Surface Color Perception under Different Illuminants and Surface Collections

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"We do not see things as they are; we see things as we are."

- Talmud

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Chapter 1

Introduction

It is important for our daily life that we are able to visually identify and discriminate objects. Our ancestors could not even have survived without the ability to identify dangerous animals or discriminate ripe from non–ripe fruit. Objects have several attributes by which we can identify and discriminate them. Important attributes are size, shape, and color.

Unfortunately, environmental conditions change every now and then and affect these attributes. Consider a table as an example of an object (Figure 1.1). If we alter the distance between us and the table, the apparent size of the table changes. If we rotate the table by some angle, the apparent shape of the table changes. We are consciously aware that these changes occur, and that the perceived picture of the object changes. However, we do not interpret these changes as though the table as an object has changed in size or shape. In fact, we perceive the table as an object roughly constant in size and shape. These two features of our visual system are called size constancy and shape constancy, respectively (see Wandell, 1995). They are examples of perceptual constancies that help us compensate for changes in our environment to keep

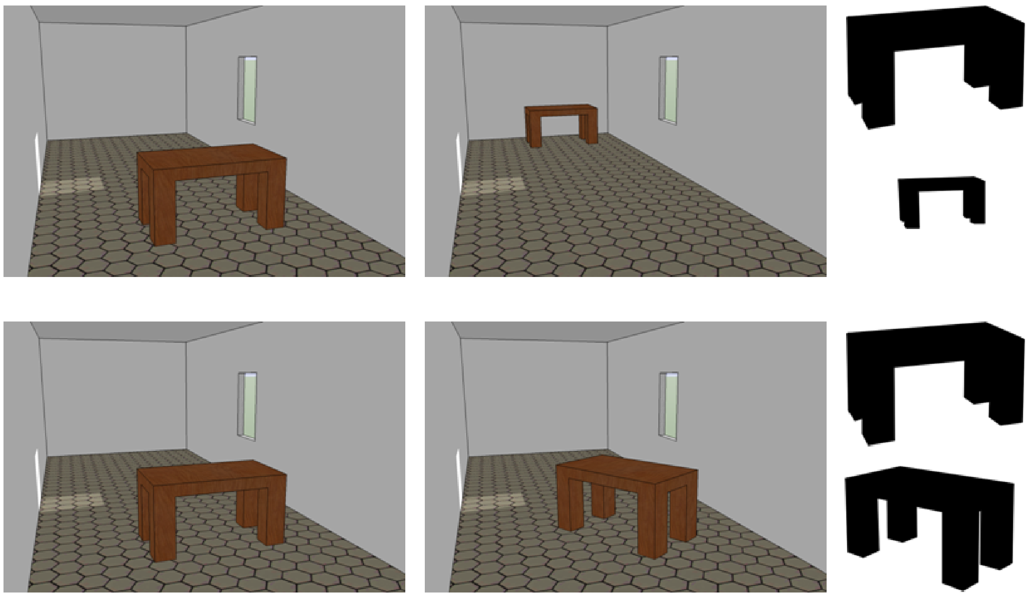


Figure 1.1: Size constancy (top row) and shape constancy (bottom row) exemplified by a table as a sample object. The object gets moved from an initial position (left column) to a new position (middle column). This transformation modulates apparent size and shape of the object. That becomes particularly obvious when depicting the objects in isolation (right column). Despite this, the table as an object within the scenes is perceived roughly constant in size and shape.

certain properties of objects at least roughly constant.

As we see in this example, for each attribute a clear distinction has to be made. First, apparent size and apparent shape correspond roughly to the retinal image of the object we look at and seems to be mediated by lower sensory processes of our visual system. Apparent size and apparent shape vary when changes in viewing distance to the object or changes in orientation of the object occur. Second, object size and object shape are mediated by higher, perceptual processes in the visual system. These processes bind the visual features of size and shape more to the object and use contextual attributes, like viewing distance and viewing angle, to generate an integral representation of the object (Rock & Linnett, 1993). Object size and object shape do not vary a lot when the context changes, thus reflecting perceptual constancies. It is important to note that we are aware of this distinction and that we can consciously switch between apparent and object code. Figure 1.1 depicts the above example of size and shape constancy and shows the distinction between apparent and object code.

1.1 Color constancy as a perceptual constancy

Another important attribute of objects is color. This attribute underlies changes in our environment as well. Consider a situation in which our table is illuminated by diffuse daylight through a window. While we are working on that table for some time the incident daylight changes rather slowly depending on daytime and weather conditions (Figure 1.2a). Despite these changes the color of the table surface remains roughly the same. Due to its slowness we are not aware of the illuminant change. The visual system is able to adjust to slow illuminant changes, discount the illuminant effect, and thus hold the color sensation, i. e. the *apparent color*, of the table roughly constant. Such adaptational mechanisms are considered to be fairly low–level, sensory processes (Kaiser & Boynton, 1996). We can describe apparent color in terms of hue, saturation, and brightness of the reflected light that meets the eye. These three attributes of color are helpful for us to give a unique description of a particular color sensation.

In another situation color can also be described as more related to the surface properties of the object itself rather than in terms of hue, saturation, and brightness of the apparent color of the reflected light. Consider our table located in a room illuminated by an ambient light. If we push the table against a window, part of the table surface may be locally illuminated by incident sunlight and the table as a whole is globally illuminated by ambient room light (Figure 1.2b). So there are two differently illuminated areas on the table surface that have distinct apparent colors. In contrast to the first situation, where illumination changed temporally slowly, the visual system has to deal with a rather abrupt spatial illuminant change. We are aware that this spatial illuminant change occurs and that rather different apparent colors are present within the scene. However, we do not interpret this change as though the table as an object has changed in color. In fact, we perceive the table as an object that has a roughly constant *object color*. Apparent color code as a description of the table surface color is of limited use in this type of situation where more than one light source is present since adaptation of the visual system is time-consuming and may take more than a minute (e. g. Fairchild & Reniff, 1994).

A third situation can be identified in which object color plays an important role to achieve constant color percepts. Consider our table located in a room diffusely illuminated by daylight through a window. When we switch on a tungsten bulb or a luminescent tube the overall illumination on the table changes abruptly (Figure 1.2c). Due to this, the apparent color of the table most likely changes as well. However, the *object color* of the table remains roughly the same. Our visual system has the ability to discriminate whether such a rapid temporal change in apparent color was due to an illuminant change or due to a change in object surface. In this situation, apparent color code is not a sufficiently useful description of the table color as well since illumination changes too fast for the visual system to use low–level adaptational mechanisms to achieve a constant color percept.

For each of the three described situations either apparent color or object color is the appropriate object description to achieve constant color percepts. Apparent color is mediated by low–level, sensory mechanisms, in which adaptation plays an important role (von Kries, 1905). In contrast, object color is mediated by higher–order, perceptual mechanisms (Helmholtz, 1866). These mechanisms relate color to the object and use contextual cues, such as illuminants and other objects in the scene, to generate an integral representation of the object. Often we are aware of the distinction between apparent color and object color and may even be able to switch consciously between the codes.

Three situations could be identified where one or both of the two descriptions of color help to achieve constant color percepts. In the first situation, illumination changes rather slowly over time. The visual system is given enough time to adapt to these changes. Apparent color serves as appropriate descriptions for a constant color. Since illumination changes rather slowly over time this ability of the visual system to adjust to such a change is called *successive color constancy.*

