subjective neutral points tend to be displaced from the illuminant
-- point toward SE when plotted in the chromaticity diagram. (p 302 CRA'87)

put ((RW / RE) + (GW / GE) + (BW / BE)) into divsum
put ((3 * RW / RE) / divsum) into hr
put ((3 * GW / GE) / divsum) into hg
put ((3 * BW / BE) / divsum) into hb

put (1 + LA^(1 / 3)) into LA3rd
put ((LA3rd + hr) / (LA3rd + (1 / hr))) into FR
put ((LA3rd + hg) / (LA3rd + (1 / hg))) into FG
put ((LA3rd + hb) / (LA3rd + (1 / hb))) into FB

-- 6. Factors for calculation of extremely rapid chromatic adaptation occurring
-- at a later cortical processsing stage: RD GD BD
-- These factors account for the Helson-Judd effect and the effect of
-- discounting the color of the illuminant (color constancy).
-- (pp. 149, 153, 168)
-- The FNfp and FL functions establish approximately square-root and
-- cube-root relationships respectively. Their combination relates
-- colorfulness (M) to the sixth-root of illumination level, which is
-- consistent with experimental evidence. (p. 151)

put ((FNfp(0.2 * FL * FG)) - (FNfp(0.2 * FL * FR))) into RD
put 0.0 into GD
put ((FNfp(0.2 * FL * FG)) - (FNfp(0.2 * FL * FB))) into BD

-- 15. Calc scotopic luminance-level adaptation factor: FLS
-- (pp. 161, 170)
-- LAS / 2.26 is used instead of LAS in the FLS equation because
-- LAS / 2.26 equals LA for SE (p. 306 CRA'87).

put ((100 * (5 * LAS / 2.26) / (5 * LAS / 2.26 + 10^5))^(1 / 3) + 0.001) into FLS

end ADAPT
```

```
-- CALCULATE CONE AND ROD RESPONSES FOR THE SAMPLE AND
REFERENCE WHITE

on CONEROD Rb, Gb, Bb, bigYb, Raf, Gaf, Baf, Af, C1f, C2f, C3f
  global bigYW, FL, FR, FG, FB, RW, GW, BW, RD, GD, BD, FLS

  -- 3 & 7. Calc cone responses after adaptation: Rab Gab Bab
  -- (pp. 149, 168)

  put ((FNfp(FL * FR * (Rb / RW))) + RD) into Rab
  put ((FNfp(FL * FG * (Gb / GW))) + GD) into Gab
  put ((FNfp(FL * FB * (Bb / BW))) + BD) into Bab
  put Rab into card field Raf
  put Gab into card field Gaf
  put Bab into card field Baf

  -- 16. Calc rod response after adaptation: Sa
  -- bigYb / bigYW is the photopic equivalent used to approximate scotopic
  -- luminance relative to the reference white scotopic luminance.
  -- (pp. 161, 167, 170)

  put (FNfs(FLS * (bigYb / bigYW))) into Sa

  -- 8. Calc color difference signals: C1 C2 C3
  -- Calc photopic achromatic signal: Aa
  -- Notes: C1=C2=C3=0 is the criterion for achromatic perception.
  -- C1:C2:C3 in constant ratio yields constant hue perception.
  -- Factors 2 and 20 in the calculation of Aa are based on the relative
  -- abundance of the three cone types (R:G:B is 40:20:1).
  -- (pp. 154, 169)
  -- 17a. Calc total achromatic response: Ab  (pp. 161, 170)

  put (Rab - Gab) into card field C1f
  put (Gab - Bab) into card field C2f
  put (Bab - Rab) into card field C3f
  put ((2 * Rab) + Gab + (Bab / 20)) into Aa
  put (Aa + Sa) into card field Af

end CONEROD
```

Intermediate Measures of Appearance

Sample

Hue Angle:	**hs**		
	359.933607		
B-Y, R-G, and Colorfulness:	**MBY**	**MRG**	**M**
	-.000557	0.486797	0.486797

Reference White

Hue Angle:	**hsW**		
	227.286743		
B-Y, R-G, and Colorfulness:	**MBYW**	**MRGW**	**MW**
	-.09235	-.085674	0.125971

Continue

Figure D.5 Card 5

Intermediate Measures of Appearance (INTAPP)
This portion of the program is a 'card script' that is called by the preceding 'Continue' button

```
on CALLS3
  global B, BW, bigY, bigYW, L, LW, C1, C2, C3, C1W, C2W, C3W
  INTAPP B, bigY, L, C1, C2, C3, "hs", "MBY", "MRG", "M"
  INTAPP BW, bigYW, LW, C1W, C2W, C3W, "hsW", "MBYW", "MRGW",
"MW"
  send mouseUp to card button "continue"
end CALLS3

----------------------------------------------------------
-- CALCULATE INTERMEDIATE CORRELATES OF APPEARANCE

on INTAPP Bb, bigYb, Lb, C1b, C2b, C3b, hsf, MBYf, MRGf, Mf

  -- The following calcs produce unique hues under these conditions:
  -- Red C1=C2, Yellow C1=C2/11, Green C1=C3, Blue C1=C2/4 (p. 154)

  -- 9. Calc hue angle (a correlate of perceived hue): hs (pp. 155, 169)
  -- The R-G axis, p (for protan), is the average of the color's
  -- difference from unique red (C1 - C2) and the difference from unique
  -- green (C3 - C1).  The average simplifies to 0.5(C3-C2).
  -- The B-Y axis, t (for tritan), is calculated using only the color's
  -- difference from unique yellow (C1 - C2/11) because it is more
  -- sharply defined than unique blue.  The '4.5' divisor is
  -- approximately equal to SQRT(20) and is used to account for the
  -- lower population of B cones.
  -- (pp. 101, 102 CRA'82)

  put ((-0.5) * (C3b - C2b) / 4.5) into t
  put (C1b - C2b / 11) into p

  if p = 0 and t >= 0 then
    put 90 into hs
  else if p = 0 and t < 0 then
    put 270 into hs
  else
    put ((Atan(t / p)) * (180 / pi)) into hs
     -- Arctan converts from cartesian BY,RG coordinates to the angular
     -- component of a polar coordinate expression (hs,M)
  end if
```

```
if p < 0 then
  put (hs + 180) into hs
else if t < 0 and p > 0 then
  put (hs + 360) into hs
end if

put hs into card field hsf

-- Set constants for calculation of es (calculation of H at Step 10
-- has been omitted because H is not used in the induction model).

