The Colour Appearance of Perceived Illuminants and Surfaces

BY

TARA SHUTE ©

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ABSTRACT

The colour appearance of a patch of light is only partly determined by the light itself. A patch's perceived colour can also be influenced by cognitive processes. Cognitive effects on colour appearance were examined by modifying an observer's perceptual representation of surface-ambiguous and textured patches of light. Observers were instructed to view a 1° square test patch as either an illuminant source or as an object reflecting light from its surface. The test patch was presented on a high-resolution Nanao 9080i colour monitor driven by a 32 bit microprocessor (TI 34020 GSP) specialized for graphics operations. The luminance of the phosphors was photometrically calibrated and linearized. The five test conditions were a(n): (1) isolated homogeneous test field (ambiguous test); (2) isolated test containing a random-dot speckled pattern (textured test surface); (3) homogeneous test with homogeneous surround (ambiguous test and surround); (4) test containing a similar texture surrounded by a homogeneous background (textured test surface with ambiguous surround); (5) textured test with a textured surround (textured test and surround surface). Changes in colour appearance were assessed using a red/green hue cancellation technique based on opponency mechanisms in the human visual pathway. The test was an admixture of "red" (λ_d = 625 nm) and "green" (λ_d = 535 nm) light. The chromaticity of the backgrounds were "red" (λ_d = 625 nm) and "green" (λ_d = 535 nm). The test patch was varied across five luminances (0.92 to 19.9 cd/m^2). Observers monocularly viewed the CRT with their left eyes, and were required to adjust the radiance of the "green" component so that the test appeared neither reddish nor greenish. Results showed that all but one observer viewed the CRT images independently of instruction set. The observer showed a greenness (redness) shift in test colour appearance for surface (aperture) mode perception when viewing a homogeneous test with a 625 nm surround. The remaining observers showed either no shifts or shifts in colour appearance that were in the same chromatic direction as the surround. The data can best be described by neural assimilation processes.

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TABLE OF CONTENTS

Page

Appendices

LIST OF FIGURES

Introduction

One of the enduring problems in visual perception has been how to explain colour appearance. Observations that lights can be perceived differently when viewed under different circumstances has been known for over a century (Chevreul, 1839) and remains a fundamental problem for visual scientists today. Parameters other than physical wavelength affect how one perceives colour. Perceptual attributes such as hue, saturation and brightness are influenced by the spatial and temporal stimulus characteristics as well as the quantal energy emitted or reflected from a surface. For these reasons, it is often difficult to specify and predict changes in colour appearance. Psychophysical attempts to understand colour perception have been made by presenting spatially simplistic "two-light" stimuli usually composed of a test light and a background (e.g., Jameson and Hurvich, 1972; Shevell, 1978; 1987; Shevell and Wesner, 1989; Walraven, 1976; 1979). Typically, the background is either a surrounding contiguous light or an adapting field upon which the test light was superimposed. The influences of impoverished backgrounds on the psychophysical measures of test light appearance provided the framework necessary to establish mechanistic theories of chromatic adaptation and contrast. The advantage of these studies was that they allowed researchers to correlate the psychophysical properties of adaptation and contrast with the known physiological properties of the visual pathway. The disadvantage of using these stimuli was they represent only a small subset of natural viewing conditions. The study of colour constancy makes this evident.

Researchers studying colour constancy develop computational algorithms that best describe the perceptions of complex scenes, often with little regard to the physiological substrates of the behavior. On the other hand, the psychophysical properties of chromatic adaptation and contrast are often inadequate in describing constancy mechanisms (e.g., Arend and Reeves, 1986; Blackwell and Buchsbaum, 1988a; Brill and West, 1986; Land, 1986; Land and McCann, 1971; Worthey and Brill, 1986).

Physiological Processes Mediating Colour Appearance

Three physiological processes are responsible for changes in colour appearance. These processes are categorized by their loci in the visual pathway, and are called the prereceptoral, receptoral and postreceptoral processes.

Prereceptoral processes. Preretinal elements such as the cornea, aqueous humour and lens can influence quantal absorption of the photoreceptors by scattering light entering the eye. Whenever quanta from one region of a stimulus physically mix with another region it is termed *physical admixture.* The amount of admixture may be known as when the energy from an adapting field admixes with a superimposed test, or it may be unknown and inhomogenous as when energy from a surrounding region (contiguous but not underneath a test) strays into the test. The amount of scattered light produced by the preretinal optics can be described by the summation of a large number of point spread functions (Vos, Walraven & van Meeteren, 1976) that lie within the spatial constructs of the stimulus (Shevell and

Burroughs, 1988).

Receptoral processes. For trichromats, three cones exist each primed to respond maximally to different regions of the spectrum. The human visual spectrum ranges from about 380 to 750 nm (Boynton, 1979). Each cone contains photopigment that is photoisomerized by a quantum of light. The photoisomerization of the photopigment will activate the cone neurally by hyperpolarizing the cell. Some cones respond maximally to short-wavelengths (400-490 nm) and are called short-wavelength sensitive (SWS) cones, while other cones respond maximally to medium (490-580 nm) and long (580-700 nm) wavelength light, and are referred to as medium- (MWS) and long-wavelength sensitive (LWS) cones, respectively. Each cone has its own absorption curve or spectral sensitivity function that reveals the portion of the visual spectrum each cone is likely to respond to. The three cones' absorption curves overlap considerably, with maximum overlap occurring between the MWS and LWS cones (Boynton, 1979; Smith and Pokorny, 1975). The extent of this overlap governs the properties of opponency located at higher levels of the visual pathway.

The dominant retinal process contributing to changes in colour appearance is receptoral desensitization. For example, when LWS cones are selectively desensitized by an extremely long wavelength "red" adapting field (e.g., 650 nm), the response from the LWS cones is lessened while the response from the MWS cones remains the same. This relative loss of LWS response will shift the appearances of spectral light towards greenness (or less redness). This is also referred to as a receptoral gain change and is specified by the von Kries Coefficient Law (von Kries, 1878; as cited in MacAdam, 1970). The von Kries Coefficient Law proposes that each cone has its own independent spectral sensitivity function that, under different states of chromatic adaptation, will weight differently the output of each of the cones. The actual coefficients are associated with each of the cone outputs. Furthermore, these coefficients are determined only by the light absorbed by each of the cone systems (Worthey, 1985; Worthey & Brill, 1989). Therefore, any changes in adapting field chromaticity will result in a proportional change in the cone responses, and these responses will be linearly related to the separate attenuating (gain) mechanisms in each receptor system.

Although receptoral gain changes drastically alter the colour appearance of light, the retinal process cannot completely describe the properties of chromatic adaptation and contrast (e.g., MacAdam, 1956; Heinrich, 1969; Hurvich and Jameson, 1958; Walraven, 1973; 1976; Walters, 1942). The von Kries Coefficient Law assumes that the spectral sensitivity functions are invariant and therefore proportionally linear (Worthey & Brill, 1989). Studies show, however, that lateral interactions between test patches and backgrounds can account for violations in von Kries Coefficient Law. These interactions appear to be opponent in nature (e.g., Jameson and Hurvich, 1972; Larimer, 1981; Shevell, 1978; 1982; Shevell and Wesner, 1989; Walraven, 1976).

Postreceptoral processes. Ewald Hering (1878, as cited in Teevan & Birney, 1961) originally proposed that colour perception could be broken down into six basic colour sensations arranged in opponent pairs: black-white, blue-yellow, and red-green. According to Hering, excitation of one member of the pair suppressed the other. Colour perception was dependent on activities from red-green and blue-yellow opponent systems. The entire gamut of colours perceived was explained as an expression of different weighting factors for each chromatic opponent pair. Colourlessness was believed to be produced by the admixture of precise complimentary proportions. For example, stimulation of blue visual substance counterbalanced equally by stimulation of yellow visual substance yielded white light. Likewise, equal stimulation of the red and green visual substance nullified or desaturated hue. Brightness (achromatic) perception was derived from the black-white mechanism.

Jameson and Hurvich (1955) capitalized on Hering's idea of opponency. They reasoned that a red (yellow) response should cancel an equal but opposite green (blue) response. They argued that a null method could be "used to measure the spectral distributions of separate chromatic responses (Jameson and Hurvich, 1955, 548)." By employing this cancellation technique, Jameson and Hurvich established chromatic valence properties to two spectrally different opponent channels, r-g and y-b. These authors were the first to quantify chromatic opponent processing. Physiological evidence supports the existence of trichromacy at the receptor level, and the existence of opponency at the LGN and cortex (for review, see Boynton, 1979).

Chromatic Adaptation and Contrast

The influences of different spatiochromatic properties of a background on test colour appearance reveal theoretical mechanisms of chromatic adaptation. One important spatial distinction is *contrast* versus *context*. Contrast is defined as the boundary between one uniform area with another. Context can be defined as a removed, noncontiguous area surrounding a test patch (Shevell & Wesner, 1989). Adapting fields larger than test fields have both contrasting and contextual influences on test colour. As will be discussed later, isolated contextual patches of light, such as outer rings, can also significantly influence test colour. Background context is particularly important in some colour constancy models.

When contrasting backgrounds are adapting fields (i.e., the test is superimposed on the background) and the diameter of the background is greater than the test, a signal from the surrounding light counterbalances (or specifically decrements) the contributions from physical admixture (Larimer, 1981; Shevell, 1982). Whether this counterbalancing signal is due to retinal response compression (MacAdam, 1961; 1963), opponency (Jameson and Hurvich, 1972), or some cortical differencing mechanism (Walraven, 1976) is open to speculation. If the adapting field is the same size as the test, however, there is little or no counterbalancing signal. In this case, the energy from the adapting field becomes a component of the test. There is little or no lateral interaction between the test and background in these conditions (Shevell, 1982).

In the case of a contrasting background that is contiguous but not immediately under a test, the test receives inhomogenous physical admixture due to scattered light from the surround (see prereceptoral processes above). There are also lateral interactions between the test and surround that typically shift the test colour towards a direction complimentary to that of the surrounding chromaticity (i.e., opponent response or *chromatic induction*).

Two-process model. Many researchers have offered a two-process interpretation to explain why linear proportionality (i.e., von Kries law) breaks down with chromatic adaptation and contrast (Helson, 1938; MacAdam, 1956; Jameson & Hurvich, 1972). The two-process model of chromatic adaptation includes an additive as well as a multiplicative component. Jameson and Hurvich (1972) attributed the multiplicative component to gain changes in the cones (i.e., receptoral desensitization) and the additive component to post-receptor opponency cells *and* physical admixture.

Theoretical integration of the trichromatic cones with opponent cells clarifies the two-process model of chromatic adaptation. The photopic, achromatic luminance channel receives a combined message from the MWS cones and LWS cones. The combined input means that the luminance channel has "broad band" sensitivity and is therefore incapable of discriminating on the basis of wavelength (Boynton, 1979). The SWS cones have little to no input into the luminance channel (e.g., Kelly, 1974; DeValois & DeValois, 1980; Williams, Collier, and Thompson, 1983). For the chromatic system, the MWS and LWS cones are not combined--rather the signals are differenced constituting the "red-green" opponent channel. A second channel conveys information from the SWS cones. The "yellow-blue" opponent channel is defined by the difference between the SWS cone signals and the luminance MWS + LWS signal (Boynton, 1979).

The two-process model has been investigated in studies that use unitary hue cancellation techniques to measure chromatic adaptation effects (DeValois & Walraven, 1967; Shevell & Wesner, 1989; for review see Pokorny, Shevell & Smith, 1991). Walraven (1976) presented observers with an annular test in the centre of a "red" (660 nm) background. The annular test was an admixture of "red" (Δ_{660} nm) and "green" (Δ_{540} nm) lights. After dark adaptation, the test annulus was varied by changing the intensity of a 660 nm component in a test light composed of an admixture of 660 and 540 nm light. The test was superimposed onto the 660 nm background of fixed illuminance.

According to opponency, red/green equilibria represents a unique neurological balance in the r-g chromatic channel. This balance is maintained across test illuminances (i.e., red/green equilibria are luminance invariant) and reflects linearity in the r-g system (Larimer, Krantz and Cicerone, 1974). For example, increasing the "red" component of a test presented alone (i.e., dark adaptation) requires an observer to add an equal amount of "green" to maintain equilibrium yellow. Chromatic adaptation to a 660 nm background, on the other hand, causes greater desensitization of the LWS cones that feed into the r-g system. This desensitization weights the opponent signal towards g. To maintain equilibrium of a test superimposed on a "red" background, observers need to compensate for the desensitized LWS cones by adding more radiance of the "red" component for red/green cancellation. Similarly, chromatic adaptation to a 540 nm background causes greater desensitization of the MWS cones that feed into r-g system. Thus, observers need more radiance of the "green" component of a test for red/green cancellation. If the system is linear, as von Kries proportionality rule suggests, then the effect of the "red" (660 nm) background on *all* test illuminances will produce only a multiplicative, gain change and not an *additive* shift away from the red/green equilibrium settings derived from dark adaptation. Walraven (1976) showed that when the surround was brighter (higher illuminance) the proportion of "red" to "green" was maintained. The Von Kries rule failed, however, at lower test illuminances. Walraven noted that the overall hue shifts of the test superimposed on a steady background were multiplicative and additive. Examining only the shifts found with the incremental "red" and "green" test light and excluding the contributions of the background light, however, revealed a von Kries - like linearity. This led Walraven to describe the additivity as a higher process that "discounted" the background energy.