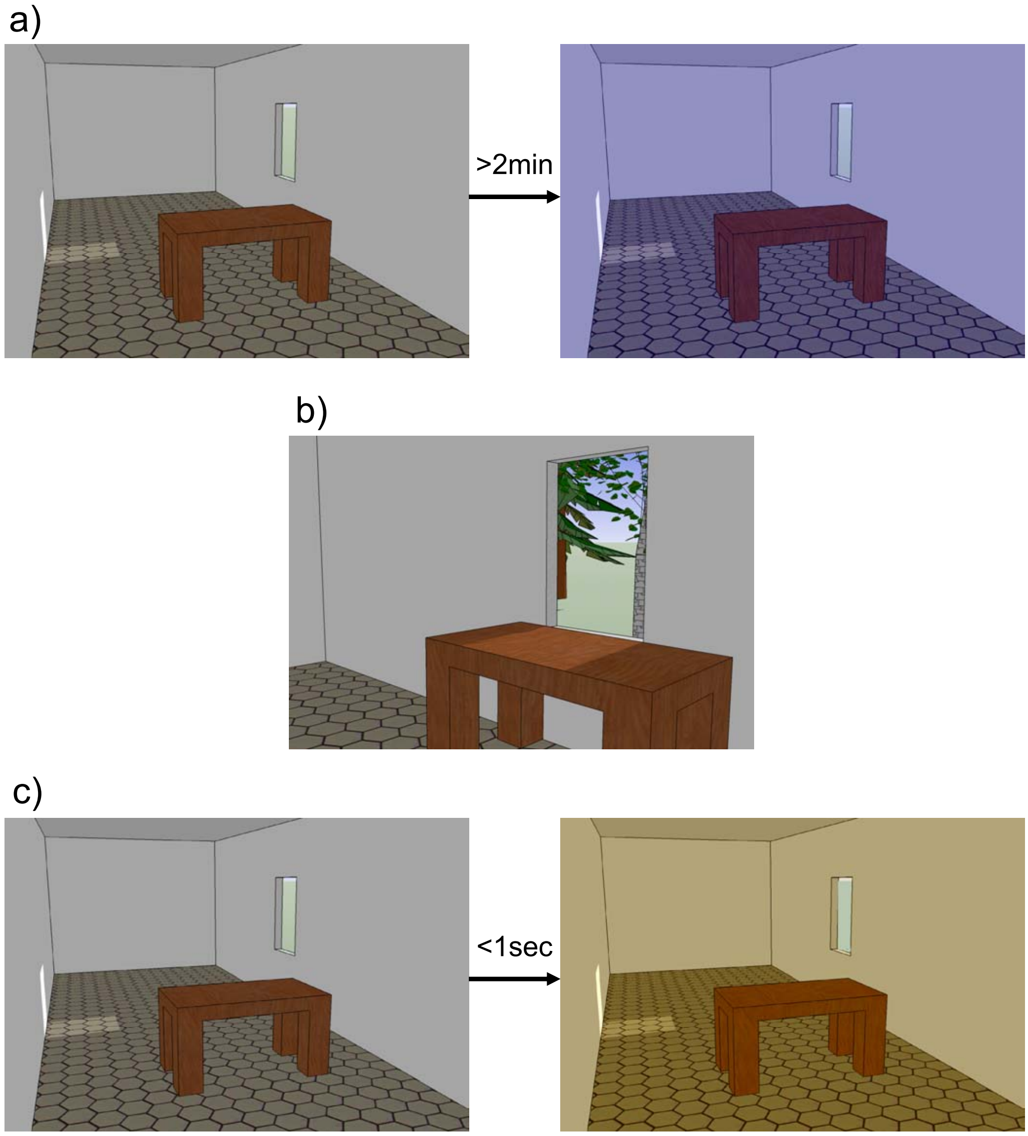


Figure 1.2: The three color constancy situations. a) The room is diffusely illuminated by daylight through the window. The illuminant changes rather slowly over time (successive color constancy). b) The table is globally illuminated by ambient room light and partly by direct sunlight through the window. The illuminant changes spatially yielding two different illuminants within the scene (simultaneous color constancy). c) The room is illuminated by daylight through the window. Then a tungsten bulb is switched on. The illuminant changes rapidly over time.

In the second situation, more than one illuminant is present within a scene, so illumination changes spatially. When a scene is illuminated by at least two illuminants apparent color processes do not provide an appropriate description of the colors since the visual system is not given enough time to adapt to either of the illuminants appropriately. Higher–order, perceptual object color processes compensate for this lack and give a roughly correct description of the color. It is important, however, that the observer shifts his view back and fourth between the differently illuminated parts of the scene to avoid strong adaptation to any of the illuminants. In this type of situation a scene is simultaneously illuminated by more than one light. Therefore, this type of visual compensation for illuminant changes is called *simultaneous color constancy*.

In the third situation the overall illumination changes rapidly over time. This change of illuminant yields a change in apparent colors of the objects located in this room. As above, apparent color processes are too slow to compensate for such a rapid illuminant change. However, perceptual mechanisms step in and help achieving an appropriate color description.

1.2 Open issues of color constancy

Previous research focussed on investigating visual adjustment to changing illumination using successive and simultaneous color constancy paradigms (e. g. Brainard & Wandell, 1992; Arend & Reeves, 1986). The goals of these studies were mainly to examine the basic characteristics of the visual adjustment processes. Some basic principles were found. A first principle states that visual adjustment can be described as an appropriate scaling of the responses of the three receptor classes to the changing illumination (see chapter 2.1 below), a principle called *receptor scaling* or *von Kries principle* (von Kries, 1905). The second principle states that the scalings of the receptor responses vary linearly with an illuminant change, a principle called *illuminant linearity*. The principles were confirmed under a variety of illuminants and surface sets of which the scenes were constructed since it is important that color constancy holds under common illuminant changes and in a variety of scenes. Additionally, there are some studies which focus on the issue to which extent color constancy works under particular illuminants or surface collections.

There is also some research which deals with color constancy in situations in which illuminant changes occur temporally abrupt (e. g. Craven & Foster, 1992). The methods used are always discrimination paradigms of some sort. Observers are presented two images in rapid succession. Between the images either an illuminant change occurs or the surfaces of which the images are made up are changed. Observers are asked to judge whether the change between the images was due to an illuminant change or due to a change in surfaces. It was shown that observers are able to make these judgments reliably and effortlessly. However, for this type of situation not much is known about how constant our visual system is under different illuminants or surface collections. For a better understanding of color constancy under rapidly changing illuminants this gap is supposed to be filled. Additionally, a comparison of the result patterns for this paradigm and successive and simultaneous color constancy paradigms would provide a better insight to which extent the paradigms are related with respect to which results they produce.

Existing theories of color constancy frequently involve the above mentioned principles of receptor scaling and illuminant linearity. Since the latter principle tells us about the dependency of visual adjustment on the illuminant change, illuminant linearity might be challenged when the degree of color constancy varies drastically with illuminant direction or surface collection. It is not clear by now which impact such results would have on existing theories of color constancy.

The aim of the present work is to give some answers to the issues described above. A series of experiments is reported in which color constancy under various rapid illuminant changes and surfaces collections is investigated. The results of the experiments are supposed to contribute to a better understanding of color constancy.

1.3 Chapter overview

The remainder of this work is structured as follows. Chapter 2 deals with the foundations of color constancy. In the first section, it is described how the light incident at the eye is composed and how this light signal is encoded at different sites within the visual system to generate a color percept. In the second section, it is explained what the fundamental problem of color constancy is like. In the third section, sensory, perceptual, and cognitive processes are described supposed to play a role in mediating color constancy.

Chapter 3 prepares the empirical part of this work. It describes which illuminants and surfaces we encounter in our everyday environment. After that it reclaims previous studies which deal with the role of illuminant color direction and surface collection for color constancy. The goals of this work are pointed out.

Chapter 4 describes the general methods applied for all the experiments in this work. Additional methodological aspects are described in the "Methods" sections of the respective experiments. In all experiments, the operational paradigm derived from Craven & Foster (1992) is used. A brief summary of the setups used in the particular experiments is also provided.

In chapter 5, four experiments are described which deal with surface color perception under different illuminants and surface collections. In Experiment 1, I investigate which role a change in luminance can play when the illumination on a scene changes. In previous color constancy experiments, the focus was on the role of chromaticity in illuminant changes while luminance of the illuminant was either held constant or was not controlled at all. In this experiment, conditions where illuminant changes were either isoluminant, or isochromatic, or where both chromaticity and luminance changed were designed. The results of the experiment show that the effect of luminance changes on color constancy is small.

Experiment 2 deals with the role of color direction in illuminant changes. Previous studies on this topic mainly focussed on illuminant changes along the daylight axis. However, since illuminations on a scene are mostly influenced by non–daylight illumination that deviates from the daylight axis it is important to investigate color constancy under illuminant changes along an orthogonal red–green axis as well. Results of this experiment show high color constancy under illumination changes along the green and blue semi–axes, medium constancy along the yellow semi–axis, and rather low constancy under changes along the red semi–axis. In a second step I tried to investigate how color constancy in further illuminant directions fit in the color constancy pattern obtained. Four additional test illuminants were introduced. Results show that color constancy performance in all eight illuminant directions yields a smooth pattern with highest constancy in greenish and bluish directions, medium constancy in yellowish directions, and lowest constancy in reddish directions. In Experiment 3, I investigate if the obtained pattern of color constancy values would be stable under variations of signal–to–noise ratios. By increasing and reducing noise in two separated conditions task difficulty is aggravated and facilitated, respectively. The results show that the basic shape of the pattern remains largely constant across conditions.

Experiment 4 deals with color constancy under variation of objects within a scene. It is investigated whether the degree of color constancy is constant or differs under changes in surface collections. Surface sets which on average appear blue, yellow, red, or green, when viewed under a neutral illuminant together with the combined set which, on average, is neutral are used in this experiment. A red and a blue illuminant are also used. Observers' task is again to discriminate illuminant changes from surface changes in the scenes. Results show high color constancy with green and blue surface collections and rather low constancy with the red collection. This pattern is rather similar under the red and blue illuminants.

In chapter 6, a general discussion is provided. After an empirical summary, I draw conclusions from the experiments presented in this work in order to give an answer to the questions raised prior in this work. There is an influence of color direction to the degree of color constancy. There is also an effect of surface collection which resembles the pattern obtained for the respective illuminants. There seems to be little difference for the amount of visual adjustment whether the resulting light incident at the eye stems from the variation of illuminant colors or from the variation of surface collections. The evolutionary approach might propose an explanation to the present results. The effect of individual differences and a comparison of the results to the findings in successive and simultaneous situations are also discussed.