put 20.14 into Rhs
put 0.8 into Res
put 90 into Yhs
put 0.7 into Yes
put 164.25 into Ghs
put 1.0 into Ges
put 237.53 into Bhs
put 1.2 into Bes

if hs >= 0 and hs < Rhs then
  put (hs + 360) into hs
end if

if hs >= Rhs and hs < Yhs then
  put Rhs into h1  -- hs and es for unique hue with nearest lower
  put Res into e1  --    value of hs
  put Yhs into h2  -- hs and es for unique hue with nearest higher
  put Yes into e2  --    value of hs
else if hs >= Yhs and hs < Ghs then
  put Yhs into h1
  put Yes into e1
  put Ghs into h2
  put Ges into e2
else if hs >= Ghs and hs < Bhs then
  put Ghs into h1
  put Ges into e1
  put Bhs into h2
  put Bes into e2
else   if hs >= Bhs and hs < Rhs + 360 then
  put Bhs into h1
  put Bes into e1
  put Rhs + 360 into h2
  put Res into e2
end if
```

```
-- 12. Calc eccentricity factor at hs: es (p. 156, 169)
-- es is also called the asymetry function (p. 304 CRA'87)
-- Eccentricity is a weighting of the hue's contribution to saturation
-- derived from the off-centered concentric equal saturation contours
-- in hue space.  These contours converge on the illumination point
-- in a lop-sided fashion and the smallest contours come nearer the
-- illuminant point for blues than for yellows (p. 102 CRA'82).

put (e1 + (e2 - e1) * (hs - h1) / (h2 - h1)) into es

-- 13. Calc low-luminance tritanopia factor: Ft
-- Ft accounts for loss of blueness-yellowness discrimination at low
-- luminance and is calculated to approximate unity above 100 cd/m^2
-- luminance levels. BL is the value of B obtained when the
-- tristimulus values XYZ are calculated such that Y is equal to
-- luminance in cd/m^2.  (pp. 159, 170)
-- Model testing reveals that this parameter is
-- poorly specified or poorly implemented.  For colors with high
-- purity and dominant wavelength greater than 560, Z and B values
-- approach or are equal to zero (x + y nears 1).  Therefore,
-- multiplying the MBY term by Ft causes the colors to collapse
-- onto the RG axis because MBY is reduced to zero, regardless of
-- the luminance level.  CRT chromaticities do not approach purity
-- and are of low luminance, so tentatively this factor will be
-- retained in the model.

put ((Lb / bigYb) * Bb) into BL
put (BL / (BL + 0.5)) into Ft

-- 14a. Blueness-yellowness, redness-greenness: bigMBY bigMRG
-- (t and p are calculated for hue angle at Step 9)
-- Correlate of colorfulness (extent to which hue is apparent): M
-- (pp. 157, 158, 170)
-- The bigMBY and big MRG equations are modified by removing the Nc
-- parameter (the same effect as making Nc a constant 1.0 as recommended
-- for normal viewing).  Nc is a general chromatic induction parameter
-- compensating for the overall (40 degree) surround effect on
-- colorfulness.  The bigMBY equation is also modified by changing
-- the sign of t (which would be reversed in an equation consistent
-- with the original model: bigMBY = -1 * t * es * 10/13 * Nc * Ft).
-- This last change is a personal preference for Y, instead of B,
-- as the positive ordinate.
```

```
  put (t * es * (10/13) * Ft) into bigMBY
  put (p * es * (10/13)) into bigMRG
  put bigMBY into card field MBYf
  put bigMRG into card field MRGf
  put (((bigMBY^2) + (bigMRG^2))^0.5) into card field Mf

end INTAPP
```

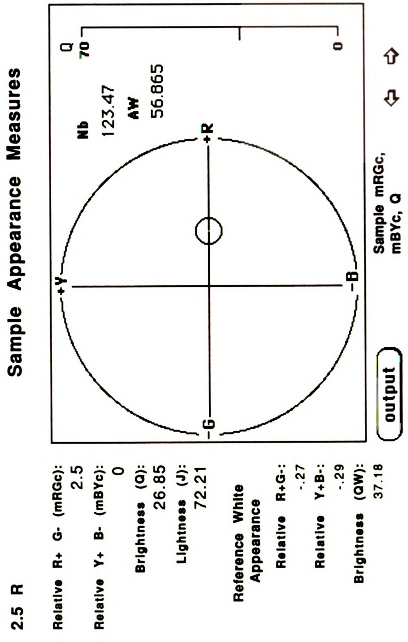

Figure D.6 Card 6

Final Results (FINAL)

This portion of the program is a 'card script' that is called by the preceding 'Continue' button

```
on CALLS4
  global label, dataStack, bigMBY, bigMRG, Ra, Ga, Ba, M, A, bigMBYW,
bigMRGW, RaW, GaW, BaW, MW, AW

  -- create new results card to carry data
  lock screen
  doMenu Copy Card
  go to last card of dataStack
  doMenu Paste Card
  set the script of this card to empty
  set name of this card to ("results," && label)
  put label into field "name of sample"
  unlock screen

  FINAL bigMBY, bigMRG, Ra, Ga, Ba, M, A, "no", "mBYc", "mRGc", "Q"
  FINAL bigMBYW, bigMRGW, RaW, GaW, BaW, MW, AW, "yes",
"mBYcW", "mRGcW", "QW"
end CALLS4

-----------------------------------------------------------
-- CALCULATE THE REMAINING CORRELATES OF APPEARANCE FOR
THE REFERENCE
-- WHITE AND SAMPLE

on FINAL bigMBYb, bigMRGb, Rab, Gab, Bab, Mb, Ab, refW, mBYcf, mRGcf,
Qf
  global MW, AW, L

  -- Measures that normally increase with increasing levels of
  -- illumination:  bigMBY, bigMRG, M, Mc, Q
  -- At extremely high or extremely low illumination, the rate of
  -- increase gradually reduces to zero.
  -- Measures that normally remain constant with increasing illuminantion:
  -- hs, H, mBYc, mRGc, s, J, C
  -- (p. 304 CRA'87)

  put (Rab + Gab + Bab) into conesum
  put (bigMBYb / conesum * 100) into mBYc
  put (bigMRGb / conesum * 100) into mRGc
```

```
-- 17b. Use total achromatic response plus colorfulness: A + M
-- 18. Calc correlate of brightness: Q
-- (pp. 162, 170)
-- Equal LOG(Q) differences correlate with equal steps perceived
-- brightness (p. 308 CRA'87)
-- QW is brightness of reference white
-- AW is total achromatic response to reference white
-- Nb is the general induction factor for brightness from a 40 degree
-- surround.
-- Nb approximations:  (p. 167)
--   400   small areas in uniform surrounds
--   100   normal scenes
--    30   television and VDU displays in dim surrounds
--    10   projected photographs in dim surrounds
--     5   arrays of adjacent colors in dark surrounds
-- As illuminanance increases, N1 represents the increase in brightness
-- and N2 represents the increase in contrast (p. 308 CRA'87).