Unfortunately, Walraven used a limited range of test illuminances. A study by Shevell (1978) highlighted this weakness. He presented a "red" (660 nm) background upon which an incremental mixture of "red" (Δ660 nm) and "green" (Δ540 nm) lights were superimposed. Observers were instructed to adjust the intensity of the "green" (Δ540 nm) component so that the test appeared neither reddish nor greenish. The test and background were varied in illuminance.

Shevell found that for the spatially transient stimuli, the ratio of Δ660 to Δ540 nm light was constant (i.e., luminance invariant). At low test illuminances (near Δ660 nm thresholds), however, the incremental intensity ratio declined (i.e., proportionally more "green" light was required to maintain equilibrium). Shevell suggested that there was more "red" additivity from the adapting field at low test illuminances than originally proposed in the Walraven (1976) study. The greater contribution of adapting field light at low test illuminances (i.e., greater percentage contribution of the total amount of test energy) was, by definition, attributed to physical admixture In effect, there was a nonlinear, "pedestal" of additivity that occurred at low test illuminances (see Shevell & Wesner, 1989). This argument elaborates on Jameson and Hurvich's theoretical discussion of the two-process theory of chromatic adaptation. Shevell argued that adapting fields influence test colour by (1) photoreceptor gain changes (as described in Walraven), and (2) additivity from physical admixture and higher-ordered incremental (or decremental) signals.

In a later experiment, Shevell (1982) further studied these additive signals using red/green cancellation tasks under a variety of spatiochromatic and temporal conditions. Shevell's prior experiment had shown that: "the fixed intensity adapting light adds physically with the test light in the test area, thus as test illuminance is increased the adapting field has a relatively smaller contribution in the test area with a consequent effect on test light mixture ratio (p279)." Of particular interest was that at low test illuminances, the actual amount of "red" energy from the adapting fields contributed *less* to the test color percept than predicted by physical admixture. This suggests that an additional *decremental* signal negates a portion of the physical admixture increment. Shevell further examined this counterbalancing effect by flashing a "red" (660 nm) adapting light briefly (150 msec) while observers adjusted the colour appearance of a steadily presented test. Data from the temporally transient adapting fields revealed a multiplicative shift from dark adaptation with a corresponding decremental shift at low test illuminances. In other words, observers required *less* "green" test light for red/green hue cancellation at low test illuminances rather than more as found with steadily presented adapting fields. These results were consistent with the argument that a more temporally sluggish additive signal such as opponency originates from a higher locus in the visual pathway than the multiplicative preretinal and retinal processes associated with chromatic adaptation.

According to Shevell, additive (and subtractive) influences from admixture and higher level restoring forces (possibly opponency) counterbalance each other. He further argued that at high test illuminances, the percentage contribution of adapting field energy is small enough that the counterbalancing signal completely negates the physical additivity (i.e., only receptoral gain changes are observed). This reasoning explained why there were little additivity shifts found in the Walraven (1976) study. By extending the range of test illuminance to lower levels than Walraven, Shevell surmounted the negating contributions from opponency.

The two-process model as it relates to the above red/green cancellation studies can be expressed by the following equation:

$$\Delta G = [\Delta R + f(x)]\, g(x) \qquad \text{eq (1)}$$

where ΔG and ΔR are the radiances of the incremental components of the test, x is the energy of the background, and f(x) and g(x) are the additive and multiplicative parameters, respectively. According to the equation, the adjusted "green" test component (ΔG) will depend on levels of the red component (ΔR), and the background radiance, which can retinally desensitize cones producing a gain change (g(x)) and/or admix physically to the test (or subtract redness from the test due to surround induction; f(x)). This last point is important. It suggests that f(x) in the two-process model can either add to or subtract from ΔR. Shevell's (1982) counterbalancing signal is one in which both properties can occur simultaneously.

Complex Colour Perception

The two-process theory can account for colour perception under a wide range of adapting conditions, but most investigators agree that the model falls short in predicting colour perception under more complex scenes. For example, contextual light can influence color appearance differently than contrasting light. Wesner and Shevell (1994) found that medium- and long-wavelength lights showed chromatic induction effects. Not surprisingly, contiguous areas composed of middle- and long-wavelength light had a greater influence than noncontiguous areas. The further removed the noncontiguous area, the less the effect. This finding had been described earlier (e.g., Blackwell & Buchsbaum, 1988; Jameson & Hurvich, 1961). Opposite effects occurred when the surrounding light was composed of short-wavelength energy. When short wavelength light was adjacent (contiguous) to a test, there was little or no change in test colour appearance. When the short-wavelength light was a noncontiguous contextual surround, however, the light markedly shifted the test towards redness. The shifts were greater the further the light was removed from the boundary of the test (up to 5° from the centre of the test). This finding suggests that the visual system is capable of differentiating contrasting light patches from contextual light patches.

Wesner and Shevell (1992) suggest that a mechanism that distinguishes context and contrast may be involved in colour constancy. They expanded their stimuli from a two-light configuration into a simple contextual, three-light arrangement in which an adapting field was surrounded by an outer ring composed of either a chromaticity complimentary to the adapting field or achromatic "white" light. With this arrangement, Wesner and Shevell were able to determine the effects of context without the confounding influences of a contrasting surround. The results of study showed that a "white" noncontiguous surround did not produce any changes in red/green equilibrium. However, when a "white" noncontiguous surround was presented with a contiguous surround (contrast) there was less energy required to reach red/green equilibrium than if the test was presented with just a complimentary surround.

The inferred-illuminant model argues that all chromaticities in a scene provide information about the chromaticity of an illuminant. In effect, the individual perceptually establishes the range or gamut of chromaticities available in a given scene from contrast and context information. This information may be simultaneous or transient, the latter of which has yet to be investigated (i.e., the effect of contextual colour memory). In the case of the "three-light" study, a white (or complimentary) outer ring produces a greater shift of test colour towards the adapting field chromaticity. The outer rings indicate to the observer that a neutral broad band illuminant is radiating the stimuli (otherwise the observer would not see a white or complimentary ring). The observer therefore does not perceive the test colour as being illuminated by energy weighted towards the spectral distribution of the background, rather as a test that has added energy from the adapting field. One shortcoming of the inferred-illuminant model is that it assumes observers view all stimuli as surfaces reflecting light regardless of their complexity. In actuality, observers may have different cognitive percepts of simple stimuli particularly with regards to aperture versus surface perception.

Chromatic induction. More recent psychophysical evidence for higher cortical processing can be seen in studies investigating the effects of chromatic induction. Generally, the opponent response is one in which the induced colour is complimentary to that of the surrounding light. Krauskopf, Zaidi & Mandler (1986) studied chromatic induction by examining the effects of surrounding a "white" disk with either a red or green surround. If the surround was temporally modulated from "red" to "green" the hue of the "white" disk appeared to modulate in complimentary directions. As the surround was modulated subjects were required to nullify the induced hue by adjusting an amount of real modulation in the "white" disk. To cancel induction, observers needed to admix a compliment of the induced hue (i.e., the hue of the surround). Krauskopf et al. (1986) argued that if colour induction is strictly an additive process, the ability to cancel hue fluctuation in the "white" disk should produce a linear relationship similar to the amount of light required to modulate the colour of the surround. The results of this initial study showed that this relationship was not linear. As the inducing modulations become larger, observers seemed to require less canceling modulation to perceive the centre as "white".

Krauskopf et al. (1986) performed a second experiment to determine whether opponent processes could explain the nonlinearity found in the first experiment. The procedure was similar to the first experiment, except that different inducing modulations were used. If chromatic induction occurred strictly at the opponent process level then changes in colour appearance would be complimentary. The inducing modulations could be conceived as points on an opponent process continuum. If observers chose a nullifying modulation that was not complimentary to the inducing modulations (i.e., off the continuum) then opponency could not adequately explain colour induction. The results of the second experiment showed that the nullify modulations were not complimentary to the inducing modulation. In summary, the first experiment showed that the responses were nonlinear, and therefore postreceptoral. The second experiment showed that the results did not match theoretical expectations of a solely opponent response. Krauskopf et al. argued the chromatic induction effects cannot be fully explained at either the receptoral or the opponent-process levels, but must include a higher cortical process.

Achromatic processing. Ironically, studies using achromatic stimuli have added to our understanding of not only lightness but colour constancy. It has also provided a better understanding of the distinctions between aperture and surface modes of perception. Shevell (1989) found evidence that achromatic processing can occur beyond the retinal and opponent level. In a study on induced blackness he examined whether a patch of light was represented in the visual system before or after binocularity. Binocular combination implies that processing occurs higher up in the visual cortex. Observers viewed different stimuli with their left and right eyes. Both eyes were presented with a fixation point and a background. Also a patch of light to the right of the fixation point was presented to both eyes. A second patch to the left of the fixation point was presented to the left eye. The patches were of lower intensity and appeared darker than the background. The stimuli were binocularly fused. The observer's task was to match the fused patch right of the fixation point to the monocularly presented patch left of the fixation point. The experimenter varied the surrounding light in the right eye. If retinal processing was solely responsible for blackness induction, then observers should make judgments independent of the fused surround.

In other words, the observer would make adjustments from the right eye surround only and ignore the combined perceived brightness of the fused surround. Results showed that observers did not make adjustments based on only the right-eye surround. Shevell's results support the idea that retinal mechanisms cannot provide an adequate explanation for induced blackness.

Uchikawa, Uchikawa and Boynton (1988) studied the influence of achromatic surrounds on the perception of surface colours. Observers were placed in a booth and presented colour samples reflected off a mirror from behind the booth. This presentation made the stimuli as ambiguous as possible. The results showed that a test patch of colour when seen in isolation is more likely to be perceived as an aperture. The addition of other patches, even one that contrasts with the test patch, however, increases the chance the test patch will be perceived as a surface. In addition, certain colours are associated with surfaces. For example, the experiment showed that "brown" was not seen in isolation. Instead, the hue of orange was perceived.

Heggelund (1974a, 1974b, 1992) argued that the unidimensional concept for achromatic colours (black-white continuum) is not sufficient. In the unidimensional model of achromatic colours, black is defined as the absence of white. However, when the luminance is zero an intrinsic gray is perceived. The perception of black seems to depend on the luminance of surrounding areas (i.e., simultaneous contrast). Heggelund defines colours that are not mutually exclusive (e.g., red and yellow makes orange) as orthogonal. Because black and white can mix, whereas complimentary colours do not, Heggelund believes that black and white pairs should be reclassified as orthogonal. In his experiment Heggelund (1974a) examined the possible bidimensional attributes of achromatic colour perceived in an aperture or surface mode. He was interested in finding out if the distinction between aperture and surface was a naming (cognitive) distinction or a distinction between two unique perceptual experiences. Using a Maxwellian-view system, Heggelund presented the observer with achromatic colours in a disc-ring configuration. The test field was presented to the right eye, and the comparison field was presented to the left eye. The test field luminance was fixed, except for its inducing field. When the inducing luminance was lower than the luminance of the test field the disc appeared to have a surface quality (i.e., appeared opaque and had blackness); when the inducing luminance was higher than the luminance of the test field the disc appeared to be an aperture.

First, in the unidimensional model of achromatic colours only white can vary in intensity. The bidimensional model can accept varying intensities across the graduations of chromatic colour. Heggelund's results supported the bidimensional model. Second, the results also showed that aperture colours and surface colours could be explained by a shift from luminous-white to white-black on a bidimensional scale. He argued that the change between colour modes means a change in achromatic processing. Heggelund (1974a, 1992) proposed two variables for measuring achromatic colours - achromatic quality and colour strength. Achromatic quality measures the variation in luminosity through white to black (luminous-black). Colour strength measures the intensity of colours, from dim to strong or dazzling colours (strength of white - strength of black).

In another study, Heggelund (1974b) showed that the achromatic quality dimension and colour strength related to luminance parameters differently. The strength of white was dependent on the local luminance. It was strongest when there was zero contrast for the test luminance and was monotonic to test luminance. That is, a positive or negative contrast produced a decrease in the strength of white. Unlike the strength of white, the luminous-black variable was zero at zero contrast, and was linearly related to contrast. Heggelund concluded that the colour strength dimension was influenced by the achromatic quality dimension. Such an influence can aid in understanding colour constancy. Surface colours tended to be more colour constant than did aperture colours on Heggelund's achromatic quality dimension. Colour strength, however, showed no constancy for either aperture or surface conditions (for review see Heggelund, 1992).

Cognitive Influences. Studies using verbal influences on image appearance also support the influence of higher processes beyond opponency, as well as highlight the distinction between aperture light and surface light. To begin, instruction set has been crucial in distinguishing brightness and lightness percepts. Brightness refers to the apparent amount of light emanating from a visual stimulus. Lightness refers to how much relative "white" can be attributed to a visual stimulus. Brightness denotes how "bright" or "dim" a stimulus appears. Lightness denotes how "light" or "dark" a stimulus appears to be in comparison to other contextual stimuli present in a scene. Thus, lightness is relative brightness (Pokorny, Shevell & Smith, 1991).