The general discussion closes with implications for further research.

Chapter 2

Foundations of color constancy

2.1 From light to color

The classic psychophysical experiment to investigate color vision is the color–matching experiment. An observer looks at a bipartite field consisting of a test side and a match side. The test side shows a particular color. The match side shows a color that is an additive mixture of so–called primary lights, which have independent spectral power distributions. The intensity of these primaries can be independently manipulated by the observer. The task of the observer is to adjust the intensities, i. e. the weights, of the primaries to match the apparent color of the match field to the apparent color of the test field. It can be shown that such a match can always be achieved with at least three primary lights[1]. Considering the high–dimensional spectral power

[1] There is a restriction to this assertion, since not every light can be matched by an additive mixture of three primary lights. For some lights, one of the primaries has to be subtracted from the match side and added to the test side to achieve a match.

distribution of a light[2], it is a remarkable feature of the human visual system to get by with only three primaries. This feature is called trichromacy. Due to this rigorous reduction of information, there are many lights which are physically different but psychophysically indistinguishable.

In addition to trichromacy, the color matching experiment reveals two other remarkable principles of color perception. First, when the intensity of the light on the test side gets scaled, e. g. by doubling it, the observer also doubles the intensity of the light on the match side to obtain a match. In general, if a and b represent the lights on the test side and on the match side and are perceptually equal, i. e. have the same color, then ka is perceptually equal to kb. This law is called *homogeneity*. Second, when adding a second light to the light on the test side to produce a color mixture, the observer adjusts the light on the match side as if he added the same light which was added to the test side. In general, if the lights a and b are perceptually equal, then the additive mixture $a + c$ is perceptually equal to the additive mixture $b + c$. This law is called *additivity*. In other words, the symmetric color matches are invariant to scaling and additive mixture.

The first to describe the three principles trichromacy, homogeneity, and additivity was Grassmann (1853), which is why they are called *Grassmann's laws*. The important conclusion from these findings is that through homogeneity and additivity the sensation 'color' can be numerically mapped into a vector space. From trichromacy we also know that the dimensionality of this space is three. However, there is no unique basis for this vector space. Any set of three primaries — as long as they are linearly independent — may

[2]The dimensionality of a spectral power distribution depends on the sampling rate. Sampled in 10 nm steps from 400 nm to 700 nm, as done for experiments in this work, the dimensionality is 31.

be chosen in order to succeed in the color–matching experiment.

Based on the information of the color–matching experiment it has been speculated that three classes of receptors in the visual system would suffice to mediate color vision (Young, 1802; Helmholtz, 1866). However, where exactly these receptors are sited, what their characteristics are, and how the signals of the receptor responses are further processed, had yet to be investigated.

2.1.1 Receptor site

The principle of trichromacy was first stated by Young (1802) and later reformulated by Helmholtz (1866). They hypothesized that there are three receptor classes in our retina, one that is mainly sensitive to short–wavelength lights, one that is mainly sensitive to middle–wavelength lights, and one that is mainly sensitive to long–wavelength lights. One approach to investigate the characteristics of these receptors was to carry out further psychophysical experiments. Important insights could be gained from color–matching experiments with observers that lack one of the three receptor types. This was done in a famous study by Smith & Pokorny (1975), who could thereby estimate the sensitivity for each of the three receptor — or cone — classes as a function of wavelength. Further estimates were done by Stockman, Sharpe, & Fach (1999) and Stockman & Sharpe (2000). Figure 2.1 shows these so–called Stockman–Sharpe estimates of the spectral sensitivity functions, which are widely used in color science.

A second approach to investigate the spectral sensitivity functions of human receptor types is to measure the receptor response signals physiologically. This was first done in 1987, when three scientists published single–cell

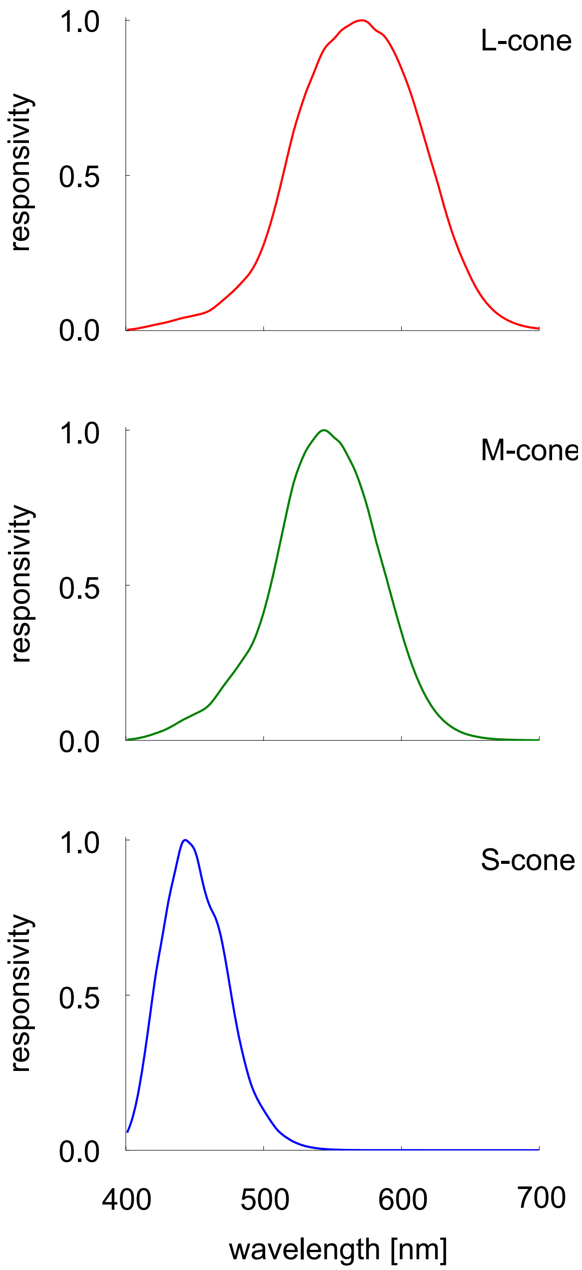


Figure 2.1: Estimated responsivities of the long–wavelength sensitive L–cone class, the middle–wavelength sensitive M–cone class, and the short–wavelength sensitive S–cone class (after Stockman & Sharpe, 2000).

conductions of the middle– and long–wavelength receptors of a human male retina (Schnapf, Kraft, & Baylor, 1987; see also Brown & Wald, 1964, and Dartnall, Bowmaker, & Mollon, 1983, for other measurement techniques). Two outcomes of this study are notable. First, the measured spectral sensitivity functions of human receptors are identical to those of receptors in macaque monkeys' retina within error of measurement (Baylor, Nunn, & Schnapf, 1987). Second, they are almost completely identical with the psychophysically obtained estimates by Smith & Pokorny (1975).

As shown, the spectral sensitivity functions of the color receptors in the human retina were assessed by two different approaches leading to similar results. This is important because the sensitivity functions provide a basis for further investigation of color vision.

2.1.2 Opponent site

Hering (1878, 1905) observed that the colors red and green as well as blue and yellow are perceptually linked as antagonistic pairs. He showed that looking at a red surface induces a green afterimage and looking at a green surface induces a red afterimage. Analogous results were obtained for the blue–yellow pair. He also asked subjects to imagine a color that is a reddish green or a yellowish blue. They could not perform the task although it was easy for them to imagine a cross–combination of other hues like a greenish yellow or a bluish red. These observations led Hering to his *opponent colors theory*. He proposed three opponent mechanisms that respond complementary to light of different intensity or wavelength: a black/white mechanism, a red/green mechanism, and a yellow/blue mechanism. Since Hering's observations had been of phenomenological nature and could not be supported by psychophysical or physiological correlates, his *opponent colors theory* was widely unaccepted for a long time, as opposed to Helmholtz' trichromacy theory.

Half a century later, Jameson & Hurvich (1955) proposed their famous hue cancellation paradigm, by which they were able to find psychophysical evidence for opponent color mechanisms. The goal of the study was to measure the redness, greenness, blueness, and yellowness for every monochromatic light of the visible spectrum. For this purpose, Jameson and Hurvich gave observers fixed red, green, blue, and yellow cancellation lights of single wavelengths. They presented monochromatic test lights and asked observers to cancel the redness out of the test light by adding the green cancellation light. To cancel out the greenness of the light, observers were asked to add the red cancellation light. The amount of added green cancellation light was taken as a measure for the redness of the test light, and the amount of added red cancellation light represented the greenness of the test light. Analog procedures were applied for measuring blueness and yellowness of test lights. Figure 2.2 shows responsivity functions of the opponent mechanisms obtained by Jameson & Hurvich (1955) together with the responsivity function of the achromatic black/white system. The two zero–crossings of the graph in the middle panel depict unique blue and unique yellow, respectively. The zero–crossing of the graph in the bottom panel indicates unique green. Unique red is non–spectral. These findings convinced the scientific community to consider Hering's theory. Since then, both trichromacy theory and opponent colors theory stood side by side. Shortly after the psychophysical findings, Svaetichin (1956) physiologically discovered opponent cells in the retina of carps, which suggested the existence of a similar correlate in humans and contributed to opponent colors theory from a physiological perspective.