-- Dr. Hunt said (personal communication April 1989) that
-- the Nb factor was producing inaccurate results in further model
-- testing.
-- Thus, these two equations were used when first selecting Exp I colors:
-- put (Ab + Mb) into Q
-- put (AW + MW) into QW
-- Initially, I wrongly omitted the N1 and N2 factors to leave all
-- induction prediction to additions from my induction model, but that
-- omission produces a non-uniform lightness scale, which is undesirable

-- (February 1991)    p. 309 CRA '87
-- If the values of AW and Nb are such that AW * Nb^1.23 = 21257, then
-- the J expression will reduce to CIE 1976 L* (with M=0 ... ).

-- Solve for Nb:
put ((21257 / AW )^.813) into Nb
put Nb into background field "Nb"
put AW into background field "AW"

-- Use original equations for Q and QW:
put ((AW^0.5) / (5.33 * (Nb^0.13))) into N1
put ((AW^1.9) * (Nb^0.362) / 2080) into N2
put (((Ab + Mb) * N1) - N2) into Q
put (((AW + MW) * N1) - N2) into QW
```

```
-- 19. Calc correlate of lightness (brightness relative to brightness
-- of reference white): J
-- J is similar to CIELUV 1976 L* when the range of LW = 100 to 10000
-- cd/m^2 and Nb is 100.  Maximum J is approximately 100 (pp. 162, 163, 171)
-- (see Q discussion for specific manipulations to set J to L*)

put (100 * Q / QW) into J


-- Final output

set numberFormat to (##0.##)
put mBYc into field mBYcf
put mRGc into field mRGcf
put Q into field Qf

if refW is "no" then
  put J into field "J"

  -- plot rel RG, rel BY, Q
  put round(281 + (mRGc * 17)) into RGpt
  put round(185 - (mBYc * 17)) into BYpt
  choose pencil tool
  click at RGpt, BYpt
  put round(Q^0.5 * 2) into radius
  put (RGpt - radius) into RGbl
  put (RGpt + radius) into RGtr
  put (BYpt + radius) into BYbl
  put (BYpt - radius) into BYtr
  choose oval tool
  drag from RGbl,BYbl to RGtr,BYtr
  put (287 - (round(Q * 2.86))) into Qpt
  choose line tool
  drag from 483,Qpt to 473,Qpt
  choose browse tool
end if

end FINAL
```

'output' Button

```
on mouseUp
  global outfile, dataCard
   put background field "mRGc" into RG
   put background field "mBYc" into BY
   put background field "J" into J
   put round(J) into Jlabel
  go to dataCard
   write"  " & Jlabel to file outfile
   write " " & background field "Name of Sample" & "," to file outfile

   write RG & ", " to file outfile
   write BY & ", " to file outfile
   write J & ", " to file outfile