Arend and Reeves (1986) suggest that colour constancy takes place high up in the visual pathway. These authors grouped colour constancy mechanisms into two classes: adaptation mechanisms and simultaneous mechanisms. Adaptation mechanisms involve changes in the visual system over time. Simultaneous mechanisms involve the responses to light from different locations in the visual field (i.e., the spatial properties of retinal images). In their study, Arend and Reeves (1986) examined the possibility that simultaneous mechanisms contribute to colour constancy. Observers were asked to colour match a test patch to a standard patch by adjusting the chromaticity of the test patch with a joy stick. Observers were then asked to do the same task but under instructions that the test patch was "cut from the same piece of paper" as the standard patch. The first condition required observers to make a brightness judgment. In the second condition, the stimuli were defined as surfaces and the observers were required to make lightness judgments. The results showed weak colour constancy in the brightness conditions and strong constancy in the lightness conditions. Because the primary distinction between the two conditions was the instruction set, one could argue that colour constancy is a mechanism primarily governed by high-level, cognitive functioning.

Foster, Craven and Sale (1992) argue that colour constancy might be better defined as the low-level processing of chromatic relationships between coloured stimuli in a scene as the illuminant varies. Moreover, they argue that some aspects of colour constancy are "determined by fast, relatively low-level, preattentive visual processes (1992, 157)." In their study, observers were required to look at a Mondrian illuminated by different phases of daylight. Each stimulus display consisted of three Mondrian patterns with 32 randomly placed coloured patches. The three Mondrians were arranged in a row. One Mondrian was identical to the centre pattern but illuminated by a different illuminant (illuminate-change condition). The second Mondrian was identical in patterning to the centre, but could not be matched under an illuminant change (material change condition). The patches in the illuminant-change Mondrian were illuminated by uniform shifts along a daylight continuum of high colour temperatures. The different phases of daylight were taken from spectral energy distributions generated by the principal components analysis (Judd, MacAdam, & Wyszecki, 1964). In the material change Mondrian, half of the patches were illuminated by high colour temperature illuminants; the others by low colour temperature illuminants. Observers had to discriminate on each trial which pattern was illuminated differently, and which Mondrian had different material (pattern) changes. The results showed that observers made accurate illuminant discriminations between the two patterns quickly and reliably. Foster et al. (1992) argued that the fast and accurate discriminations made with these experiments were indicative of preattentive colour constancy mechanisms.

Troost and de Weert (1991) further studied the possible distinction between sensory and cognitive mechanisms of colour constancy. Sensory explanations tend to be mechanical with the system partitioning out light source variation. Cognitive explanations argue that the visual system uses information from the light source and from the object surface. Troost and de Weert believe that neither sensory nor cognitive explanations are independently sufficient to explain colour constancy. These authors replicated Arend and Reeves' 1986 study with some simple modifications. The first experiment used a simultaneous matching task. In the first condition, observers were simply asked to match the test pattern to the standard. Observers in the second condition were given instructions about object colours and how light sources influence the perception of colour. Observers were told the colour difference between the target and the test was caused by different illuminants. The second experiment used a successive matching task where observers were required to adjust the test pattern to match the standard without having the standard simultaneously displayed. Observers viewed either the test or the standard at different presentations until a match was made. The results showed that the instructions influenced the simultaneous and successive experiments. The first condition of each experiment revealed poor colour constancy. Troost and de Weert interpreted this as evidence against colour constancy being mediated simply by an early-stage sensory processes such as receptoral desensitization or lateral inhibition. The results of the second condition revealed better judgments of colour constancy.

Troost and de Weert point out that under this condition, observers made judgments based on information provided by the instruction set. The improved constancy measured in the second condition suggests higher-level cognitive processing.

Summary

Past theories of colour perception have been based on studies using simple, impoverished "one or two light" stimuli (Wesner & Shevell, 1992). Accurate depictions of chromatic processing must also address issues of complex imagery and cognitive states that are more representative of natural viewing conditions. The influences of the spatiochromatic and temporal properties of stimuli and the cognitive percepts of these stimuli must be systematically investigated.

Wesner and Shevell (1992) were the first to study the simultaneous effects of chromatic context using the three-light stimulus configuration. The visual processes revealed in this study were considered in terms of inferred illumination and surface reflectance; a position that posits the physiological substrates of light and colour constancy. Two predictions can be made based on the above "inferred-illuminant" model: (1) that the chromatic surrounds generated on a CRT will affect test colour appearance more if the stimuli are viewed as surfaces rather than light sources; (2) textured stimuli will be more readily viewed as surfaces than the ambiguous, homogeneous stimuli.

The present experiments examined directly the influences of higher cognitive processing. Colour appearance was measured using a red/green hue cancellation technique. Similar to Arend and Reeves'

1986 study, the experiments presented two instruction sets to the observers before testing. The first set emphasized the stimuli as aperture light sources. The second emphasized the stimuli as surfaces. The instruction variable was examined with five stimulus configurations varying from an isolated homogeneous test field that may be perceived as an illuminant to a test field and surround containing random-dot textures that may be perceived as surfaces. The first experiment presented "red" surrounds (dominant wavelength, $\lambda_d = 625$ nm) and the second experiment presented "green" surrounds (dominant wavelength, $\lambda_d = 535$ nm). These configurations, in conjunction with the two instructions, revealed how individuals perceive CRT images (i.e., illuminant, solid object, or a combination of both), and the magnitude by which higher cognitive processes influence the lower processes of simultaneous chromatic adaptation and contrast.

Method

Observers

Five observers participated in the "red" surround experiment (C.W., D.S., K.G., M.M., P.K.) and five observers (C.B., J.M., M.M., P.R., R.C.) participated in the "green" surround experiment. Observer M.M. participated in both the "red" and "green" surround experiments. All the observers were colour normal (as defined by the Ishihara's test for colour-blindness - 24 Plate Edition). Observers D.S., K.G., M.M., P.K., R.C. were male. Three observers (J.M., P.K. & P.R.) were emmetropic. The remaining observers were myopic (<-5.00 D) and wore nontinted corrective lenses. Observer C.W.'s results were eliminated because of presentation errors (i.e., presented with incorrect stimuli in two experimental sessions).

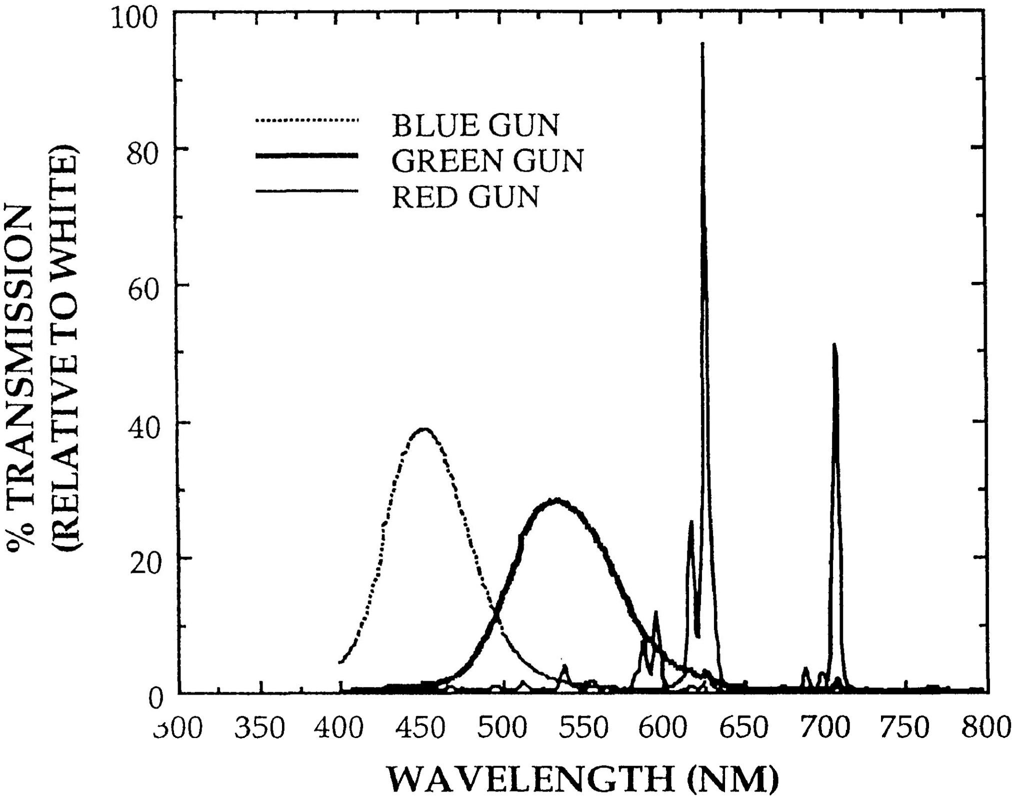
Apparatus

A 1° square test patch with or without a 5°, 535 nm or 625 nm surround was presented on a high-resolution Nanao 9080i colour monitor driven by a 32 bit microprocessor (Texas Instruments 34020 GSP) specialized for graphics operations. The luminance range of each of the phosphors were calculated with a photometer interfaced with the computer. The depth of each pixel was 8 bits. The luminance of each of the phosphors was therefore calculated for 256 levels. The values for each phosphor level was then linearly transposed into separate R, G and B lookup tables. We assumed phosphor constancy and phosphor and spatial independence (Vingrys and King-Smith, 1986). The spectral distribution of each phosphor gun was independently determined with

FIGURE 1a: The spectral energy distribution for the red, green and blue phosphors of the Nanao 9080i colour monitor. Measurements were made with an International Light IL1700 spectroradiometer (August, 1993).

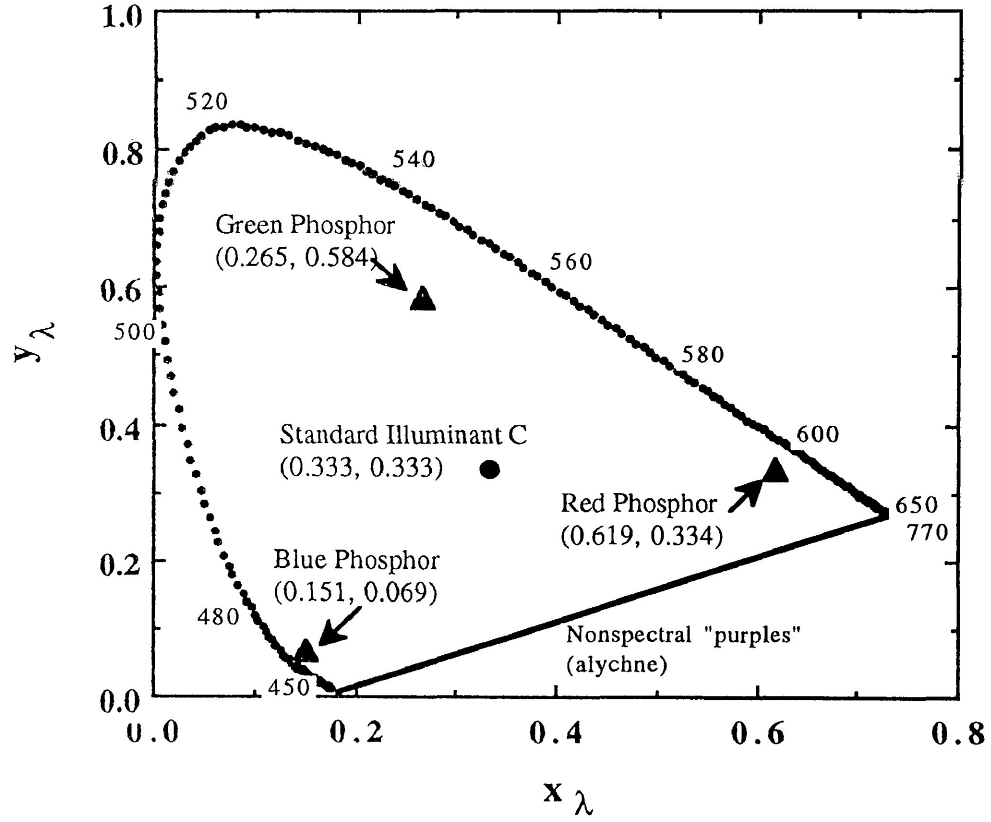
FIGURE 1b: CIE 1931 (x,y) chromaticity diagram showing red, green and blue phosphor loci for the Nanao colour monitor.

1a



NANAO 9080i CRT CALIBRATION
(AUG. 31, 1993)

1b



CIE 1931 (x,y) CHROMATICITY DIAGRAM

a spectroradiometer. The spectral distributions for the R, G and B phosphors are shown in Fig. 1a. Convolving these distributions with the standard 2° CIE 1931 colour match functions and summating across 1 nm wavelength increments within the visible spectrum (Wyszecki and Stiles, 1982) we calculated the CIE X, Y and Z tristimulus values for each of the phosphors. These values were then converted into x and y chromaticity coordinates. The loci for the red, green and blue phosphors in CIE 1931 (x, y) chromaticity space are shown in of Fig. 1b. The dominant wavelengths (λ_d) for the red and green phosphors were 625 and 535 nm, respectively. The blue phosphor was never used in the study.

Procedure

Two experiments were conducted in which either a "red" (λ_d = 625 nm) or "green" (λ_d = 535 nm) 5° square surround was presented to the observers. In addition to the surround, a 1° square test field composed of an admixture of "red" (λ_d = 625 nm) and "green" (λ_d = 535 nm) light was presented to the observers. The experiments were conducted monocularly. All the observers' right eyes were patched (left eye viewing).

In each experiment, one session (or block of conditions) was defined by the type of *a priori* instructions an observer received about the CRT-generated stimuli. The instructions described the stimuli as either an illuminant (source mode) or an object reflecting light (surface mode). The instructions were read to the observers before entering the laboratory. The instructions are shown in Appendices A and B.