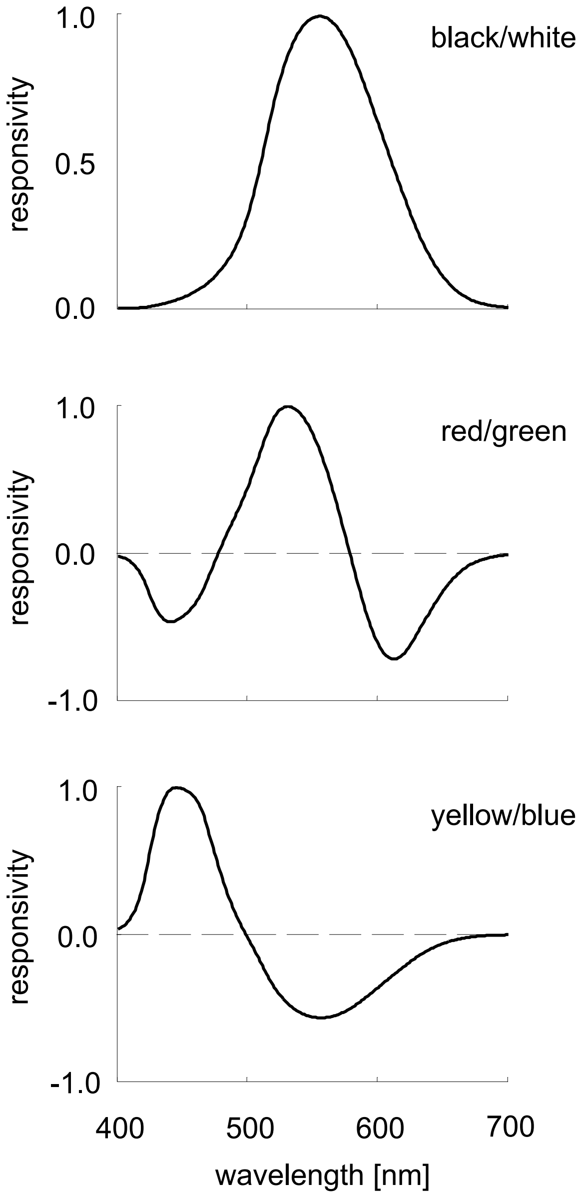


Figure 2.2: Spectral responsivity functions of the achromatic black/white system and the chromatic red/green and yellow/blue opponent color systems (after Jameson & Hurvich, 1955).

Krauskopf, Williams, & Heeley (1982) psychophysically obtained cardinal color directions for the three opponent color mechanisms. They found that the L-, M-, and S-cone signals were roughly recoded into L-M, S-(L+M), and L+M opponent color signals representing the red/green, yellow/blue, and black/white channel, respectively. Although this simple transformation of the cone signals was psychophysically confirmed, it was shown that the neural correlates of the recoding are far more complex (Lee, 2004).

Yet we have a rather good understanding about color opponency from further psychophysical studies (Gordon & Abramov, 1988; Abramov & Gordon, 1994; Bäuml & Wandell, 1996; Poirson & Wandell, 1993). The basics of the neural structure and wiring of receptor cells and opponent cells are also known (Lee, 2004). However, since the end of the 19th century, a visual cortex was postulated, where the signals from the retina converge and are further processed (Verrey, 1888).

2.1.3 Cortex site

Verrey (1888) was the first to suggest the existence of a center for the chromatic sense in the human cortex (Zeki & Marini, 1998). Almost a century later, Zeki (1973) could physiologically confirm color–specialized cortical cells of rhesus monkeys. fMRI studies showed that there exists a visual pathway leading through functionally separable cortical areas (Zeki & Marini, 1998). This pathway starts at the area striata, also called V1, where retinal signals converge. This area consists of small receptive fields that are highly sensitive to changes in wavelength composition of light (Zeki, 1983). These V1 cells, however, seem to be influenced by signals outside their receptive fields which account for discounting the color of the background (Wachtler, Sejnowski,

& Albright, 2003; Hurlbert, 2003), thus being a first candidate for holding colors constant by some color contrast mechanism. The signals are further transferred to area V2, where different types of opponent color cells were found (e. g. Derrington, Lennie & Krauskopf, 1983; de Valois & Jacobs, 1984). Area V4 consists of large receptive fields, which are activated when looking at large multicolored scenes. This area is supposedly responsible for global processing of images and is therefore a first candidate for mediating color constancy (Bartels & Zeki, 2000). A recent study showed that the majority of V4 cells also shift their color–tuning functions appropriately when illumination changes (Kusunoki, Moutoussis, & Zeki, 2006). However, V4 cells responsible for color vision and those responsible for spatial vision are still hard to separate (Solomon & Lennie, 2007).

Despite these findings, the understanding of the functions of separate areas in the visual cortex is far from complete. Investigating the cortical site of color processing is a rather complex topic, and the description of the color pathway still has substantial gaps. For good reviews of cortical processing of color signals see Bartels & Zeki (2000) and Solomon & Lennie (2007).

2.2 The color constancy problem

In chapter 1, it was pointed out that the human visual system is capable of holding object colors constant, despite variation in ambient illumination. Successive color constancy refers to the finding that apparent colors remain roughly constant when illumination changes rather slowly. Simultaneous color constancy refers to the finding that object colors remain roughly constant when illumination changes spatially in an abrupt way. A third type of constancy refers to the finding that object colors remain roughly constant when illumination changes temporally fast. However, when an illuminant change takes place, photoreceptor responses, which are the first stage of color coding, do not remain constant. Figure 2.3 depicts how the light incident at the eye occurs. It is shown which receptor signals arise when a surface is illuminated by two different lights. There are two factors mediating the light reaching the eye: the illuminant and the surface. An illuminant may be specified by its spectral power distribution. This is the radiant power as a function of wavelength. Daylight illumination can vary drastically over the day from white to bluish and yellowish (Judd, MacAdam, & Wyszecki, 1964). A surface may be specified by its reflectance function, which is a physical attribute of the surface. It expresses the fraction of reflected light as a function of wavelength. When an illuminant meets a surface, the reflected light may be expressed by the wavelength–by–wavelength product of the spectral power distribution and the surface reflectance function. This light stimulates the receptors in the retina, whose excitatory pattern r_i can be expressed by

$$r_i = \sum_{\lambda} E(\lambda)\, S(\lambda)\, R_i(\lambda)$$

where E is the spectral power distribution of the illuminant, S is the surface reflectance function, and R_i are the sensitivity functions of the three receptor classes $i = L, M, S$. It is shown in Figure 2.3 that a change in the spectral power distribution of the illuminant leads to a different light incident at the eye. As a result, the excitatory pattern of the receptors typically changes with illumination. If our visual system solely relied on the information of the receptor responses, colors would change drastically with illuminant changes. It is therefore obvious that the visual system has to further process the receptor signals to adjust to changes in illuminant and create robust color