   write background field "L" & ", " to file outfile
   write background field "x" & ", " to file outfile
   write background field "y" to file outfile
   write return to file outfile
end mouseUp
```

APPENDIX E

APPENDIX E

Experiment 2 Color Information

The listing in this appendix summarizes the map color schemes used for Experiment 2. The map number, map title, and a summary of the center-surround pairings for each map is given. Tables list **RG YB J, L x y, R G B** specifications for the colors. The legend category names and approximate descriptive color names are also listed (the second set of color names for each map have rounded lightness-number prefixes).

After the Experiment 2 work was completed, we moved the computer to another location and the colors on the screen changed markedly with the different voltage at the new electrical outlet. This change provides a reminder of the variation to which commercial monitors are subject. The measured specifications listed are a much more precise documentation of the test colors than the **R G B** numbers, which should not be trusted for precise replication of the test schemes.

Table E.1 Experiment 2 Color Specifications

Map 1: Soil-Drainage Classes for Forested Areas 1 DE

Correct response for all trials is **Different**

Induced trial:	gray surrounds gray magenta
	dark magenta surrounds medium magenta
Controlled trial:	dark magenta surrounds gray magenta and md magenta

Map Category	Color Name	In 100's R	G	B
Soil Drainage:				
very poor	dk blue	63	335	437
poor	gray blue	284	403	437
poor-imperfect *(s: gray magenta)*	gray	437	437	437
imperfect	**gray magenta**	437	323	376
imperfect-well	**md magenta**	398	213	293
adjust by decreasing lightness:		344	171	245
well drained *(s: md magenta & c.)*	dk magenta	347	77	182
non-agricultural land	brown	220	156	110

Color Name	Hunt: RG	YB	J	cd/m² L	CIE: x	y
47 dk blue	-1.36	-3.74	46.59	10.7	0.174	0.172
55 gray blue	-0.01	-2.06	55.48	16.3	0.226	0.219
62 gray	1.16	-0.95	62.43	21.5	0.275	0.246
55 gray-magenta	2.34	-0.94	55.10	15.3	0.298	0.230
46 md magenta	3.57	-0.77	46.15	9.74	0.326	0.218
40 md magenta adj	3.70	-0.61	40.14	7.09	0.332	0.217
35 dk magenta	5.47	0.15	35.17	5.12	0.404	0.223
29 brown	2.38	1.10	29.06	3.71	0.382	0.312

Table E.1 (continued)

Map 2: Land Use 2 QL

Correct response for all trials is **Different**

Induced trial:	light orange surrounds light cyan
	dark cyan surrounds medium cyan
Controlled trial:	light orange surrounds light and medium cyan

Map Category		Color Name	In 100's R	G	B
residential		dk orange	569	262	49
commercial	*(s: lt cyan & control)*	lt orange	655	383	142
farm buildings		green	154	500	162
livestock: fowl	*(s: md cyan)*	dk cyan	59	384	325
livestock: cattle		**md cyan**	184	564	432
other agricultural		**lt cyan**	410	578	448
adjust by desaturating:			477	551	492
recreational		gray	530	581	647
wildlife reserve		magenta	526	162	269

Color Name	Hunt: RG	YB	J	cd/m^2 L	CIE: x	y
61 dk orange	2.94	3.20	61.09	19.2	0.505	0.421
73 lt orange	1.76	2.85	72.72	30.4	0.451	0.420
68 green	-2.97	2.77	68.50	28.0	0.274	0.510
58 dk cyan	-2.46	0.02	58.36	19.0	0.213	0.328
76 md cyan	-2.39	0.30	75.68	36.6	0.227	0.346
80 lt cyan	-1.08	0.49	79.95	42.0	0.266	0.340
79 lt cyan adj	-0.48	0.14	79.21	41.0	0.272	0.315
85 gray	-0.19	-0.87	84.45	48.0	0.256	0.271
55 magenta	4.34	0.42	54.61	14.2	0.395	0.262

Table E.1 (continued)

Map 3: Soil-Type Distributions for Agricultural versus Non-Agricultural Land Uses 2 DE/N

Correct response for all trials is **Different**
Induced trial: light yellow-green surrounds dark orange
medium red surrounds dark red
Controlled trial: light yellow-green surrounds dark orange and dark red

Map Category	Color Name	In 100's R	G	B
Soil Type:				
Ag.				
peat	md green	0	228	0
gleyed and/or peat *(s: dk or & c.)*	lt yellow-green	341	444	161
gleyed	gray	564	450	412
gleyed and/or orthic	lt orange	530	262	206
orthic *(s: dk red)*	md red	392	22	11
Non-Ag.				
peat	dk green	0	120	0
gleyed and/or peat	dk yellow-green	254	331	120
gleyed	dk gray	400	320	293
gleyed and/or orthic	**dk orange**	341	121	90
adjust toward yellow:		381	152	62
orthic	**dk red**	280	160	8

Color Name	Hunt: RG	YB	J	cd/m^2 L	CIE: x	y
29 md green	-1.48	1.94	29.00	3.89	0.284	0.534
57 lt yellow-green	-0.14	1.94	56.87	17.3	0.351	0.427
67 gray	1.97	-0.10	67.28	25.3	0.323	0.271
54 lt orange	4.11	1.44	54.30	14.1	0.439	0.309
36 md red	6.76	2.23	36.42	5.45	0.601	0.339
16 dk green	0.25	1.03	15.77	1.33	0.300	0.422
45 dk yellow-green	0.00	1.80	45.39	10.1	0.350	0.425
52 dk gray	2.02	-0.03	52.06	13.5	0.321	0.268
36 dk orange	4.99	1.93	35.54	5.32	0.507	0.323
39 dk orange adj	5.04	2.38	38.99	6.55	0.542	0.357
27 dk red	5.60	1.78	27.47	3.13	0.573	0.333

Table E.1 (continued)

Map 4: Soil-Drainage Classes for Agricultural Land 1 DE

Correct response for all trials is **Different**

Induced trial:	dark orange surrounds gray orange
	dark purple surrounds light gray
Controlled trial:	dark purple surrounds gray orange and light gray

Map Category		Color Name	In 100's R	G	B
Soil Drainage:					
very poor	*(s: gray orange)*	dk orange	535	302	9
poor		md orange	588	386	138