Observers participated in two sessions per day. For example, an observer who received instructions to view the stimuli as a light source in the first session received instructions to view the stimuli as an object in the second session. Sessions were counter-balanced over replications on the following day. This provided the necessary data for calculating standard mean errors for each observer. After receiving the instructions, the observers dark adapted for 7 min and light adapted to either a 625- or 535 nm 5° square adapting field for 3 min.

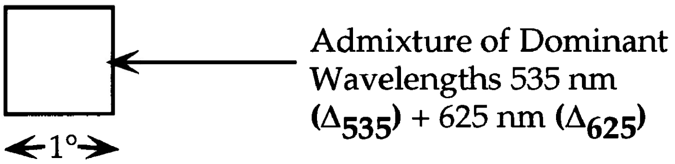
Five stimulus configurations (or stimulus conditions) were randomly interleaved throughout one session (see Fig. 2). The configurations were defined as follows: (1) a 1° homogeneous test field (ambiguous test surface), (2) a 1° test field containing a random-dot speckled pattern (textured test surface), (3) a 1° homogeneous test field surrounded by a 5° homogeneous 625- or 535-nm surround (ambiguous test and surround surface), (4) a 1° homogeneous test surrounded by a 5° speckled 625- or 535-nm surround (textured surround); (5) a speckled 1° test field and 5°, 625- or 535-nm surround (textured test and surround). The luminance of the homogenous test surrounds were 0.39 candelas/ metre^2 (cd/m^2). The speckled surrounds reduced the luminance by 10%.

Five retinal luminances of the test, ranging from 0.92 to 19.9 cd/m^2, (-0.40 to 1.30 log cd/m^2) were presented for each condition. The computer controlled the luminance of the 625 nm test component. The luminance of the 535 nm test component was adjusted by the observers. The task of the observers was to adjust the "green" component of the test until they perceived neither redness nor greenness (i.e., red/green equilibria). When equilibrium was achieved, the observers pressed a response button that was followed by a 7 sec delay and then the presentation for the next trial. The luminance of the "green" component of the test was randomly changed after each response. Each of the test luminances was presented four times in ascending order to prevent adaptation confounds (i.e., beginning with -0.40 log cd/m^2 and ending with 1.30 log cd/m^2). The four responses for each test luminance were averaged and any intraobserver variability showing standard deviations greater than 0.3 cd/m^2 were omitted (Shevell, 1982; Wesner & Shevell, 1993; 1994). Thus, one session consisted of 100 observations (4 presentations of each luminance level x 5 test luminance levels x 5 stimulus configurations). For one observer, the total number of observations was 400. Typically, one session for a practiced observer lasted approximately 120 min.

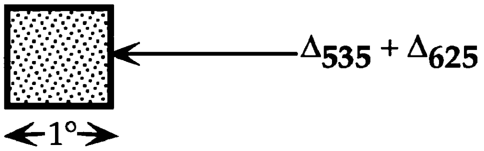
FIGURE 2: Stimulus Configurations (or conditions) used for "Red" surround & "Green" surround experiments.

Stimulus Configurations

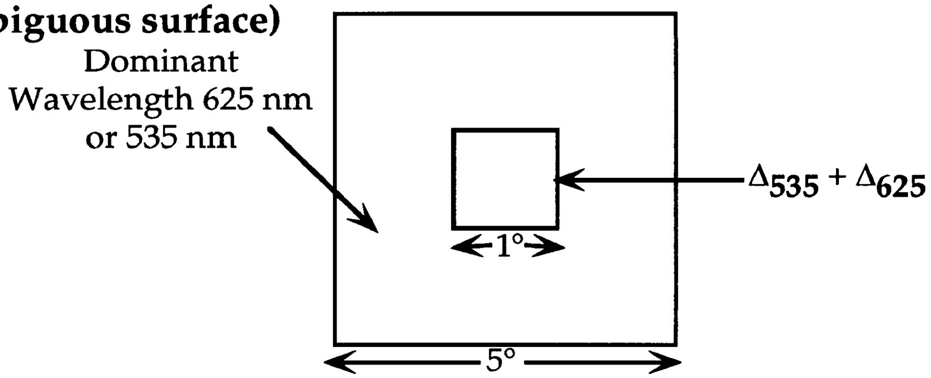
1. Homogeneous Test Field (ambiguous surface)



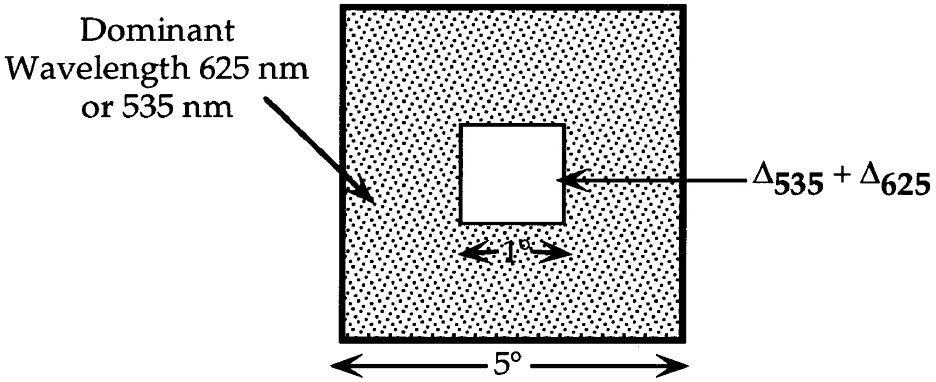
2 Test Field with Random-Dot Speckled Pattern (textured surface)



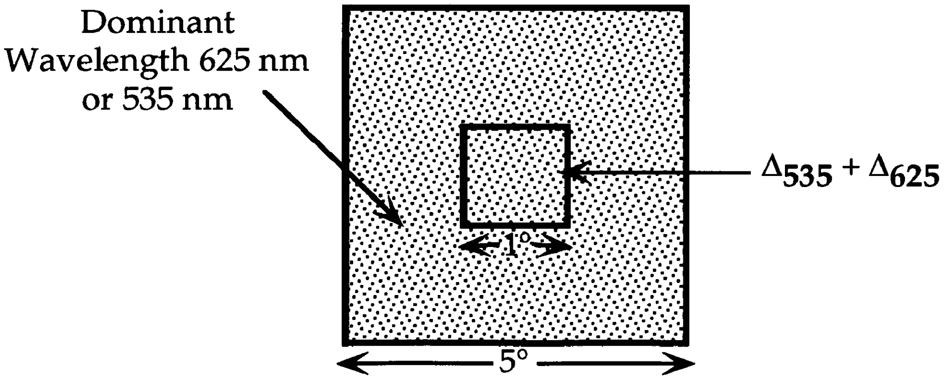
3 Homogeneous Test Field with Homogeneous Surround (ambiguous surface)



4. Homogeneous Test Field with Speckled Surround (ambiguous test with textured surround)



5. Speckled Test Field with Speckled Surround (textured test with textured surround)



Results

Shifts in adjusted red/green equilibria were assessed by plotting the adjusted "green" illuminance (Δ_{535}) as a function of the "red" illuminance (Δ_{625}) of the test.[1] Observer M.M.'s data for "red" and "green" surround experiments are shown in Figs. 3 and 4, respectively. The open (filled) symbols denote adjustments made while viewing the stimuli as sources (surfaces). The upper left panel show measurements for homogeneous and speckled-test only conditions (i.e., ambiguous- and textured-test only). Because there were no surrounds in these two conditions, observer M.M. was presented with the same stimuli for both "red" and "green" surround experiments. The data, however, were analyzed as separate data sets. Test-only data obtained from the first (second) experiment were evaluated in conjunction with the "red" ("green") surround data. The remaining observers participated in only one experiment. The continuous curves denote least square fits of the two-process model of chromatic adaptation (eq. 1). The parametric values f(x) and g(x) obtained from the fit for each data set are shown in each panel. The error bars for all figures are the standard error of the means (SEM) across days.

The test with "red" (or "green") surround data are shown in the remaining Fig. 3 (Fig. 4) panels. The upper right panel shows data measured from the ambiguous test contrasting with an ambiguous surround. The lower panels show data measured with either an

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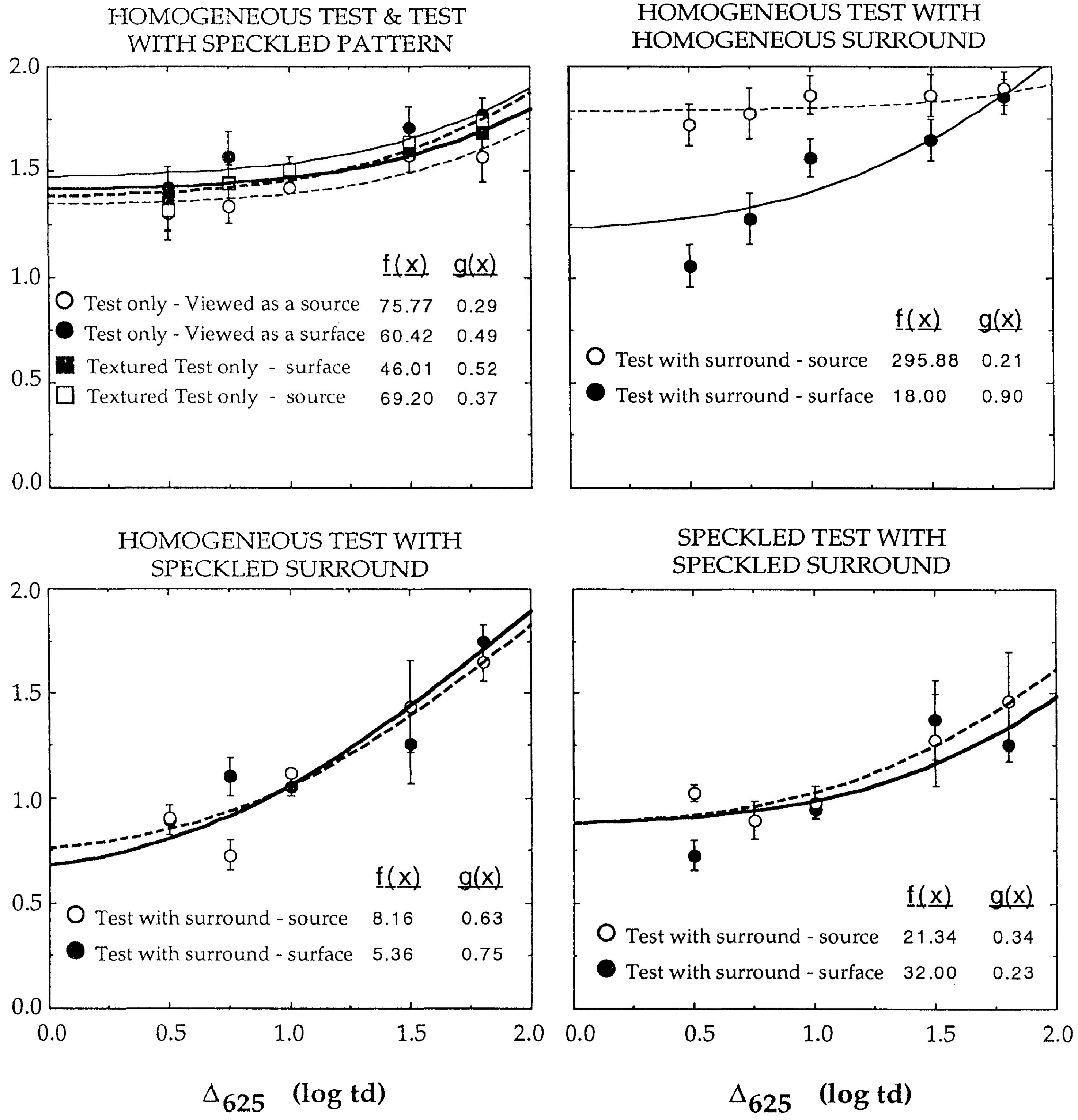
[1] For these plots, we assumed a 2 mm diameter pupil size when converting photometric luminance (cd/m^2) into retinal illuminance (trolands, td). We continue to use luminance units for the remaining difference plots.

FIGURE 3. Red/green equilibrium measurement for Observer M.M. - "Red" surround conditions. Open (filled) symbols denote light source (surface) instructions. The dotted (solid) continuous lines are the best fits of the two-process template curve (eq. 1) to the light (surface) instruction data. The parameters of the fit are included in each panel. Note: Positive f(x) values indicate a nonlinear additive redness from the "red" surround.