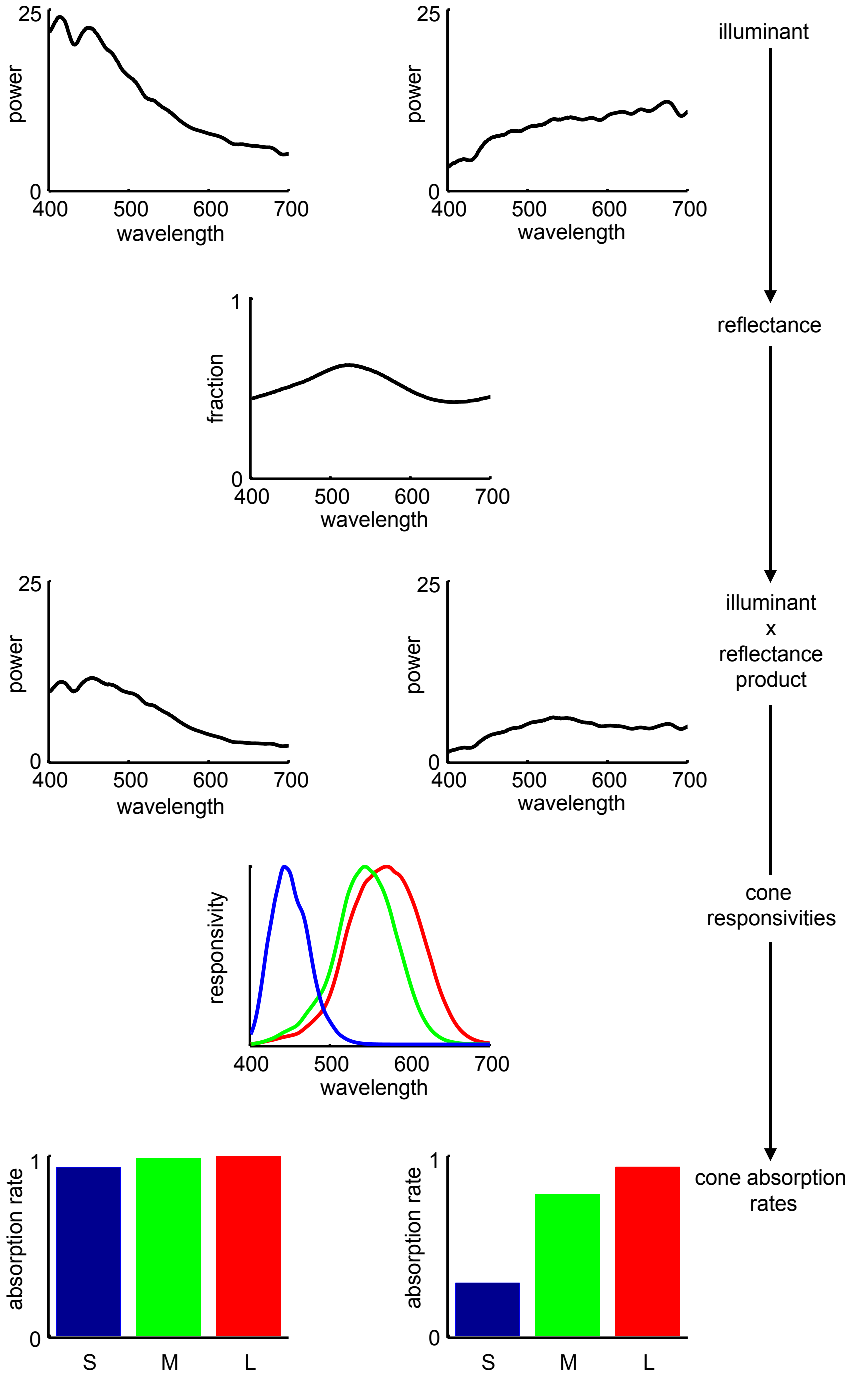


Figure 2.3: Depiction of the color constancy problem. When a surface is illuminated by two different lights, different cone absorption rates might result. To achieve a constant surface color, the visual system must compensate for this illuminant change.

signals. Investigating the nature of these processes is the subject of color constancy research.

The next section gives a brief overview of the levels of the processes supposed to be involved in mediating color constancy.

2.3 Sensory, perceptual, and cognitive processes of color constancy

In section 2.1, the color pathway from the photoreceptors to the primary visual cortex was described. Anywhere along this pathway, there have to be one or more stages that process the light from objects viewed in a scene to a constant color, with only small dependency on the surrounding illumination. Physiologically, it is not entirely known where in the color pathway responsible processing stages are located. Psychophysically, the basic characteristics of the visual adjustment process were already identified (e. g. Brainard & Wandell, 1992; Bäuml, 1999a). However, it is not known in detail how different processes work and how they interact with each other to achieve color constancy in different everyday situations. It is common belief nowadays, that there are several stages that mediate color constancy at different levels of color processing (see Arend & Reeves, 1986; Hansen, Olkkonen, Walter, & Gegenfurtner, 2006). This chapter deals with the question which processes have already been identified that contribute to color constancy. Following the color pathway, these processes can be classified into sensory, perceptual, and cognitive categories.

2.3.1 Sensory processes

The retinal receptors are the stage where color processing begins, and their responses provide the basis for every further operation on the signal. So, the receptors are the first candidate to contribute to color constancy. From our experience of coming from the outside into a dark room or vice versa, we know that the visual system is able to adapt to darkness and brightness. This ability also holds in situations where the color hue of the surrounding illumination changes. Von Kries (1905) suggested that the visual system is able to adapt to the surrounding illumination, and that this adaptation is simply an appropriate scaling of the receptor responses that result from a viewed stimulus. In detail, if the illuminant mainly consists of long–wave light, mainly the receptor which is sensible to long–wavelength light becomes scaled. If the illuminant mainly consists of short–wavelength light, mainly the receptor which is sensible to short–wave light becomes scaled. Early studies tested this suggestion experimentally. Hurvich & Jameson (1958) used simple center–surround stimuli, where some test light was presented against a uniformly colored background. The task of the observer was to match a second light, presented against a second, differently colored background, to the test light. The illuminants were simulated through the colors of the background. It was found that the von Kries principle failed. Hence, the authors proposed a two–stage adaptation model where an additional additive process at the opponent color site modifies the scaled receptor signals. However, it was later shown that the failure of the receptor scaling principle was due to the binocular presentation of the stimuli, and that it was more the receptor responses of the center relative to the surround that were scaled, rather than the receptor responses of the center itself (Walraven, 1976; Werner & Walraven, 1982).

It was shown later that the findings with the simple center–surround paradigm could be generalized to more complex stimuli. Brainard & Wandell (1992) used more natural stimuli, so–called Mondrian patterns. The uniform surround representing the illuminant was replaced by a number of rectangular, differently colored patches. These patches were CRT simulated matte surfaces, uniformly illuminated by some simulated light. By testing several models to describe the form of visual adjustment to the illuminant, the authors could show that the fit of the simple von Kries receptor scaling model was as good as the fit of other more general models. Bäuml (1995) also used Mondrian stimuli and tested the hypothesis that the site of adjustment to illumination is at opponent color stage rather than at receptor stage. He showed that an adjustment of opponent color signals provided a much worse description of his data than an adjustment of receptor signals.

Receptor scaling has turned out to be a good model to describe experimental data of color constancy studies. However, it is silent about how these scalings depend on illuminant changes. Brainard & Wandell (1992) were able to identify another principle. They conducted a successive color matching experiment and showed that the scalings depend linearly on changes in illumination. They called this principle *illuminant linearity*. If the adjustment for two illuminant changes is known, the adjustment for a third illuminant change can be predicted by a linear combination of the two. Bäuml (1995) and Chichilnisky & Wandell (1995) were able to confirm their results and extended them to a wider range of viewing contexts.

There is some empirical evidence that at least the von Kries principle is not only valid in simulated Mondrian worlds but also holds in real–world situations. Brainard, Brunt, & Speigle (1997) used real papers rendered under real illuminants rather than CRT simulated illuminants and surfaces.

They measured color appearance in a simultaneous color constancy situation, where stimuli were presented side by side, and found good evidence for the von Kries principle. These studies indicate that receptor scaling plays a major role in adjusting to ambient illumination.

In addition to the validity of the receptor scaling principle, Brainard et al. (1997) found a color constancy index of about 60%. This is rather high when compared to similar simultaneous color constancy paradigms with simulated scenes, where constancy is on the order of 25% for color appearance (Arend & Reeves, 1986; Bäuml, 1999a). Brainard (1998) examined successive color constancy in real–world scenes with an achromatic adjustment paradigm. He found a color constancy index of 82%. This is again much better constancy than typically obtained in analogous CRT–simulated Mondrian scenes, where constancy is about 50–60% (e. g. Brainard & Wandell, 1992; Bäuml, 1994). Kraft & Brainard (1999) found a similar degree of color constancy in a rich real scene. The differences between real and simulated stimuli might be due to additional clues that are present in real–world scenes, which help the visual system to adjust better to the illuminant. It was also suggested that the visual system treats real and simulated stimuli different (Brainard et al., 1997). However, even in rich, three–dimensional real–world scenes rendered on a computer monitor, color constancy is higher than in classical flat Mondrian worlds (Delahunt & Brainard, 2004a).

The von Kries principle and illuminant linearity are substantiated rather well. They are considered to be low–level sensory processes. However, other higher–level mechanisms were identified that support the visual system in situations where sensory processes are of limited use for holding colors constant.

2.3.2 Perceptual processes

Von Kries adaptation proposes a single low–level mechanism: a simple scaling of the receptor signals. However, there is strong evidence that processes at higher perceptual levels have a large influence on how we perceive color. As mentioned in chapter 1, there are two different types of color codes, one referring to apparent color and one referring to object color. Arend & Reeves (1986; see also Arend, Reeves, Schirillo, & Goldstein, 1991) showed that the two types of color codes can be evoked just by giving the appropriate instruction to the observer. They carried out a simultaneous asymmetric color matching task presenting two Mondrian patterns side by side. They gave the observers one of two instructions. Either they were supposed to match hue, saturation, and brightness, i. e. the apparent color, of the matching surface to the test surface (appearance match), or they were supposed to set the match so that test and matching surface looked as if they were cut from the same piece of paper (surface match). The authors found relatively low color constancy of about 20% when observers were asked to make appearance matches, and relatively high color constancy of about 78% when asked to make surface matches. It is important to note that in simultaneous color constancy situations adaptational processes are excluded to a large extent, reducing low–level von Kries adaptation. Thus, the low constancy for color appearance is not surprising. However, the visual system is nonetheless able to compensate for illuminant changes concerning surface color to a fairly large extent. This ability has hence to be attributed to higher–level perceptual processes that are important for judging color in our everyday life.

In most three–dimensional scenes we encounter more than one illuminant.