poor-imperfect		**gray orange**	513	441	308
adjust toward orange:			545	433	262
imperfect		**lt gray**	437	437	437
imperfect-well		gray purple	406	325	437
well drained	*(s: lt gray & control)*	dk purple	345	195	437
non-agricultural land		dk gray	175	175	175

Color Name	Hunt: RG	YB	J	cd/m² L	CIE: x	y
61 dk orange	2.15	3.16	60.56	19.1	0.487	0.441
69 md orange	1.41	2.73	68.62	26.5	0.437	0.425
71 gray orange	0.46	1.09	70.87	29.9	0.336	0.357
71 gray orange adj	0.66	1.55	71.08	29.8	0.362	0.379
69 lt gray	0.19	-0.27	68.96	28.5	0.274	0.287
60 gray purple	1.05	-1.25	60.12	19.6	0.264	0.236
50 dk purple	2.04	-2.72	49.73	11.9	0.244	0.172
35 dk gray	0.35	0.19	35.28	5.82	0.271	0.290

Table E.1 (continued)

Map 5: Soil Drainage and Distance to Surface Water 2 SS/SS

Correct response for all trials is **Different**
Induced trial: medium cyan surrounds light cyan
light magenta surrounds light purple
Controlled trial: light magenta surrounds light cyan and light purple

Map Category		Color Name	In 100's R	G	B
Soil Drainage:					
Distance to Surface Water in Kilometers:					
poor					
0-1		**lt purple**	594	513	620
adjust by increasing lightness:			636	578	655
1-2		**lt cyan**	375	490	570
2-3	*(s: lt cyan)*	md cyan	157	466	521
imperfect					
0-1	*(s: lt purple & control)*	lt magenta	624	347	470
1-2		md purple	404	258	504
2-3		blue	185	235	454
well drained					
0-1		md magenta	655	180	320
1-2		magenta-purple	434	92	354
2-3		purple	214	3	388

Color Name	Hunt: RG	YB	J	cd/m² L	CIE: x	y
76 lt purple	1.22	-1.32	76.42	35.6	0.270	0.234
81 lt purple adj	1.09	-1.09	80.92	41.5	0.274	0.244
68 lt cyan	-0.11	-1.91	68.11	27.2	0.232	0.229
62 md cyan	-1.69	-2.35	62.21	21.9	0.197	0.228
67 lt magenta	2.90	-0.71	67.34	24.6	0.322	0.237
55 md purple	2.17	-2.83	54.62	14.8	0.246	0.170
45 blue	0.25	-4.04	44.99	9.62	0.192	0.148
60 md magenta	5.29	0.27	59.79	17.2	0.409	0.248
46 magenta-purple	4.70	-1.84	45.92	9.27	0.313	0.173
33 purple	2.27	-4.71	33.46	4.77	0.202	0.104

Table E.1 (continued)

Map 6: Soils Series 1 QL

Correct response for all trials is **Different**
Induced trial: light purple surrounds yellow
dark green surrounds light green
Controlled trial: light purple surrounds yellow and light green

Map Category		Color Name	In 100's R	G	B
Red River		dk purple	494	67	513
Marquette & Kline		pink	655	223	525
Kline		orange	646	269	54
Osbourne		**yellow**	610	655	60
adjust toward orange:			655	579	119
Inwood & Meleb		cyan	151	543	527
Berry Is. & Beaverdam		blue	188	322	547
Inwood & Beaverdam		md purple	422	330	607
Inwood	*(s: yellow & control)*	lt purple	548	438	590
Leary		**lt green**	441	655	51
Gunton		md green	171	482	179
Aneda & Gunton	*(s: lt green)*	dk green	28	383	43

Color Name	Hunt: RG	YB	J	cd/m² L	CIE: x	y
53 dk purple	4.34	-3.27	52.55	12.6	0.270	0.140
66 pink	3.86	-1.56	66.38	22.9	0.313	0.198
65 orange	3.57	3.27	64.57	21.7	0.518	0.406
88 yellow	-0.89	3.49	87.72	51.5	0.390	0.513
84 yellow adj	-0.08	3.01	84.19	45.9	0.407	0.478
74 cyan	-2.29	-0.88	73.92	34.4	0.208	0.289
58 blue	-0.88	-3.45	57.54	17.7	0.191	0.182
65 md purple	1.00	-2.71	65.02	23.4	0.233	0.188
75 lt purple	0.94	-1.17	75.36	34.7	0.268	0.243
84 lt green	-1.97	3.67	84.27	46.9	0.351	0.543
66 md green	-2.68	2.48	66.40	25.9	0.274	0.486
56 dk green	-3.34	3.28	56.24	17.1	0.279	0.576

Table E.1 (continued)

Map 7: Agricultural Land Uses and Aquifer Recharge 1 QL/N

Correct response for all trials is **Different**

Induced trial:	pink surrounds gray yellow
	gray blue surrounds gray green
Controlled trial:	pink surrounds gray yellow and gray green

Map Category	Color Name	In 100's R	G	B
Aquifer Recharge Zone:				
Inside				
hay	yellow	621	621	61
crops	orange	655	460	87
pasture	green	474	633	144
non-agricultural *(s: gray y & c.)*	pink	655	524	536
Outside				
hay	**gray yellow**	483	483	47
adjust toward orange:		522	452	0
crops	gray orange	500	352	66
pasture	**gray green**	368	492	112
non-agricultural	gray pink	483	387	395
agricultural clearing in progress *(s: gray gn)*	gray blue	271	513	443

Color Name	Hunt: RG	YB	J	cd/m² L	CIE: x	y
84 yellow	-0.49	3.36	83.74	45.4	0.403	0.502
75 orange	1.13	3.17	74.80	33.0	0.451	0.453
81 green	-1.33	3.08	81.15	42.5	0.352	0.500
81 pink	0.97	-0.13	80.81	41.7	0.301	0.284
71 gray yellow	-0.40	3.18	70.86	29.6	0.401	0.500
70 gray yellow adj	0.13	3.12	69.94	28.4	0.423	0.488
63 gray orange	1.10	2.97	62.63	21.2	0.445	0.454
69 gray green	-1.31	3.01	68.84	27.9	0.350	0.502
66 gray pink	0.98	-0.05	66.01	24.9	0.300	0.285
70 gray blue	-1.54	-0.31	70.18	30.1	0.235	0.305

Table E.1 (continued)

Map 8: Agricultural Land Uses and Aquifer Recharge 2 QL/N

Correct response for all trials is **Different**

Induced trial:	dark green surrounds dark yellow
	light gray surrounds light yellow
Controlled trial:	light gray surrounds dark yellow and light yellow

Map Category		Color Name	In 100's R	G	B
Aquifer Recharge Zone:					
Inside					
hay		**dk yellow**	446	530	189
crops		dk yellow-green	256	495	210
pasture	*(s: dk yellow)*	dk green	114	461	220
non-agricultural		dk gray	353	353	353
Outside					
hay		**lt yellow**	548	612	317
adjust by desaturating:			559	607	405