RED/GREEN EQUILIBRIUM MEASUREMENT FOR OBSERVER M.M. - "RED" SURROUND CONDITIONS



HOMOGENEOUS TEST & TEST WITH SPECKLED PATTERN

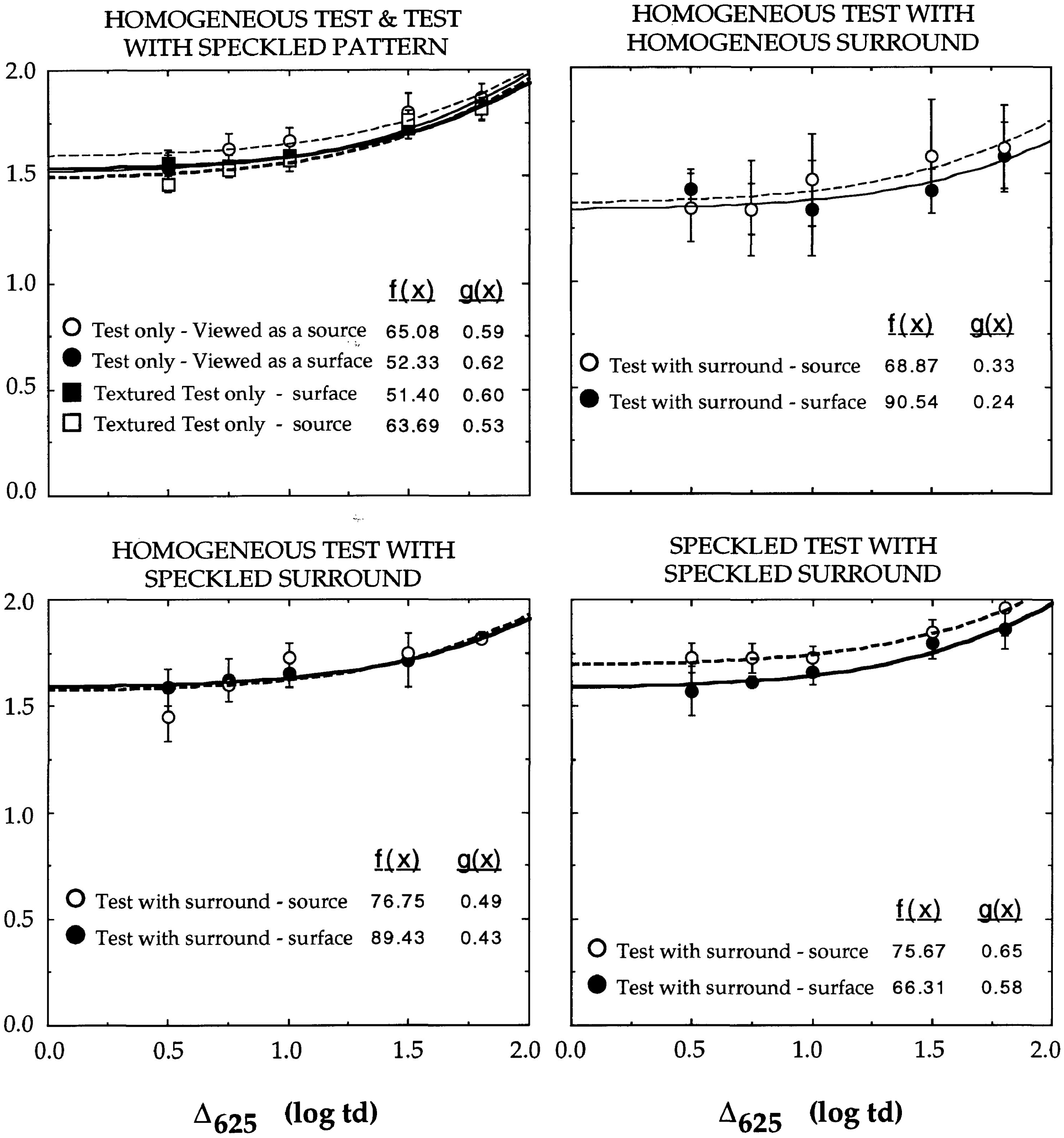
HOMOGENEOUS TEST WITH HOMOGENEOUS SURROUND

HOMOGENEOUS TEST WITH SPECKLED SURROUND

SPECKLED TEST WITH SPECKLED SURROUND

FIGURE 4. Red/green equilibrium measurement for Observer M.M. - "Green" surround conditions. Open (filled) symbols denote light source (surface) instructions. The dotted (solid) continuous lines are the best fits of the two-process template curve (eq. 1) to the light (surface) instruction data. The parameters of the fit are included in each panel. Note: Positive f(x) values indicate a nonlinear additive redness from the "green" surround.

RED/GREEN EQUILIBRIUM MEASUREMENT FOR OBSERVER M.M. - "GREEN" SURROUND CONDITIONS



HOMOGENEOUS TEST & TEST WITH SPECKLED PATTERN

HOMOGENEOUS TEST WITH HOMOGENEOUS SURROUND

HOMOGENEOUS TEST WITH SPECKLED SURROUND

SPECKLED TEST WITH SPECKLED SURROUND

ambiguous test (lower left) or textured test (lower right) contrasting with a textured surround.

The data usually are easier to discern when plotted as the *change* in the spectral composition of the test light (change in Δ_{535}) as a function of (Δ_{625}). This was accomplished by differencing the homogeneous test data (test-only) viewed as a source from the remaining surround and textured data. Figures 5-8 show the difference plots for observers in the "red" surround experiment. Figures 9-13 show the difference plots for observers in the "green" surround experiment.

Only homogeneous test fields viewed as light sources provided the *test only - source* baseline data (shown in Figs 5-13 as horizontal dashed lines at 0.0). Error bars indicate ±1 SEM. Data above the test-only line indicate shifts in the colour appearance of the test towards redness (i.e., an increased amount of Δ_{535} was needed to reach red/green equilibrium). Data below the test-only line indicate shifts towards greenness (i.e., a decreased amount of Δ_{535} was needed to reach red/green equilibrium). The magnitude of the shift above or below the test-only line denotes the amount of change in colour appearance. We calculated the amount of change in relative energy of the test required for red/green cancellation and expressed these terms in CIE equivalent wavelengths. These calculations showed that approximately ±0.5 log cd/m^2 shifts are equivalent to shifts of approximately ±6 nm in CIE 1931 space. Assuming 580 nm represents spectral unique yellow, wavelengths

FIGURE 5. Difference Plot for Observer M.M. - "Red" Surround (λ_d = 625 nm). Open symbols represent the light source condition. Filled symbols represent the surface condition. The dot-dashed line represents the homogeneous test viewed as a surface minus the homogeneous test viewed as a source. The *test only - source* dashed line is the reference dark adapted line. Shifts above (below) the line represent a shift towards redness (greenness). The long dashed line represents the maximum amount of energy the background can contribute to the test if the background were an adapting field. Calculations reveal that only 10.8% of this energy actually falls onto the boundary of the test due to spread light. Error bars are ±1 SEM.

DIFFERENCE PLOTS FOR OBSERVER MM - RED SURROUND

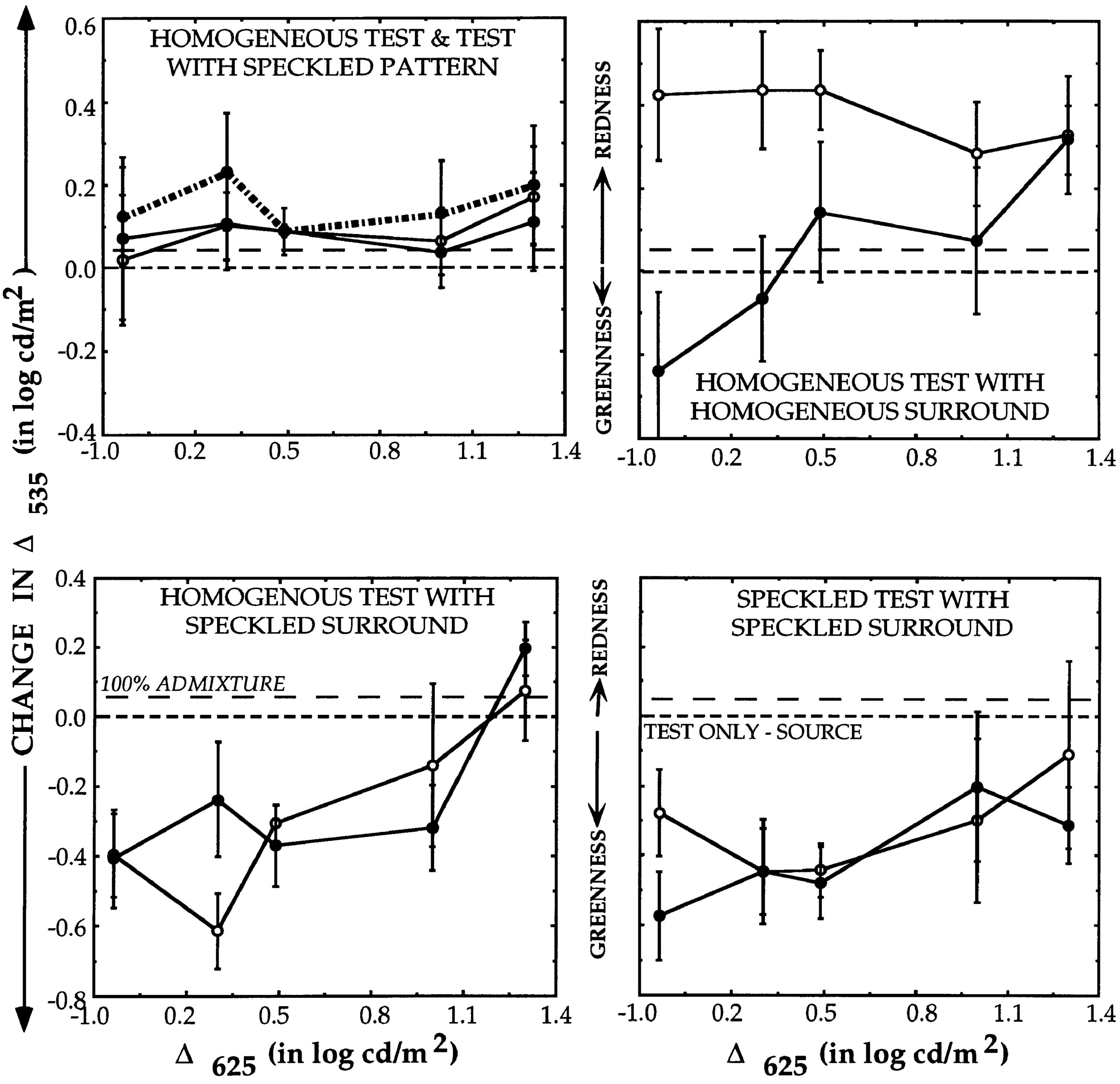


FIGURE 6. As Fig. 5 but for Observer D.S.

DIFFERENCE PLOTS FOR OBSERVER DS - RED SURROUND

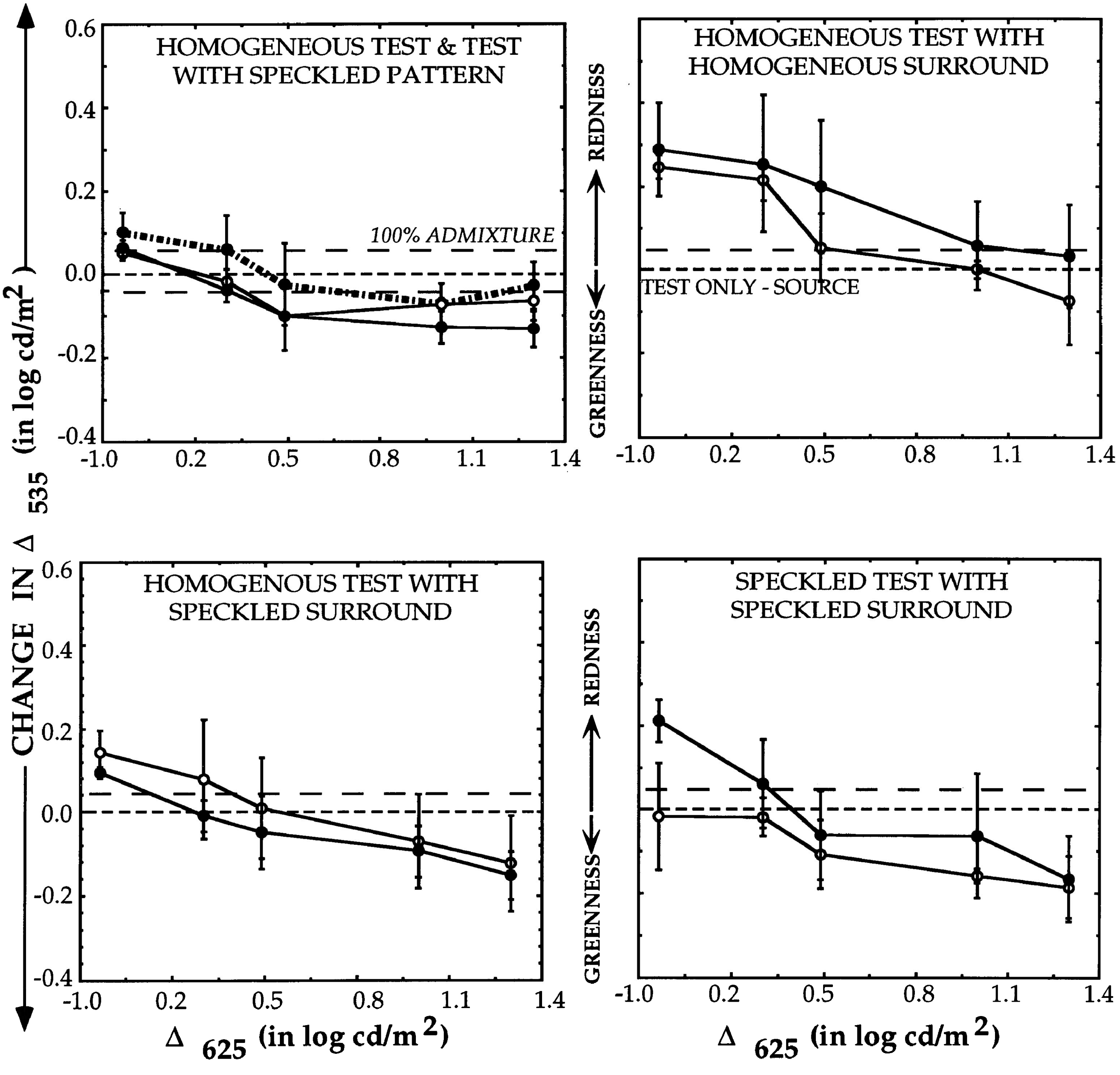


FIGURE 7. As Fig. 5 but for Observer K.G.