Shadows, mutual reflections or multiple direct illuminants generate a fairly complex image, where low–level von Kries adaptation can only fail. The facility to perceptually separate apparent color from surface color supports the visual system in achieving color constancy in situations where sensory processes are of limited use.

From the results of the studies mentioned above, it might be concluded that the visual system must be able to somehow estimate the illumination to extract approximately correct color codes. Helmholtz (1866) suggested that the visual system disentangles the effects of illuminant and surfaces by estimating the illuminant and discounting it. In his view, color is generated by higher–level judgment rather than adaptation. Several cues to the illuminant within scenes have been identified, e. g. specular highlights, mutual reflections and spatial chromatic mean of the image, and there is evidence that the visual system combines them to achieve color constancy. Kraft and Brainard (1999) measured successive color constancy in nearly natural scenes. While successively reducing cues to the illuminant in the scenes, they observed a decline in the degree of constancy. Their results suggest that the illuminant is indeed estimated by the visual system.

In a rather different approach, it is assumed that there is no need for the visual system to estimate the surrounding illumination. It was computationally shown that, within receptor class, cone–excitation ratios from a pair of illuminated surfaces are almost invariant under changes of daylight illuminant (Foster & Nascimento, 1994). It was also shown that even in highly reduced experimental setups where no utilizable cue to the illuminant in the scene is given there is a considerable amount of color constancy. Amano, Foster, & Nascimento (2005) presented two Mondrians side by side in a simultaneous color constancy paradigm. Each of the patterns consisted of only two surfaces whereas one surface of one of the patterns served as the match surface. Observers were asked to make surface matches. Though it was impossible to estimate the illuminant in such a situation, the degree of color constancy was almost as high as in richer scenes with patterns of 49 surfaces. The authors proposed the invariance of cone–excitation ratios as the explanation of the results. This invariance yields the concept of *relational color constancy* (Craven & Foster, 1992). Craven & Foster (1992) developed an interesting approach to examine the concept of relational color constancy. They argued that it is vital for a human visual system to be able to discriminate whether a change of a scene is due to a change of illumination or due to a change in surfaces. Indeed, this is the case in situations where an illuminant changes abruptly, e. g. by switching a tungsten bulb on or off in a room already illuminated by daylight (see section 1.1). The authors presented two identical, yet differently illuminated, Mondrians in rapid succession. In some of the trials, there was an additional change in surfaces between the two stimuli. They asked observers to judge whether a change in illuminant or a change in surfaces occurred. They found that observers were able to make these judgments reliably and effortlessly.

The evidence of the physical invariance of cone–excitation ratios under illuminant changes is striking and offers an alternative to explain findings from several simultaneous color constancy studies. However, it is the task of physiological research to examine which site of color processing accounts for the ability to achieve constant surface colors.

Nowadays, there is high agreement that color constancy is not mediated by a single mechanism but by a combination of low–level adaptational and higher–level perceptual mechanisms (see Kaiser & Boynton, 1996). In addition, there is evidence that even cognitive mechanisms influence the apparent color of objects.

2.3.3 Cognitive processes

In recent years, support has emerged for the hypothesis that cognitive processes play a role in color perception. Hurlbert & Ling (2005) tested color memory for a real known object, a banana. In symmetric and asymmetric memory matching tasks, they found that the color match of the banana was shifted towards a too saturated yellow, while matches of color chips did not produce such a shift. While Hurlbert and Ling presented color chips for observers to choose from to make a match, Hansen et al. (2006) used achromatic adjustment as a measure for color memory. They asked observers to adjust the colors of simulated fruits and vegetables until they appeared grey. Similar to Hurlbert & Ling (2005), their results showed a shift of adjustment towards the opponent colors of the objects. For example, the adjustment for the banana was a slight blue, while the adjustment for a cabbage patch was a slight red. Achromatic adjustments of simple color chips, however, were close to the neutral grey point. These studies show that color memory of well–known objects has a considerable effect on color perception and helps us recognize the colors of objects.

2.4 Measuring color constancy

Apparent color and object — or surface — color was investigated using various experimental approaches. Experimenters typically use CRT–simulated surfaces and illuminants as experimental stimuli. As a paradigm, asymmetric color matching[3] is often employed. Observers are shown a set of grid–like arranged, rectangle, matte surfaces, so–called Mondrian patterns, which are illuminated by some light.

Apparent color can be measured both under successive and simultaneous color constancy conditions. In successive situations, observers have to memorize the color of a particular surface after visually adapting to the Mondrian pattern. After that, the same Mondrian is shown again but illuminated by a different light. After adapting to this new stimulus, observers have to adjust the apparent color of a particular surface in terms of hue, saturation, and brightness to make a match to the memorized color (e. g. Brainard & Wandell, 1992). A second popular paradigm is called achromatic adjustment. Here, the task for the observer is to adjust hue and saturation of a certain patch until it appears achromatic, i. e. until it appears neither bluish nor yellowish nor reddish nor greenish. Again, this is done successively under two different illuminants. In simultaneous color constancy situations, the two differently illuminated Mondrian patterns are presented side by side. The observer is asked to look back and fourth between the patterns to reduce adaptation to any of the stimuli. The task for the observer is to match hue, saturation, and brightness of a particular patch of the, say, right pattern to the corresponding patch of the left pattern (Arend & Reeves, 1986).

Surface color is typically measured in simultaneous color constancy situations. Two patterns are presented side by side, each rendered under a different illuminant. Observers are asked to match the color of a particular surface in one pattern to the color of the related surface in the other pattern. However, instead of adjusting the apparent color in terms of hue, saturation,

[3]The paradigm of asymmetric color matching is based on that of symmetric color matching, which is described in chapter 2.1.

and brightness, observers are asked to adjust the surface color so that it seems as if the two patches were cut from the same piece of paper (Arend & Reeves, 1986). It should be noted that the *apparent* colors of the two patches are usually different in this situation.

For both apparent and surface color, color constancy is usually measured with an index ranging from 0 to 1. The index is 0 when no constancy is observed, and 1 when perfect color constancy is found.

In the third situation described in the preceding section, the illuminant changes rapidly over time. The visual system must be able to assign the resulting change in apparent colors correctly to either a change in illuminant or to a change in surfaces. An interesting way to investigate this ability is the operational approach developed by Craven & Foster (1992). An observer is briefly shown two illuminated Mondrians in succession, each for one second. There is always an illuminant change between the two Mondrians and sometimes an additional change in surfaces. The task for the observer is to discriminate a pure change in illuminant from a change in surfaces. In the operational paradigm, discriminating illuminant changes from surface changes in a scene produces a class of constant color percepts (Foster, Nascimento, Craven, Linnell, Cornelissen, & Brenner, 1997). In matching paradigms, the corresponding class consists of all adjustments the observer is satisfied with. The paradigms are related insofar as both try to identify and describe the situations in which constant color percepts are yielded.

In the operational approach, color constancy can be measured in terms of the discrimination index d' (see chapter 4.4). The index is 0 when no constancy is observed and approaches infinity if color constancy is perfect.

2.5 Summary

Results from psychophysical studies using the symmetric color matching paradigm led to the suggestion that the human visual system encodes light with three classes of photoreceptors, which are sensitive to short–wavelength light, middle–wavelength light, and long–wavelength light, respectively. Psychophysical hue cancellation experiments showed that the three resulting signals are then recoded by opponent color mechanisms into light/dark, red/green, and blue/yellow signals. The receptoral and opponent color mechanisms were also confirmed, at least in part, by finding physiological correlates. It was further shown by fMRI studies that color signals are further processed in the primary visual cortex.

The color constancy problem describes the mismatch between different physical lights reaching the eye and perceptual equality of resulting color. When an observer is looking at a surface illuminated by a light that slowly changes over time, the apparent color of the surface remains roughly the same, although receptor responses, in general, change with the illumination. When an observer is looking at a surface which is rendered under an illuminant that changes spatially or temporally in a rapid manner, the resulting light incidents at the eye are also different, yielding different photoreceptor responses. In this situation, apparent color can only marginally be maintained. However, the surface color code generated in the visual system remains roughly the same.

Three stages can be identified where color constancy might be mediated. First, sensory processes are assumed to scale photoreceptors in order to achieve adjustment to a surrounding illumination. The so–called von Kries adaptation could be demonstrated in simple center–surround situations, as well as with Mondrian patterns. In a rather different approach, called *relational color constancy*, it was shown that — within receptor class — cone–excitation ratios from a pair of illuminated surfaces are almost invariant under changes of illuminant, ruling out any need for the visual system to adapt to the illuminant or to estimate it. Second, perceptual processes are assumed to estimate the ambient illumination by using a range of different cues typically present within a scene. In simultaneous color constancy paradigms, it was shown that a high level of color constancy can be found when observers were asked to regard all colors as surface colors instead of apparent colors. Automatic adaptational processes are reduced in such a paradigm, resulting in the assumption that the illuminant has to estimated by the visual system. Third, cognitive aspects are assumed to have a considerable effect on color perception. In fact, color memory was found to help us recognize the colors of common objects.