crops		lt yellow-green	424	577	338
pasture		lt green	290	584	383
non-agricultural	*(s: lt y & c.)*	lt gray	480	480	480
agricultural clearing in progress		pink	638	478	391

Color Name	Hunt: RG	YB	J	cd/m^2 L	CIE: x	y
76 dk yellow	-0.95	2.52	75.87	35.8	0.344	0.464
69 dk yellow-green	-2.12	2.24	69.47	29.0	0.286	0.460
64 dk green	-2.84	1.94	64.50	24.2	0.250	0.451
61 dk gray	0.10	-0.05	60.74	20.8	0.275	0.295
84 lt yellow	-0.56	1.72	84.37	47.4	0.328	0.412
85 lt yellow adj	-0.36	1.04	84.61	48.1	0.308	0.369
79 lt yellow-green	-1.09	1.40	79.03	40.4	0.294	0.395
78 lt green	-1.93	0.96	77.61	38.9	0.255	0.377
74 lt gray	0.10	-0.18	74.32	34.6	0.276	0.293
78 pink	0.90	0.83	78.44	38.4	0.339	0.334

Table E.1 (continued)

Map 9: Land Cover 1 QL

Correct response for all trials is **Different**
Induced trial: dark brown surrounds dark blue
yellow surrounds light blue
Controlled trial: dark brown surrounds both blues

Map Category		**Color Name**	**In 100's R**	**G**	**B**
non-vegetated		gray	327	323	328
forested recreation site		magenta	604	206	323
mixedwood		lt brown	371	271	175
hardwood	*(s: dk blue & control)*	dk brown	224	112	0
willow and shrub		**dk blue**	56	251	336
adjust by desaturating:			152	259	310
prarie and meadow		**lt blue**	84	376	500
cultivated hayland	*(s: lt blue)*	yellow	606	612	319
cultivated cropland		lt green	326	483	48
pasture		dk green	224	332	33
agricultural land being cleared		purple	287	138	371

Color Name	**Hunt: RG**	**YB**	**J**	**cd/m^2 L**	**CIE: x**	**y**
57 gray	0.18	-0.09	57.08	17.8	0.274	0.291
60 magenta	4.26	0.27	60.50	18.2	0.388	0.259
53 lt brown	0.97	1.62	52.96	14.3	0.370	0.377
30 dk brown	2.34	1.79	29.95	3.94	0.489	0.429
45 dk blue	-1.66	-2.29	44.92	10.0	0.187	0.221
47 dk blue adj	-1.05	-1.38	46.54	10.9	0.215	0.250
60 lt blue	-2.03	-2.58	59.61	19.7	0.186	0.221
86 yellow	-0.26	1.68	85.67	49.1	0.340	0.408
69 lt green	-1.95	3.54	69.10	28.2	0.349	0.548
54 dk green	-1.78	3.14	53.50	15.0	0.345	0.551
42 purple	2.39	-2.90	41.57	7.80	0.241	0.157

Table E.1 (continued)

Map 10: Soil-Drainage Classes for Forested Areas 2 SS

Correct response for all trials is **Different**
Induced trial: dark gray surrounds medium-light gray
white surrounds light gray
Controlled trial: white surrounds medium-light gray and light gray

Map Category		**Color Name**	**In 100's R**	**G**	**B**
Soil Drainage:					
very poor		black	0	0	0
poor	*(s: md-lt gray)*	dk gray	175	175	175
poor-imperfect		md gray	284	284	284
imperfect		**md-lt gray**	437	437	437
adjust by decreasing lightness:			381	381	381
imperfect-well		**lt gray**	568	568	568
well drained	*(s: lt gray & control)*	white	655	655	655
not forested		gray magenta	314	204	229

Color Name	**Hunt: RG**	**YB**	**J**	**cd/m^2 L**	**CIE: x**	**y**
13 black	0.94	0.81	12.75	0.97	0.294	0.320
37 dk gray	0.29	0.20	37.11	6.50	0.272	0.293
51 md gray	0.28	-0.07	51.46	13.8	0.274	0.288
70 md-lt gray	0.14	-0.25	70.42	30.1	0.274	0.289
64 md-lt gray adj	0.18	-0.19	63.64	23.3	0.274	0.289
83 lt gray	0.12	-0.31	83.42	46.6	0.275	0.289
91 white	0.12	-0.32	90.71	58.1	0.276	0.289
46 gray magenta	1.64	0.18	46.21	10.3	0.317	0.279

Table E.1 (continued)

Map 11: Land Use 1 QL

Correct response for all trials is **Same**
Induced trial: dark purple surrounds orange
beige surrounds orange
Controlled trial: beige surrounds both oranges

Map Category		Color Name	In 100's R	G	B
residential		lt purple	425	322	655
commercial	*(s: orange)*	dk purple	215	122	409
farm buildings		red	453	0	90
livestock: fowl		**orange**	655	326	121
livestock: cattle		**brown**	530	284	149
adjust by desaturating:			530	332	223
other agricultural	*(s: orange & c.)*	beige	608	459	188
recreational		pink	565	282	376
wildlife reserve		green	32	474	331

Color Name	Hunt: RG	YB	J	cd/m^2 L	CIE: x	y
66 lt purple	1.07	-3.09	66.00	24.1	0.227	0.175
39 dk purple	1.45	-4.31	39.37	6.93	0.201	0.126
43 red	6.68	2.28	42.99	7.80	0.550	0.313
69 orange	2.65	2.94	68.89	26.0	0.477	0.405
61 brown	2.41	2.37	60.86	19.3	0.445	0.385
65 brown adj	1.63	1.70	64.75	23.0	0.393	0.365
76 beige	0.71	2.39	75.96	34.9	0.403	0.424
64 pink	2.73	-0.07	64.20	22.0	0.341	0.263
66 green	-2.75	0.62	66.39	26.2	0.221	0.366

Table E.1 (continued)

Map 12: Soil Drainage and Distance to Surface Water 1 SS/SS

Correct response for all trials is **Same**
Induced trial: dark gray surrounds gray yellow
light yellow surrounds gray yellow
Controlled trial: dark gray surrounds both gray yellows

Map Category		Color Name	In 100's R	G	B
Soil Drainage:					
Distance to Surface Water in Kilometers:					
poor					
0-1	*(s: gray yellow & control)*	dk gray	120	120	120
1-2		gray blue	146	190	388
2-3		md blue	177	283	655
imperfect					
0-1		gray yellow	392	307	79
adjust by decreasing lightness:			343	269	69
1-2		md gray	347	347	347
2-3		lt blue	375	428	614
well drained					
0-1		md yellow	564	416	17
1-2	*(s: gray yellow)*	lt yellow	569	495	295
2-3		lt gray	573	573	573

Color Name	Hunt: RG	YB	J	cd/m² L	CIE: x	y
7 dk gray	0.44	0.65	27.11	3.38	0.284	0.316
42 gray blue	-0.11	-3.53	41.84	8.26	0.191	0.163
56 md blue	-0.75	-4.76	56.24	16.4	0.176	0.141
56 gray yellow	0.56	2.76	56.40	16.6	0.422	0.466