DIFFERENCE PLOTS FOR OBSERVER KG - RED SURROUND

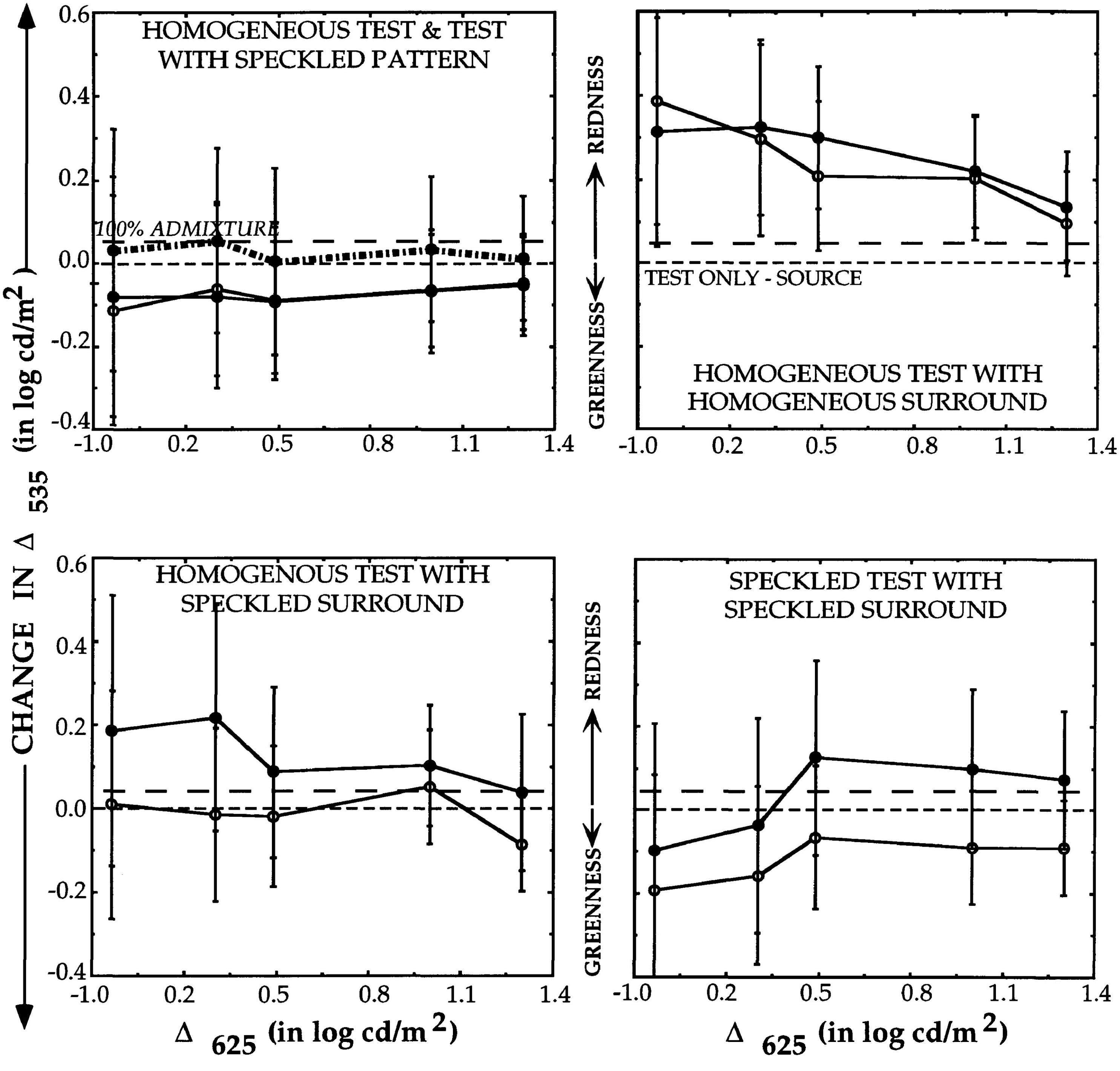


FIGURE 8. As Fig. 5 but for Observer P.K.

DIFFERENCE PLOTS FOR OBSERVER PK - RED SURROUND

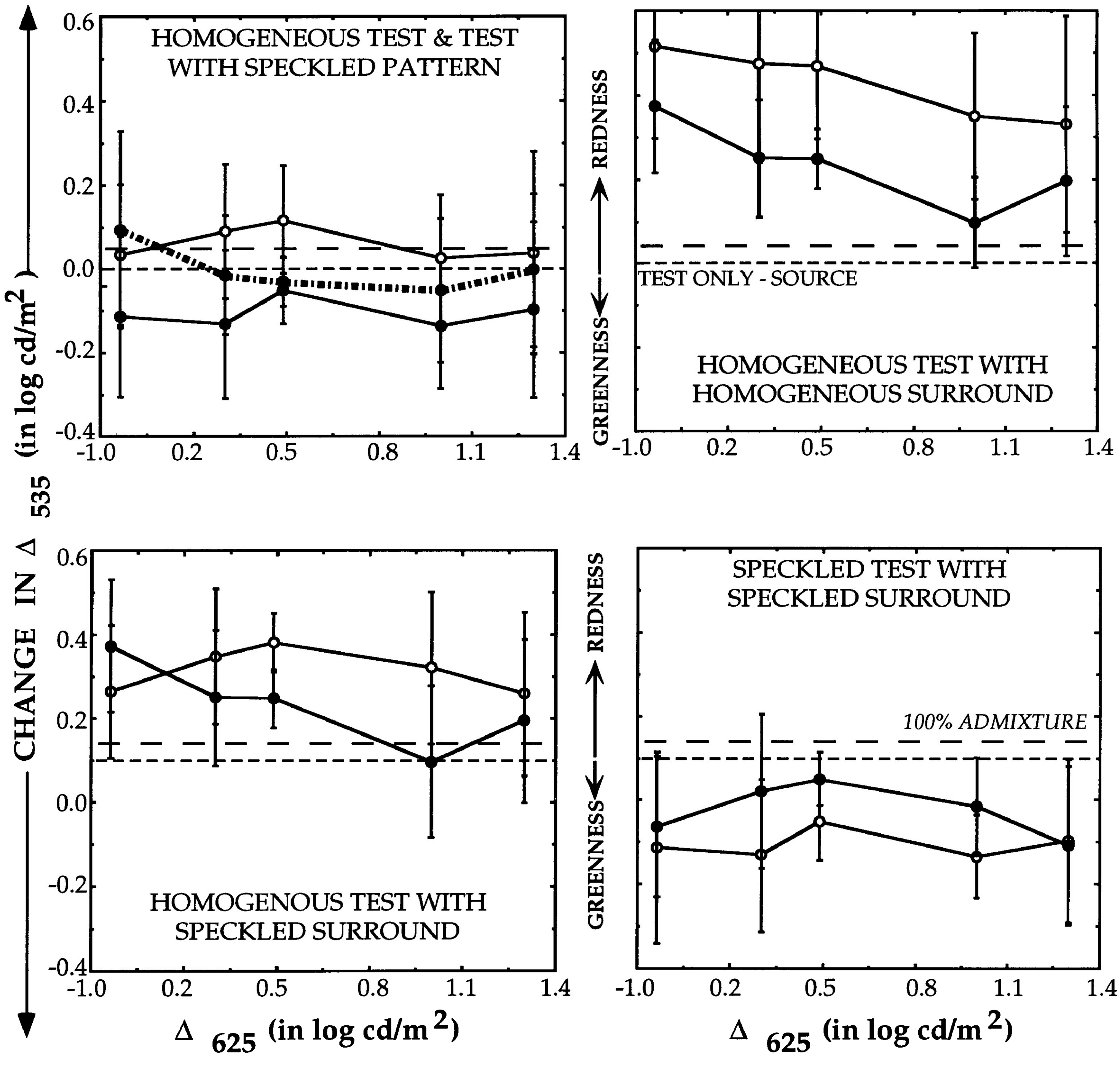


FIGURE 9. Difference Plot for Observer M.M. - "Green" Surround (λ_d = 535 nm). Open symbols represent the light source condition. Filled symbols represent the surface condition. The dot-dashed line represents the homogeneous test viewed as a surface minus the homogeneous test viewed as a source. The *test only - source* dashed line is the reference dark adapted line. Shifts above (below) the line represent a shift towards redness (greenness). The long dashed line represents the maximum amount of energy the background can contribute to the test if the background were an adapting field. Calculations reveal that only 10.8% of this energy actually falls onto the boundary of the test due to spread light. Error bars are ±1 SEM.

DIFFERENCE PLOTS FOR OBSERVER MM - GREEN SURROUND

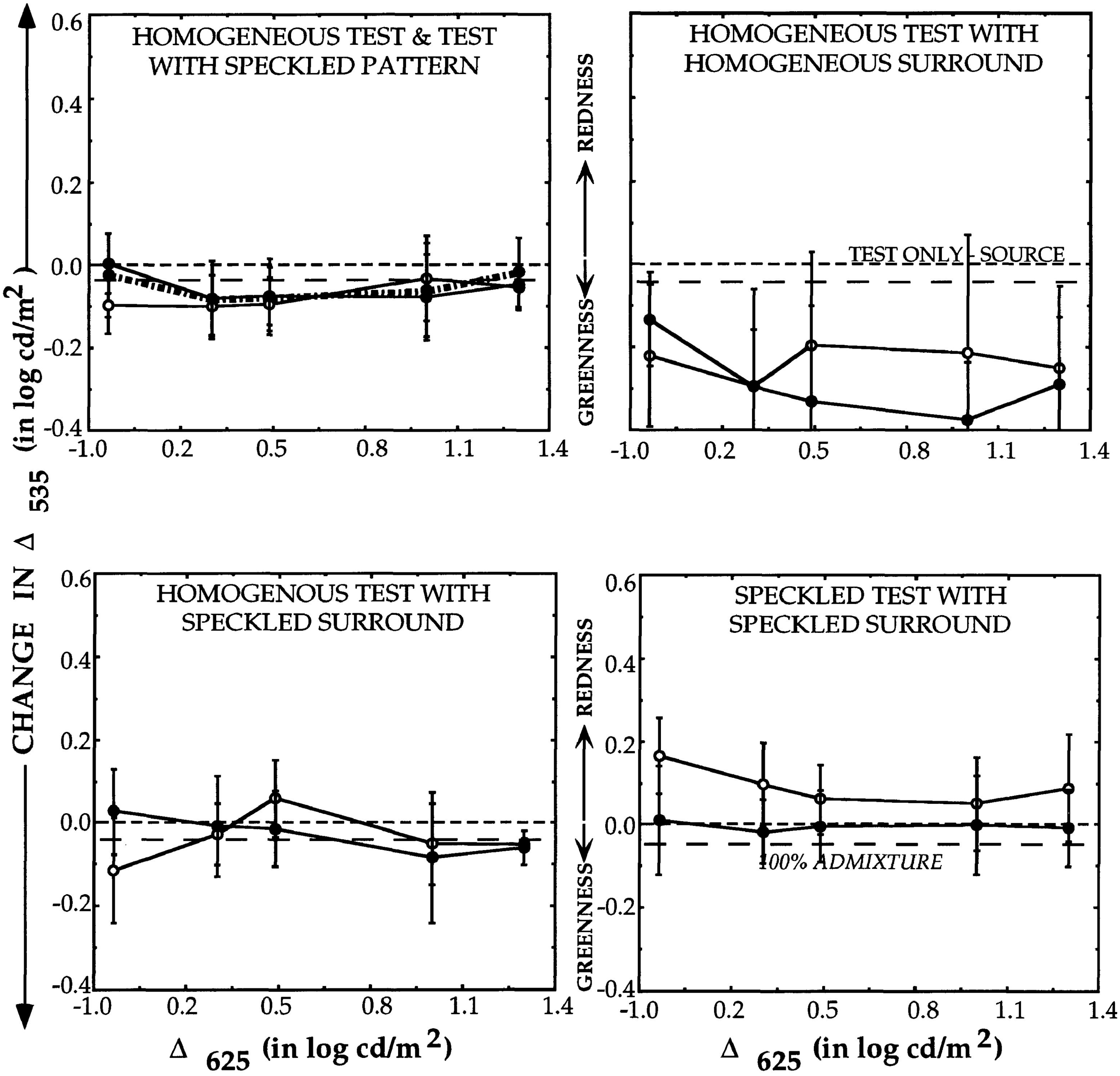


FIGURE 10. As Fig. 9 but for Observer C.B.