Chapter 3

Color constancy under different illuminants and surface collections

3.1 Illuminants and surfaces in our environment

There are three classes of illuminants in our environment. First, daylight illuminants are a mixture of sunlight and skylight, and vary from blue to white to yellow, depending on daytime and weather conditions. Judd et al. (1964) and DiCarlo & Wandell (2000) extensively measured spectral power distributions of daylight at various daytimes and weather conditions. The chromaticity coordinates of the daylights obtained by these measurements form a point cloud in CIE u'v' color space, and the fitted curve through this cloud is called the CIE daylight locus (Wyszecki & Stiles, 1982). Figure 3.1 shows that coordinates of 10760 daylight measurements roughly fall on a line. The basic shapes of spectral power distributions of daylights are rather similar and can be approximated by a low–dimensional linear model. It was shown that the first three basis functions derived from a principal component analysis are sufficient to render these illuminants almost exactly (Judd et al., 1964). Second, artificial illuminants include tungsten bulbs, fluorescent lamps, as well as any other artificially produced illuminant. Even though the spectral power distributions of artificial illuminants are different from those of daylights, it is notable that common artificial illuminants have chromaticity coordinates similar to that of daylights (Barnard, Martin, Funt, & Coath, 2002). Third, indirect illumination arises through mutual reflections of light at surfaces. As opposed to daylights and common artificial light sources, non–daylight illumination may have chromaticity coordinates far off the daylight locus, as can be seen in Figure 4.1. In everyday environments, we are exposed to a great deal of illumination resulting from mutual reflections at object surfaces. Such reflections alter the spectral composition as well as the intensity of the original light. For example, in forest areas, almost the entire illumination is indirect. A neutral daylight, say at noon, is reflected various times by leaves or other greenish surfaces. The resulting light which incidents at our eyes is then shifted towards green. Depending on the direct illuminant and the reflecting surfaces, non–daylight illumination can have a broad range of colors. It has been shown that it takes up a considerable proportion of the overall illumination within three–dimensional scenes (Ruppertsberg & Bloj, 2007) and can notably affect color appearance of three–dimensional objects (Langer, 2001). Non–daylight illuminants can be simulated in different ways. Since there is no direct natural equivalent to daylight illuminants, unique spectral power distributions corresponding

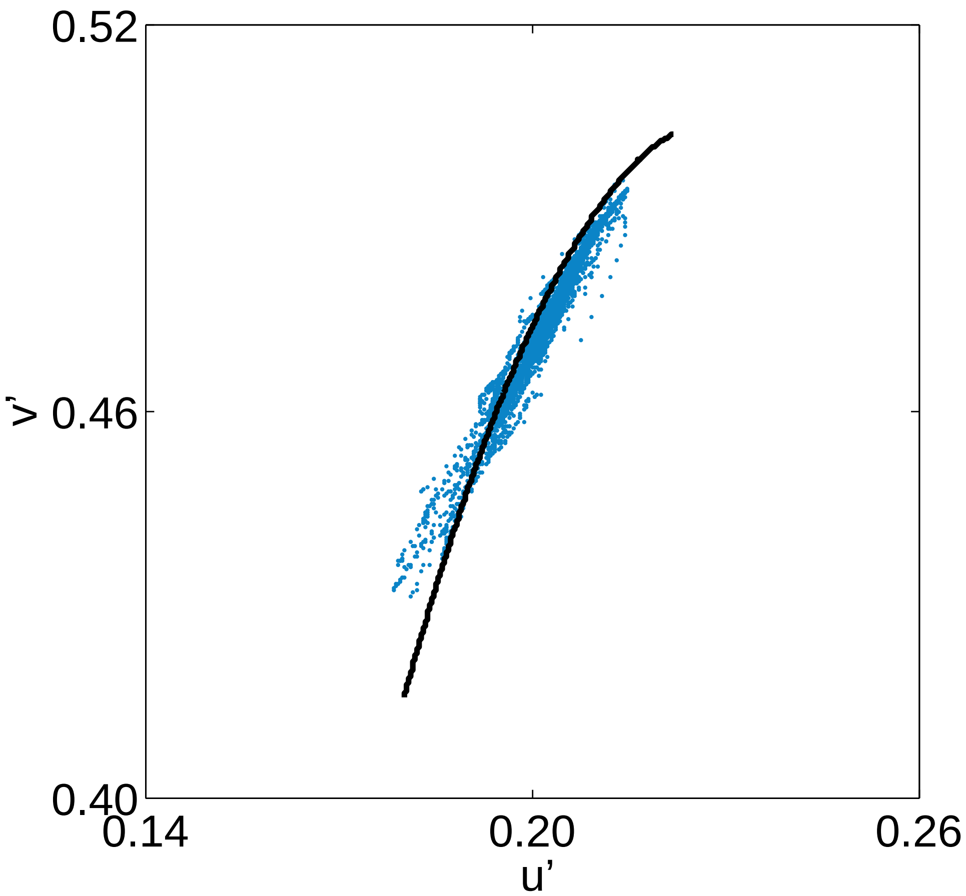


Figure 3.1: CIE u'v' coordinates of 10760 daylights, measured by DiCarlo & Wandell (2000). The solid line is the daylight locus.

to particular chromaticity coordinates do not exist. One way to construct a non–daylight illuminant is to use the daylight basis functions (Delahunt & Brainard, 2004a, 2004b). This is a convenient method used to construct a wide range of non–daylight illuminants. However, some illuminants do not lie within the three–dimensional model for daylight illuminants, resulting in spectral power distributions with negative power at some wavelengths. This is an undesired feature, since such spectra only exist virtually. These illuminants, lying mainly in the green area, can instead be constructed by a three–dimensional model of the spectral power distributions emitted by monitor phosphors. This method was used by Delahunt & Brainard (2004a, 2004b), who measured the basis functions of their laboratory monitor and provided them as supplemental material of their studies.

Furthermore, illuminant changes in our environment might not only involve changes in the relative spectral composition, i. e. the color hue, of the light but also an additional change in light intensity. For example, when coming out of a dark room to the outside into daylight, light intensity increases by several times. Thus, color should be regarded as having an intensity dimension in addition to the color hue dimensions.

Daylights and artificial lights are rather well–defined sets of illuminants, since spectral power distributions of daylights vary smoothly along the daylight axis and artificial illuminants have fixed and easily measurable spectral power distributions. Surfaces in turn are defined by their spectral reflectance functions, which do not represent a closed set as opposed to daylights, since there is an almost infinite number of natural and artificial surface reflectances (Nascimento, Ferreira, & Foster, 2002). Nascimento et al. (2002) made 640000 measurements of surface reflectance spectra in rural and urban scenes. It is notable that chromaticity coordinates of the mean reflectance spectra in rural scenes were shifted towards the green area compared to that of urban scenes, which gathered largely along the daylight locus. Similar results for natural scenes were obtained by Webster & Mollon (1997). Hendley & Hecht (1949) made measurements for foliage and earth surfaces, which clustered in a very small area in the green–yellow and yellow area, respectively. Burton & Moorhead (1987) measured reflectances of terrain scenes and found their data points scatter mainly in the green area. The mean reflectance had chromaticity coordinates of u'=0.191 and v'=0.473 which is a point that lies in the green direction relative to that of CIE D65 standard illuminant. Overall, spectral reflectances of urban scenes are rather equally distributed in color space with mean chromaticities clustering along the daylight locus. Reflectances of rural scenes are distributed more in the green area with means lying to the green side of the daylight locus. It is notable that, from the mentioned measurements, by far the fewest reflectances fall to the red side of the daylight locus.

Munsell tried to establish a classification system of a closed set of selected surfaces. These surfaces are perceptually ordered and span a wide range of spectral reflectances. The resulting *Munsell Book of Color* is considered representative for all natural and artificial surfaces (Maloney, 1986) and is widely used in color science. A representative subset of the Munsell surface collection is used in this work. Since the shapes of reflectance functions representing Munsell papers are not as similar as the set of spectral power distributions of daylights, it is not possible to fit low–dimensional models well enough to obtain acceptable results. However, it has been shown that five to seven basis functions are sufficient to properly approximate the reflectance functions of Munsell papers (Maloney, 1986).

3.2 Color constancy under different illuminants

Most previous color constancy experiments used daylight illuminants as experimental stimuli (e. g. Brainard & Wandell, 1992; Bäuml, 1999a; Craven & Foster, 1992). However, there is a number of studies which compared the degree of color constancy along the daylight axis and along other color axes. Most of them examined the role of color direction in successive color constancy situations, using asymmetric matching or achromatic adjustment. Lucassen & Walraven (1996) found better constancy in the blue direction than in the yellow direction using the neutral CIE D65 as a standard illuminant. Brainard (1998) used real illuminants and surfaces as stimuli. He found only slight differences in color constancy along several color axes. Rüttiger, Mayser, Serey, & Sharpe (2001) measured color constancy along the daylight axis and the red–green cardinal directions in color space. They found better color constancy along the red–green axis. Delahunt & Brainard (2004a, 2004b) conducted a detailed study regarding the issue of color direction. They used a simulated three–dimensional room in order to investigate successive color constancy in blue and yellow daylight color directions and orthogonal red and green color directions. They found rather high constancy along blue and green axes, mediocre constancy along the yellow axis, and rather low constancy along the red axis.