51 gray yellow adj	0.51	2.63	51.40	13.3	0.418	0.468
60 md gray	0.09	0.00	60.02	20.2	0.276	0.297
71 lt blue	-0.26	-2.13	70.55	29.7	0.226	0.223
71 md yellow	0.60	3.29	71.10	29.3	0.446	0.481
77 lt yellow	0.25	1.52	77.15	37.1	0.351	0.389
84 lt gray	0.07	-0.20	83.56	46.9	0.277	0.294

Table E.1 (continued)

Map 13: Sand & Gravel Resources 2 QL

Correct response for all trials is **Same**

Induced trial:	blue surrounds dark green
	dark brown surrounds dark green
Controlled trial:	dark brown surrounds both dark greens

Map Category		Color Name	In 100's R	G	B
beach ridges		red	530	148	158
littoral sand & gravel		orange	655	276	226
glaciofluvial sand & gravel		dk beige	582	357	272
glacial till		lt beige	655	494	342
alluvium	*(s: dk green)*	blue	222	352	418
lacustrine clay		**blue-green**	258	444	379
peat		**dk green**	185	319	272
adjust by increasing saturation:			113	319	253
no data		gray	567	567	567
roads	*(s: dk green & control)*	dk brown	151	95	23

Color Name	Hunt: RG	YB	J	cd/m² L	CIE: x	y
51 red	5.30	1.86	51.11	11.9	0.487	0.311
64 orange	3.93	1.73	63.65	20.8	0.449	0.326
65 dk beige	2.38	1.19	64.84	22.7	0.388	0.325
75 lt beige	1.53	1.08	74.88	33.4	0.365	0.335
54 blue	-0.49	-2.09	53.92	15.3	0.217	0.223
61 blue-green	-1.03	-0.45	60.76	20.9	0.241	0.291
48 dk green	-0.82	-0.22	48.34	12.0	0.242	0.293
47 dk green adj	-1.57	-0.01	46.91	11.2	0.226	0.311
78 gray	0.59	-0.62	78.40	39.0	0.276	0.269
24 dk brown	1.68	1.49	23.91	2.59	0.412	0.389

Table E.1 (continued)

Map 14: Soil-Drainage Classes for Agricultural Land 2 SS

Correct response for all trials is **Same**

Induced trial:	light gray surrounds medium gray
	black surrounds medium gray
Controlled trial:	light gray surrounds both medium grays

Map Category		**Color Name**	**In 100's** **R**	**G**	**B**
Soil Drainage:					
very poor		white	655	655	655
poor	*(s: md gray & control)*	lt gray	568	568	568
poor-imperfect		**md-lt gray**	437	437	437
imperfect		**md gray**	306	306	306
adjust by decreasing lightness:			284	284	284
imperfect-well		dk gray	175	175	175
adjust by decreasing lightness:			150	150	150
well drained	*(s: md gray)*	black	43	43	43
non-agricultural land		gray blue	187	258	263

Color Name	**Hunt:** **RG**	**YB**	**J**	**cd/m²** **L**	**CIE:** **x**	**y**
91 white	0.06	-0.27	90.75	58.3	0.276	0.292
83 lt gray	0.07	-0.23	82.94	46.0	0.276	0.293
70 md-lt gray	0.07	-0.15	69.80	29.5	0.275	0.294
54 md gray	0.14	-0.01	54.34	15.8	0.274	0.294
51 md gray adj	0.14	0.04	51.07	13.6	0.274	0.295
36 dk gray	0.25	0.30	36.28	6.19	0.274	0.300
31 dk gray adj	0.33	0.39	31.43	4.56	0.274	0.301
14 black	0.80	0.84	14.02	1.11	0.292	0.330
46 gray blue	-0.69	-0.30	46.24	10.8	0.242	0.287

Table E.1 (continued)

Map 15: Soils Series 2 QL

Correct response for all trials is **Same**
Induced trial: dark orange surrounds medium purple
light purple surrounds medium purple
Controlled trial: light purple surrounds both medium purples

Map Category	Color Name	In 100's R	G	B
Red River	red	565	167	47
Marquette & Kline *(s: md purple)*	dk orange	608	292	101
Kline	lt orange	655	380	217
Osbourne	yellow-orange	655	520	255
Inwood & Meleb	**dk purple**	302	58	517
Berry Is. & Beaverdam	**md purple**	378	175	655
adjust by desaturating:		369	220	590
Inwood & Beaverdam	gray purple	500	380	580
Inwood *(s: md purple & control)*	lt purple	608	537	655
Leary	cyan	27	411	655
Gunton	lt blue	305	515	582
Aneda & Gunton	dk blue	142	311	448

Color Name	Hunt: RG	YB	J	cd/m² L	CIE: x	y
54 red	5.21	3.02	53.78	13.5	0.552	0.373
63 dk orange	3.18	2.95	62.99	20.6	0.492	0.398
70 lt orange	2.24	2.08	70.36	27.8	0.427	0.372
78 yellow-orange	0.81	1.96	78.45	38.0	0.387	0.398
43 dk purple	2.48	-5.05	42.79	8.04	0.207	0.105
54 md purple	1.86	-4.74	54.02	14.1	0.208	0.121
54 md purple adj	1.74	-4.00	54.45	14.6	0.218	0.141
68 gray purple	1.37	-1.90	68.21	26.4	0.257	0.211
81 lt purple	0.86	-1.15	81.09	42.0	0.268	0.245
62 cyan	-1.80	-3.90	62.39	21.7	0.174	0.176
72 lt blue	-1.13	-1.81	71.65	31.3	0.219	0.245
52 dk blue	-1.05	-3.00	51.76	13.8	0.192	0.196

Table E.1 (continued)

Map 16: Land Cover 2 QL

Correct response for all trials is **Same**
Induced trial: blue surrounds orange
yellow surrounds orange
Controlled trial: blue surrounds both oranges

Map Category		Color Name	In 100's R	G	B
non-vegetated		gray	206	206	206
forested recreation site		pink	655	115	476
mixedwood		**brown**	497	218	125
adjust by desaturating:			439	230	162
hardwood		**orange**	655	304	65
willow and shrub	*(s: orange & c.)*	blue	173	320	586
prarie and meadow		cyan	171	556	529
cultivated hayland	*(s: orange)*	yellow	611	616	64
cultivated cropland		green	214	655	217
pasture		red	444	99	212
agricultural land being cleared		purple	470	96	655

Color Name	Hunt: RG	YB	J	cd/m² L	CIE: x	y
39 gray	-0.23	0.01	39.09	7.41	0.277	0.291
60 pink	4.78	-1.76	60.04	17.5	0.337	0.185
53 brown	3.53	2.47	53.36	13.7	0.480	0.371
51 brown adj	2.77	1.81	51.11	12.6	0.427	0.350
65 orange	3.28	3.33	65.37	22.5	0.515	0.415
56 blue	-0.88	-4.01	56.22	16.6	0.183	0.164
73 cyan	-2.19	-1.02	72.59	32.8	0.208	0.282
83 yellow	-0.45	3.38	82.83	44.1	0.406	0.503
78 green	-2.92	2.66	77.79	38.8	0.274	0.499
45 red	5.25	0.61	44.77	8.75	0.422	0.254