DIFFERENCE PLOTS FOR OBSERVER CB - GREEN SURROUND

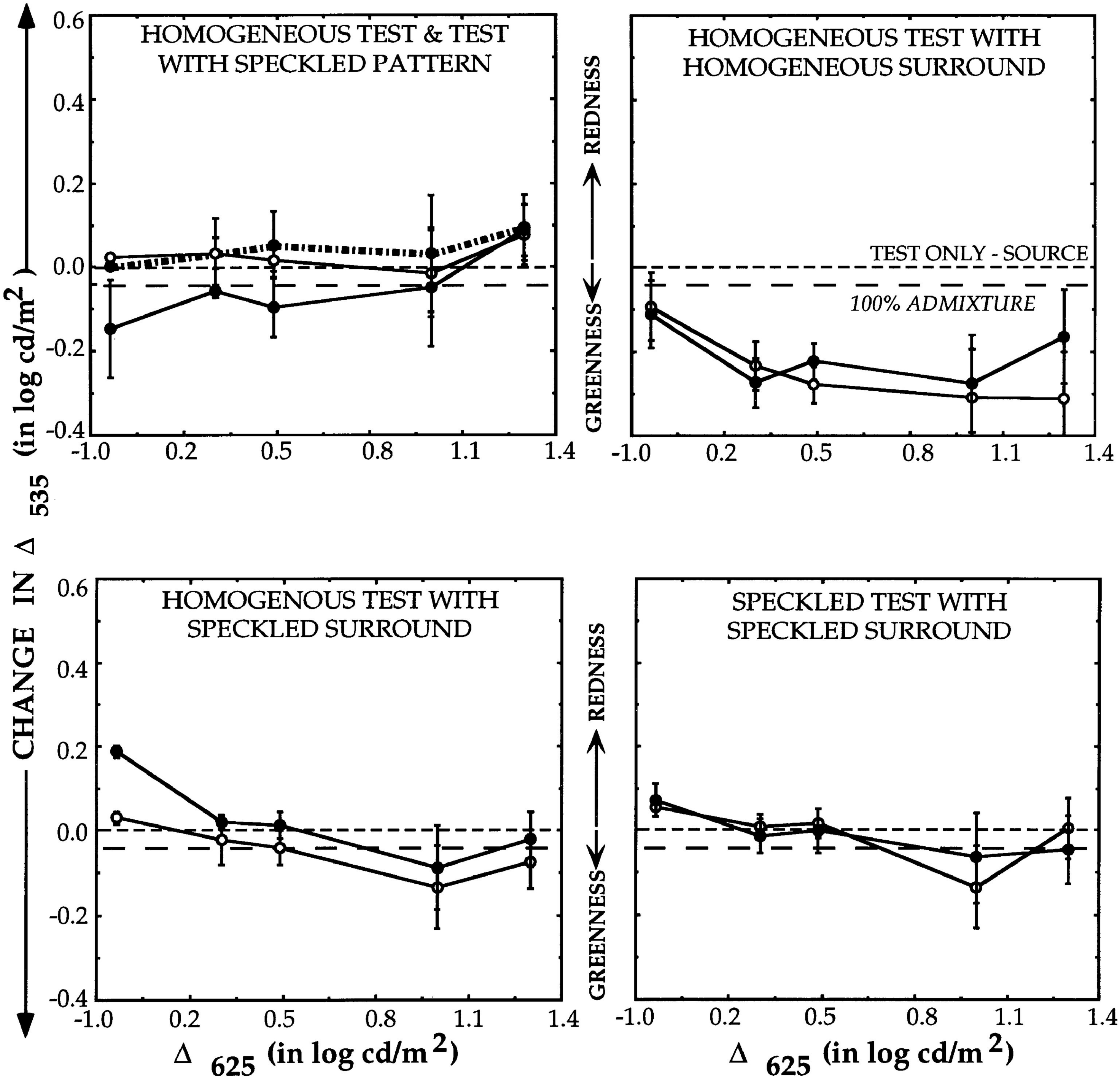


FIGURE 11. As Fig. 9 but for Observer J.M.

DIFFERENCE PLOTS FOR OBSERVER JM - GREEN SURROUND

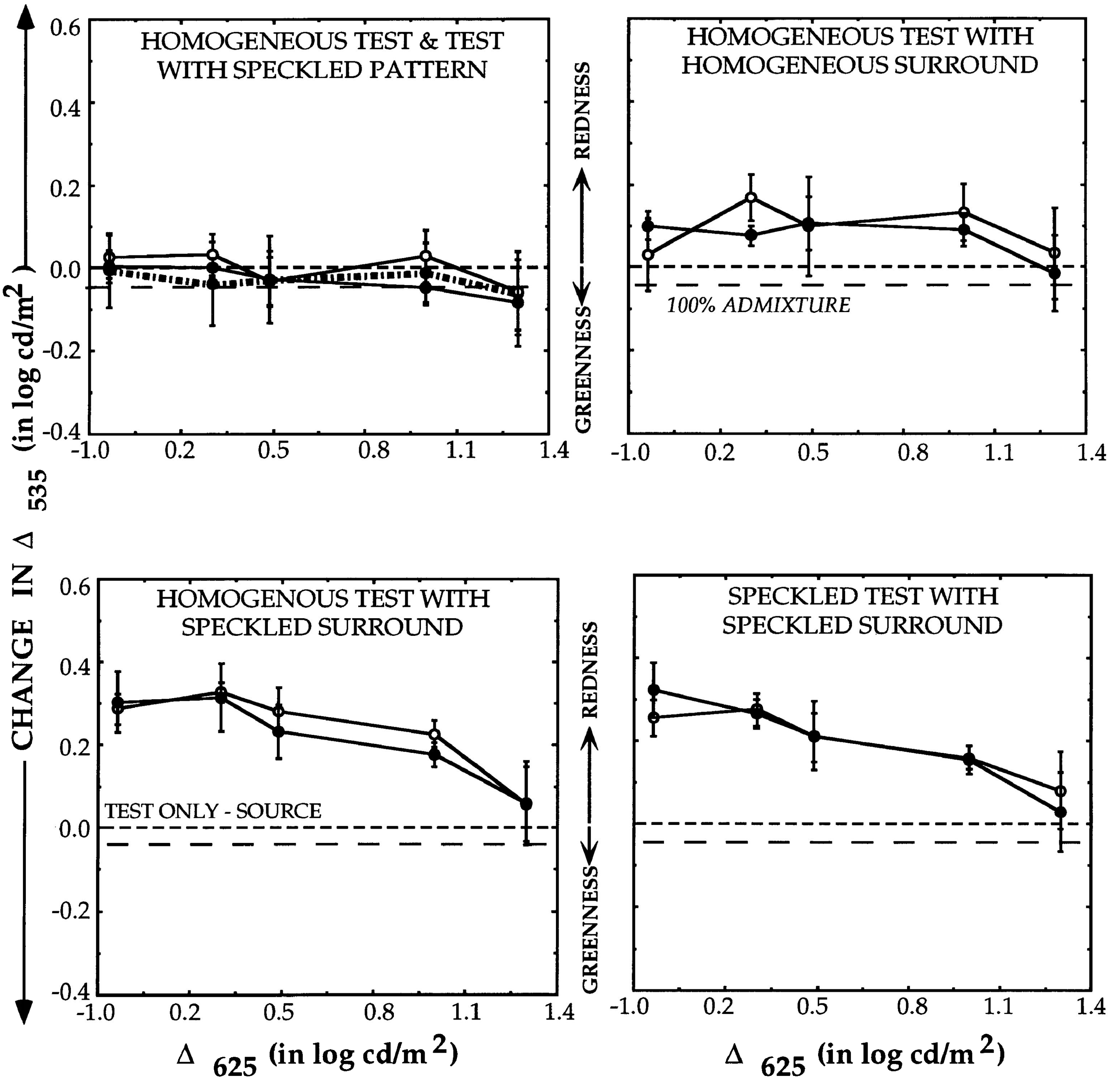


FIGURE 12. As Fig. 9 but for Observer P.R.

DIFFERENCE PLOTS FOR OBSERVER PR - GREEN SURROUND

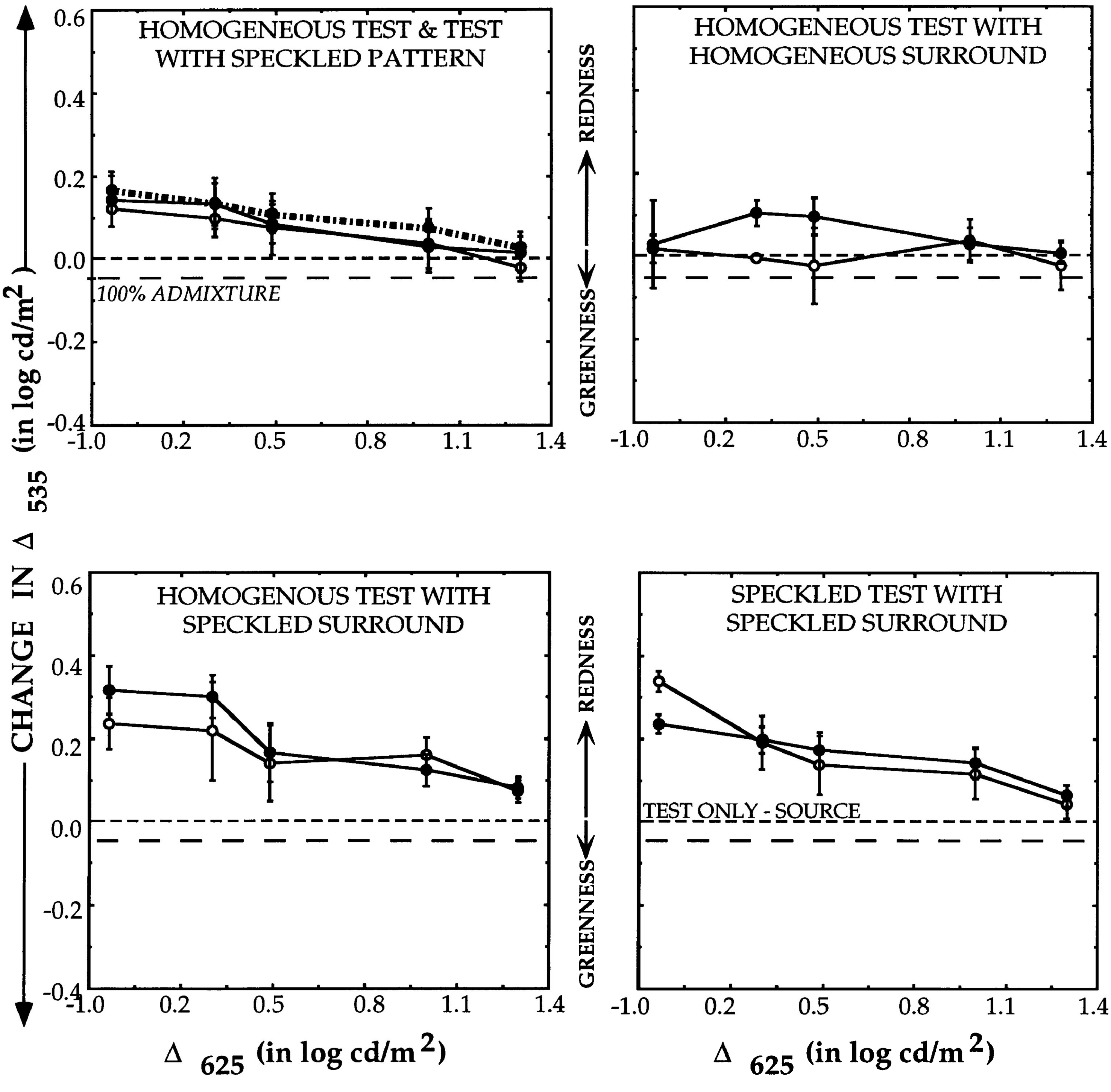
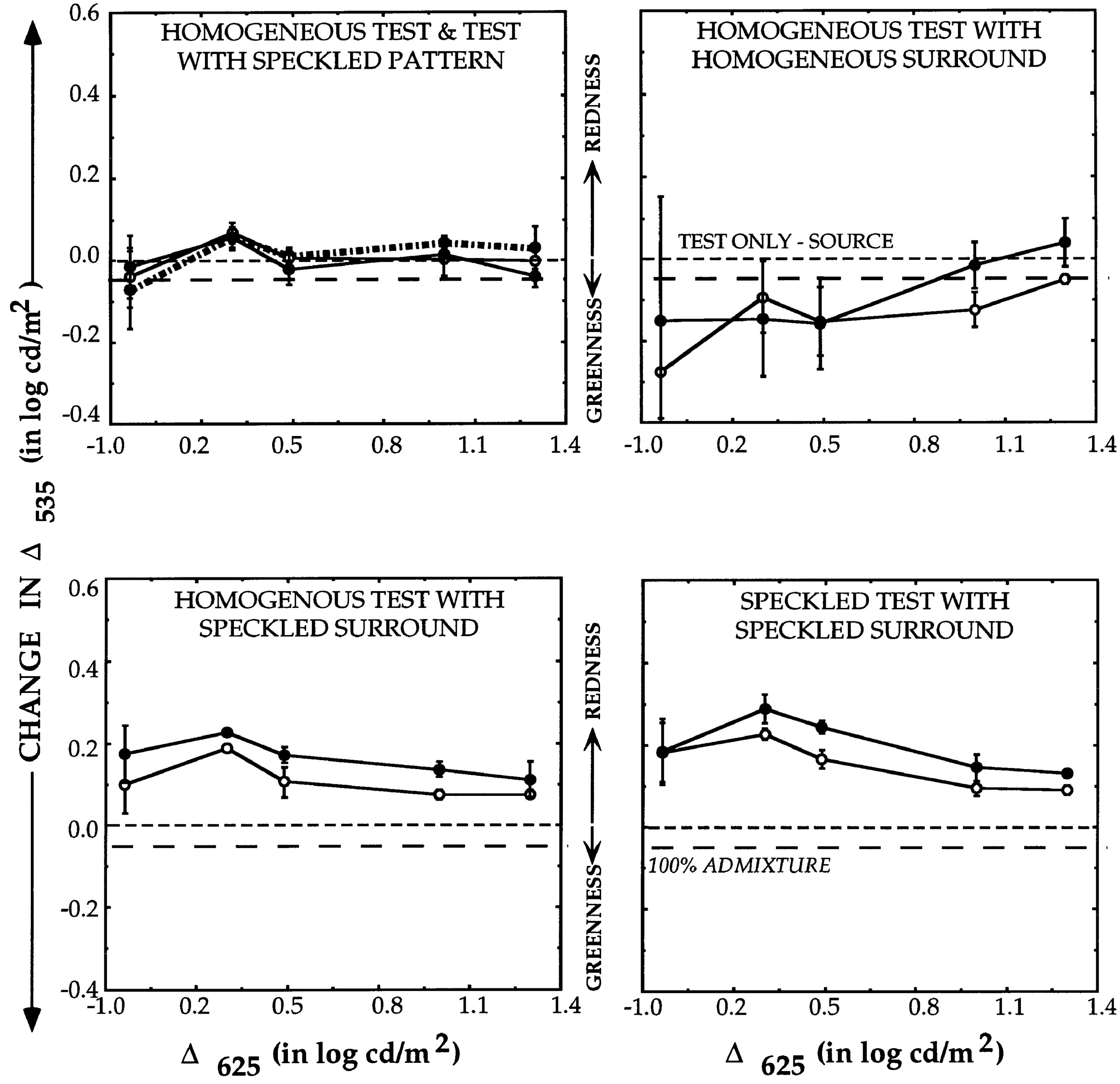


FIGURE 13. As Fig. 9 but for Observer R.C.