54 purple	3.23	-4.52	54.32	13.8	0.229	0.117

Table E.1 (continued)

Map 17: Soil-Type Distributions for Agricultural versus Non-Agricultural Land Uses 1 SS/N

Correct response for all trials is **Same**

Induced trial:	dark blue surrounds medium blue-green
	gray surrounds medium blue-green
Controlled trial:	gray surrounds both medium blue-greens

Map Category	Color Name	In 100's R	G	B
Soil Type:				
Ag.				
peat	md blue	0	265	383
gleyed and/or peat	**md blue-green**	114	371	347
adjust by increasing lightness:		126	413	385
gleyed	md green	126	543	379
gleyed and/or orthic	lt green	375	599	503
orthic	white	575	655	608
Non-Ag.				
peat *(s: md blue-green)*	dk blue	17	151	211
gleyed and/or peat	**dk blue-green**	67	256	238
gleyed	dk green	117	362	266
gleyed and/or orthic	gray green	240	398	328
orthic *(s: md blue-green & c.)*	gray	466	526	486

Color Name	Hunt: RG	YB	J	cd/m² L	CIE: x	y
47 md blue	-1.74	-2.92	46.91	11.0	0.179	0.202
56 md blue-green	-2.11	-0.65	56.22	17.3	0.209	0.292
61 md blue-green adj	-2.18	-0.64	60.69	20.9	0.210	0.295
71 md green	-2.68	0.53	71.38	31.5	0.223	0.361
80 lt green	-1.39	0.00	79.58	41.6	0.247	0.319
87 white	-0.24	-0.26	87.49	53.1	0.270	0.296
30 dk blue	-0.84	-1.76	29.67	4.07	0.187	0.211
43 dk blue-green	-1.82	-0.27	43.22	9.26	0.210	0.299
55 dk green	-2.23	0.55	54.87	16.3	0.227	0.352
60 gray green	-1.34	0.19	60.37	20.6	0.246	0.323
76 gray	-0.30	-0.06	76.30	37.2	0.271	0.303

Table E.1 (continued)

Map 18: Sand & Gravel Resources 1 QL

Correct response for all trials is **Same**
Induced trial: light green surrounds dark beige
dark green surrounds dark beige
Controlled trial: dark green surrounds both dark beiges

Map Category		Color Name	R (In 100's)	G	B
beach ridges		**lt beige**	651	545	349
littoral sand & gravel		**dk beige**	522	437	280
adjust by decreasing lightness:			487	408	261
glaciofluvial sand & gravel		lt cyan	313	552	477
glacial till		dk cyan	222	392	339
alluvium	*(s: dk beige)*	lt green	377	625	351
lacustrine clay		md green	263	435	244
peat	*(s: dk beige & control)*	dk green	153	306	153
no data		lt gray	409	398	397
roads		dk gray	216	216	216

Color Name	Hunt: RG	YB	J	cd/m^2 L	CIE: x	y
84 lt beige	0.42	1.32	83.67	45.7	0.349	0.373
72 dk beige	0.41	1.38	71.88	30.9	0.348	0.376
69 dk beige adj	0.42	1.39	68.95	27.8	0.348	0.376
77 lt cyan	-1.58	-0.04	76.84	38.0	0.241	0.319
61 dk cyan	-1.50	0.12	61.29	21.4	0.241	0.322
83 lt green	-1.65	1.47	82.54	45.4	0.279	0.406
65 md green	-1.61	1.59	65.12	24.7	0.279	0.411
50 dk green	-1.86	1.92	49.99	12.9	0.274	0.443
66 lt gray	0.18	-0.06	66.47	26.0	0.279	0.295
43 dk gray	0.17	0.19	42.84	8.99	0.274	0.299

Table E.1 (continued)

Map 19: Evaluation of Potential Campground Sites 1 DE

Correct response for all trials is **Same**
Induced trial: pink surrounds dark magenta
dark brown surrounds dark magenta
Controlled trial: dark brown surrounds both dark magentas

Map Category	Color Name	In 100's R	G	B
Ranking of Sites:				
1 optimal	**dk red**	272	58	127
adjust by increasing saturation:		272	5	87
2	**dk magenta**	366	116	191
3	md magenta	426	212	296
4	gray magenta	437	280	359
5 *(s: dk magenta)*	pink	487	396	434
6 minimally acceptable	lt gray	480	480	480
7	gray brown	437	388	335
8	md brown	345	255	154
9 unacceptable *(s: dk magenta & c.)*	dk brown	246	182	110
roads	black brown	125	92	56

Color Name	Hunt: RG	YB	J	cd/m² L	CIE: x	y
31 dk red	4.39	0.86	30.55	3.93	0.420	0.263
29 dk red adj	5.05	1.52	28.61	3.41	0.494	0.295
41 dk magenta	4.00	0.55	40.99	7.39	0.391	0.263
51 md magenta	2.71	-0.12	51.49	12.9	0.334	0.256
58 gray magenta	1.72	-0.39	58.04	17.7	0.303	0.259
69 pink	0.80	-0.23	68.80	27.8	0.290	0.280
74 lt gray	0.08	-0.16	74.22	34.5	0.276	0.294
65 gray brown	0.39	0.53	65.46	24.7	0.308	0.324
50 md brown	0.99	1.70	50.42	12.7	0.375	0.383
39 dk brown	0.94	1.70	39.24	7.15	0.375	0.392
22 black brown	1.08	1.31	22.13	2.28	0.366	0.385

Table E.1 (continued)

Map 20: Evaluation of Potential Campground Sites 2 DE

Correct response for all trials is **Same**
Induced trial: yellow surrounds green-yellow
dark green surrounds green-yellow
Controlled trial: dark green surrounds both green-yellows

Map Category	Color Name	In 100's R	G	B
Ranking of Sites:				
1 optimal	dk red	409	16	12
2	md red-orange	521	169	34
3	lt red-orange	588	303	96
4	lt orange	648	435	158
5	orange-yellow	650	545	260
6 minimally acceptable *(s: green-y)*	yellow	652	655	361
7	**green-yellow**	431	465	242
adjust by increasing lightness:		479	517	269
8	**md green**	291	359	167
9 unacceptable *(s: green-y & c.)*	dk green	141	241	87
roads	brown	185	131	33

Color Name	Hunt: RG	YB	J	cd/m² L	CIE: x	y
39 dk red	6.64	2.31	38.62	6.20	0.600	0.347
50 md red-orange	5.20	2.93	50.39	11.6	0.563	0.381
61 lt red-orange	3.20	3.02	60.83	18.9	0.498	0.403
71 lt orange	1.87	2.70	71.02	28.6	0.447	0.411
77 orange-yellow	0.89	1.92	77.35	36.6	0.387	0.394
84 yellow	0.27	1.28	83.81	46.1	0.343	0.375
66 green-yellow	0.10	1.42	65.51	24.6	0.339	0.387
70 green-yellow adj	0.07	1.39	69.90	29.0	0.338	0.386
53 md green	-0.29	1.71	53.21	14.8	0.331	0.413
38 dk green	-0.87	2.02	37.64	6.68	0.316	0.468
28 brown	1.58	1.74	27.94	3.48	0.440	0.429