DIFFERENCE PLOTS FOR OBSERVER RC - GREEN SURROUND



differenced by ±2 nm or more (~ 1.79 cd/m^2 or 0.25 log cd/m^2 change in Δ535) are at suprathreshold (MacAdam, 1943). Therefore, any change at or greater than 0.4 cd/m^2 (-0.4 log cd/m^2) is viewed as a perceptible difference in colour appearance.

Measures from the random-dot speckled test presentation included in the experiments are shown in the upper left panel with the homogeneous test viewed as a surface data (dot-dashed line). Only the surface data is presented in the panel because the baseline data was from the homogeneous test viewed as a source. No significant differences were found between surface and source viewing for the test-only conditions nor between the surface and textured test conditions for all observers (cf. dot-dashed with continuous lines).

Most of the observers in both experiments failed to show any systematic changes due to the light source and surface instructions for *any* stimulus configuration (cf. open and filled symbols in all panels). Only observer M.M. in the "red" surround experiment showed a separation between light source mode and surface mode (Fig. 5 - Upper right panel). Interestingly, the stimulus configuration that produced the separation was the most ambiguous (homogeneous test with homogeneous surround). The shift in the surface mode at low test luminances was characteristic of chromatic induction (i.e., an opponent response). The light source response exhibited characteristics of physical admixture (i.e., more Δ535 was used to reach red/green equilibrium); however these redness shifts were greater than expected from scattered light (up to 0.8 log cd/m^2 at low test luminances) and do not show the characteristic "pedestal" effects associated with physical admixture. The large dashed line above the dark adapted line in Figs 5-8 represents the maximum amount of light that can be expected to admix into the test were the "red" background an adapting field. The large dashed line below the dark adapted line in Figs 9-13 indicates the same admixture for a "green" adapting field. We calculated that for a 5° square surround, 10.8% of the light spreads into at the test boundary and 6.5% of the light spreads to the centre of the 1° square test. This translates into less than 0.32 cd/m^2 (-0.5 log cd/m^2) scattering into the centre test from the surround.

The remaining observers (D.S., K.G. and P.K.) in the ambiguous "red" surround conditions showed colour shifts towards redness (cf. Figs. 6-8, upper right panels). There were greater shifts (up to 0.5 cd/m^2 or -0.3 log cd/m^2) at low Δ_{625} illuminances indicating again, that an increase in relative percent admixture from the surround was contributing to the colour appearance of the test. However, as was the case with Observer M.M., spread light from the "red" surround cannot account for the pedestal effects seen in these observers.

For the textured surrounds (lower panels) Observer M.M. continued to show strong opponent responses for both instruction sets. The strongest induction effects (greenness shifts of up to 1.3 cd/m^2 or 0.1 log cd/m^2) were measured with the least surface-ambiguous stimuli (speckled test and surround). The other observers continued to show admixture effects, although observer K.G. did show slight deviations towards greenness at low test illuminances for the textured test and surround condition (Fig. 7, lower right panel).

As found in the "Red" surround experiment, the test-only data measured in the "Green" surround experiment revealed no differences in colour appearance due to texture or instruction set (cf. Figs. 9-13, upper left panels). Observers C.B., M.M. and R.C. in the homogeneous test and surround condition exhibited shifts that resembled physical admixture (i.e. greenness shifts below the dark adapted line; Figs 9, 10 and 13). The remaining observers (J.M. & P.R.) showed virtually no shifts from the baseline condition (Figs 11 & 12).

For the textured stimuli (cf. Figs. 9-13, lower panels), all observers either showed no change from baseline (Observer C.B. and M.M.) or shifts characteristic of physical admixture (Observer J.M., P.R., and R.C.). However, as was the case in the "Red" surround experiment, the magnitude of the shift cannot be accounted for by spread light (see dashed line below baseline).

Discussion

Viewing instructions affected the perception of colour for only Observer M.M., and occurred when he was presented with a surface-ambiguous test surrounded by an ambiguous "red" surround. Surface viewing produced a greenness shift while source viewing produced a redness shift that can be partially attributed to preretinal processes. Observer M.M.'s surface mode data can be explained by retinal desensitization (less sensitive LWS cones) and higher-ordered mechanisms (e.g., opponency). The redness shifts found with the source mode data, however, cannot be fully accounted for by physical admixture.

Surprisingly, more than half of the observers in both "red" and "green" surround experiments showed chromatic shifts in the direction of the surround chromaticity. Less shifts in the direction of the surrounds were found for the textured stimuli than for the homogenous stimuli, suggesting that less scattered light from the textured surrounds were admixing with the test. Indeed, the dark random dots reduced the total amount of light by 10%. However, as mentioned earlier, these values fall far short of the measured shifts. These findings challenge the normal properties of chromatic contrast, in which test colour shifts in an opposite direction to that of the surround. A change in colour appearance that is in the same direction as the surround is sometimes referred to as *assimilation* and usually occurs with small regions bounded by large chromatic backgrounds (Jameson & Hurvich, 1989). The exact mechanism for the assimilation-like effect we observed, however, is unknown because assimilation is attributed primarily to preretinal spreading in aperiodic stimuli (see Boynton, 1979). A possible explanation for these large shifts may be related to CRT viewing. The combination of relatively low stimuli luminances, broad band phosphor chromaticities and spatial inhomogeneities found in CRTs may establish surface mode viewing. Perhaps the large shifts towards surround chromaticity are properties of surface mode perception, suggesting a high level process that influences surface colour appearance in much of the same way as preretinal assimilation.

Another unexpected finding was that of the test-only measures. Usually, presenting a test field in an otherwise dark environment will show luminance invariance characterized as a linear function with a slope of one. The present study shows, however, that the test-only data for all observers were nonlinear and in some cases the data were approaching zero slope. (see Fig. 3 and 4) Two possible reasons for this behaviour are the limitations of the CRT phosphors and the spatial characteristics of the stimuli (i.e., square instead of circular). The former explanation deals with the broad band characteristics of the green and red phosphors. It is possible that the desaturated primaries used in this study, particularly that from the G phosphor which showed significant truncation from spectral "green" (see Fig. 1), may not be appropriate for procuring a unique balance between r-g and y-b pathways. Spectral or near spectral lights with narrow band properties may be a prerequisite for consistent unitary hue cancellation measures. This is unlikely, however, due to the apparent algebraic additivity of the chromatic pathways. For example, additivity is well recognized in colour matching tasks, in which any combination of three chromatic lights (no matter how broad band) can serve as primaries as long as no two add up to match the third. In fact, a quantal match made across the boundary of a bipartite field is maintained when different chromatic and/or achromatic (desaturating) light is added to both sides of the bipartite field. This demonstrates the scalar property of metameric matching and convincingly establishes additive linearity in chromatic processing (for review see, Wyszecki and Stiles, 1982).

On the other hand, the square shape of the stimulus may have produced the "pedestal" like responses of the test-only data. Activity of spatial channels in the visual pathway can influence chromatic processing, particularly if the high spatial frequency channels are active. A circular patch is less effectual in activating medium to high spatial frequency channels than a square patch (Graham & Nachmias, 1971). Many researchers have used circular patches to study chromatic adaptation and contrast for this reason. Unfortunately, our CRT programs restricted us to presenting square patches. The square patch may have been viewed as an inhomogenous field with luminance and chromatic variations near the boundaries of the test. Shevell (1982) found that adapting fields equal in size to the superimposed test patches produce the greatest "pedestal" effects. In the present study, observers may have perceived inhomogeneities in the square test as an indication of background energy contributing to the colour of the test. This could account for the notable nonlinearites at low Δ_{625} test luminances.

It is important to note that some observers in the "green" experiment did show opponent responses for the homogeneous test and homogeneous surround conditions. Once again, this condition was the most ambiguous because the stimuli contain no texture. Perhaps, these observers were interpreting the configuration as a aperture despite instruction set, thus providing data that conform to classic contrast induction. This trend is worth investigating. It implies that opponent processes are involved with illuminant but not surface perception.

The effect of instruction mode on Observer M.M. for the homogeneous test and homogeneous surround condition suggests that when cognitive awareness of a stimulus influences colour appearance, the effect manifests itself as an opponent response. Unfortunately, only Observer M.M. showed the effect. Perhaps this is consistent with Troost and de Weert (1991)'s argument that cognitive explanations are not sufficient to explicate processes involved in colour perception. For example, observers may use illuminant and surface reflectance information as stipulated by cognitive explanations of colour constancy, but the high-level mechanism that mediates its effect may do so by controlling low-level sensory mechanisms (i.e., a cortical feedback system). Understanding the interaction between cognitive and sensory mechanisms may aid in our understanding of why the observers in this study failed to demonstrate a consistent pattern of variability across observers and conditions.

While shifts indicative of opponency, desensitization and physical admixture were found, the apparent neural assimilation response found in many of the observers cannot be accounted for by any known mechanism. Possibly a high-ordered cognitive process is involved when viewing stimuli on a CRT that is not present when viewing true surfaces or illuminants. A future direction to studying these higher-ordered processes may relate to chromatic context. Wesner and Shevell (1992) have shown that contrast and context effect the colour appearance of a test field differently. Removing an area contiguous to the test field in the present study could reduce the effects of local contrast. A negligible contribution by physical admixture and opponency can be achieved by calculating the maximum distance necessary to reduce these opposing effects. Of course, to reduce opponent processes, the chromaticity of the noncontiguous surround has to be middle- or long-wavelength light (Wesner and Shevell, 1994). The inferred-illuminant model was derived from studies that were sensitive to the differences between contrast and context. Perhaps using similar configurations in the present study will increase the effects of instruction set by reducing or eliminating the potential confounds of local contrast.

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APPENDIX A

Instructions for Subjects

Your task in this experiment is to adjust the target color at the centre of the monitor until the test appears neither reddish nor greenish. The target is a light source, just like the sun or a fluorescent light. On some trials you will see just a single coloured light in the centre of the monitor. On other trials you will see either a coloured light containing dark specs or coloured light surrounded by another coloured field.

You can adjust the color by depressing the mouse on your left hand side. The left button will make the test appear greener, the middle button will make the test appear redder. When you believe the test appears neither reddish nor greenish, press the right button (OK button).

The target color will change on the monitor while you make the adjustment. After you press the right OK button, there will be a delay. You will be told when to start the next presentation.

Remember, you are looking at a light source, and your task is to remove any reddish or greenish tinge from it. Please make your judgments as quickly and accurately as possible.

DO YOU HAVE ANY QUESTIONS?

You will be dark adapted for 7 minutes and than presented a square light for 3 minutes.

APPENDIX B

Instructions for Subjects

Your task in this experiment is to adjust the target color at the centre of the monitor until the test appears neither reddish nor greenish. The target color is a surface, just like a book or a table. On some trials you will see just a single patch of color in the centre of the monitor. On other trials you will either see a patch of color containing dark specs or a solid patch of color surrounded by another coloured field.

You can adjust the color by depressing the mouse on your left hand side. The left button will make the test appear greener, the middle button will make the test appear redder. When you believe the test appears neither reddish nor greenish, press the right button (OK button).

The target color will change on the monitor while you make the adjustment. After you press the right OK button, there will be a delay. You will be told when to start the next presentation.

Remember, you are looking at an object and your task is to remove any reddish or greenish tinge from it. Please make your judgments as quickly and accurately as possible.

DO YOU HAVE ANY QUESTIONS

You will be dark adapted for 7 minutes and than presented a square adapting field for 3 minutes.