Simultaneous color constancy was investigated using asymmetric matching paradigms (e. g. Arend & Reeves, 1986; Bäuml, 1999a). None of these studies focused on constancy along different illuminant color directions. Bäuml (1999a), however, compared observers' appearance and surface matches and found them to differ only in a quantitative but not in a qualitative way. This qualitative similarity of appearance and surface matching might suggest similar constancy patterns along different color directions in successive color constancy and in simultaneous color constancy situations.

Some studies investigated performance at discriminating illuminant changes from surface changes using an operational paradigm similar to the one used in this work. Observers were shown two differently illuminated Mondrian patterns in succession. In some trials, an additional change in surfaces was applied. The task was to discriminate trials where a pure illuminant change occurred from trials where surfaces were changed. Foster, Amano, & Nascimento (2003) and Amano, Foster, & Nascimento (2003) examined performance in a blue and a green illuminant color direction and found similar performance. There are some further studies which also used this or slight variations of the discrimination paradigm (Craven & Foster, 1992; Foster, Craven, & Sale, 1992; Nascimento, 1995; Nascimento & Foster, 1997; Nascimento & Foster, 2000; Linnell & Foster, 2002; Foster, Amano, & Nascimento, 2001). However, there was no focus on performance along different illuminant directions.

Besides color hue, another important attribute of illuminants is their intensity. Most previous studies about color constancy either did not involve luminance changes or did not control them systematically. However, Werner & Walraven (1982) found an effect of luminance on the achromatic locus in an achromatic adjustment paradigm involving chromatic adaptation. Their experiment is somewhat related to successive color constancy studies, but very simple center–surround stimuli rather than Mondrian patterns were used. Brainard et al. (1997) examined simultaneous color constancy using a simultaneous matching paradigm and did not find an effect of luminance on observers' settings. They conducted their experiments in a room with real illuminants and surfaces to simulate natural viewing conditions. There is no experiment which investigates the role of luminance changes in situations where illumination changes abruptly over time. In studies examining this situation, luminance was either held constant (Craven & Foster, 1992; Foster et al., 1992; Nascimento & Foster, 1997; Nascimento & Foster, 2000; Foster, Amano, & Nascimento, 2001) or it was not controlled at all (Nascimento, 1995; Linnell & Foster, 2002; Foster et al., 2003; Amano et al., 2003). It is notable that in almost every study investigating the role of illuminant direction and luminance, considerable observer differences were found.

3.3 Color constancy under different surface collections

A color constant visual system is able to maintain object colors despite changes in surrounding illumination. To get along in different environments, this feature must hold across a variety of scenes. Those scenes can, for instance, be rural, forested, or urban. From our daily experience, our visual system compensates well for illuminant changes without dependence on scene surface composition. However, it has been mentioned above that there are also irregularities in color constancy under illuminant changes with different color directions which are hardly recognized in everyday life. Despite some research on this issue we do not know exactly how different surface collections influence the degree of color constancy.

There are a few studies that deal with the issue of the role of surface collection for successive color constancy. Bäuml (1994) examined achromatic loci in successive color constancy situations and found them to vary with surface collection. This effect was particularly large for surface collections with rather different mean chromaticity coordinates. He also found slight observer differences. Bäuml (1999b) also found observers' settings to vary with surface collection with different mean chromaticities. He found a slight interaction of the effect of illuminant and the effect of surface collection. Bäuml (1995) tested successive color constancy under different surface collections varying mainly in mean luminance rather than in mean chromaticity. He did not find an effect of surface collection on the color matches, but again there were individual differences. Brainard (1998) examined achromatic loci under differently colored backgrounds. He found detectable but small differences in adjustment.

Bäuml (1999a) investigated apparent and surface color constancy in a simultaneous situation. He found almost no differences between color matches under a neutral and a bright neutral collection, but some differences under a neutral and a red collection and under a bright neutral and a red collection. He compared results of his apparent and surface color matching paradigms and found them to be rather similar in a qualitative way.

Apart from the role of illuminant color direction and surface collection, it is important to investigate to which extent these two factors influence each other. A slight interaction of illuminant direction and surface collection was found by Bäuml (1999a) in both apparent and surface color matching situations. However, as the role of illuminant direction and surface collection is not clear in situations with abrupt temporal illuminant changes, we do not know if there is an interaction regarding the amount of visual adjustment.

3.4 Goals of the study

It was mentioned that there are studies showing at least slight effects of illuminant color direction and surface collection on the degree of color constancy. The vast majority of studies investigated this issue in successive or simultaneous color constancy situations. The results are, however, rather contradictory in regard to the pattern of constancy under different illuminants and surface collections. This might be due to some observer differences found along with a rather small number of tested observers. There is also some research to date dealing with the color constancy situation in which an illuminant changes abruptly over time. However, most of them do not examine constancy under different illuminant directions or surface collections.

This study is being done for two reasons. First, the influence of color direction in illuminant changes, as well as the role of surface collection, is unclear in color constancy situations with abrupt temporal illuminant changes. This gap is intended to be filled. If results from successive and simultaneous color constancy studies generalize to situations with rapid temporal illuminant changes, similar patterns would be obtained in this study. For instance, the studies of Delahunt & Brainard (2004a, 2004b) show reliable effects of illuminant direction on the degree of successive color constancy being highest in blue and green directions and lowest in the red direction. It was shown above that in successive or simultaneous color constancy paradigms the amount of visual adjustment in particular illuminant directions correlates somehow with the frequency of occurrence of the respective illuminants in our environment. If this feature is intrinsic to our visual system then similar result patterns should show up in the present paradigm as well.

Second, it is not clear if the degree of color constancy depends on the surface collection in situations with abrupt temporal illuminant directions. Further, this issue was not investigated in detail with other paradigms. It was shown that at least small effects were found in successive and simultaneous color constancy paradigms. If the amount of visual adjustment under particular surface collections also correlate with the occurrence of surfaces in natural environment then rather high constancy under a green, medium under yellow and blue, and low constancy under a red collection would be expected.

It should be noted that there is strong evidence for the validity of some basic principles like the von Kries law or illuminant linearity. These principles were tested under a large number of illuminant changes and surface collections and were confirmed rather well in a variety of viewing contexts. On the other hand, some effects of illuminant direction and surface collection were found. Since the models which were fitted in these studies seem to be rather robust against such effects, the operational paradigm used throughout the present study might provide detailed insights regarding to which extent the visual system adjusts to illuminant changes along different color directions and under different surface collections. If the expected results are obtained in this study, however, the principle of illuminant linearity should be reviewed. Illuminant linearity states that an observers' setting in a matching paradigm depends linearly on the illuminant change. If the amount of visual adjustment varies with the color direction of the illuminant change then this principle may be challenged. Dependent on how strong such a result pattern influences illuminant linearity, the findings should be incorporated in the principle.

Chapter 4

General methods

4.1 Apparatus

All stimuli were generated by a ViSaGe Visual Stimulus Generator (Cambridge Research Systems Ltd., U. K.) with a resolution of 8 bit per gun. A DELL Precision 670 Minitower host computer with a VSG Toolbox (Cambridge Research Systems Ltd., U. K.) was used for running the Matlab programs and controlling the ViSaGe. Stimuli were presented on a 19" RGB monitor (Mitsubishi Diamond Pro 2070SB) with a screen resolution of 1280x961. The monitor was calibrated before each experiment using a ColorCAL colorimeter (Cambridge Research Systems Ltd., U. K.). Observers were sitting directly in front of the stimulus monitor viewed at a distance of approximately 80 centimeters without a chin rest. Experiments were carried out in a darkened room.

4.2 Experimental illuminants and surfaces

Daylight as well as non–daylight illuminants were used in this work. Wyszecki & Stiles (1982) provide an algorithm that maps an arbitrary point on the daylight locus to the corresponding spectral power distribution using a three–dimensional model. The daylight illuminants used in this work were drawn out of this pool of spectral power distributions. Non–daylight illuminants were constructed using the same daylight basis functions, or the monitor basis functions of Delahunt & Brainard (2004a, 2004b) if illuminants lied outside of the daylight model (see section 3.1). The daylight basis functions, as well as the monitor basis functions, are plotted in Appendix A. All experimental illuminants were sampled from 400 nm to 700 nm in 10 nm steps.

For experimental surfaces, the set of 226 spectral reflectance functions used by Brainard & Wandell (1992) was chosen. These surfaces were simulated flat Lambertian papers from the *Munsell Book of Color — Matte Finish Collection* and were approximated using a six–dimensional linear model whose basis functions were the first six principal components of the data set of Kelly, Gibson, & Nickerson (1943). Figure 4.1 shows the CIE u'v' coordinates of the entire surface set rendered under the D65 standard illuminant. The six basis functions to model the reflectance functions of the set of surfaces used are plotted in Appendix A. The CIE u'v' chromaticity coordinates of the surfaces are also listed in Appendix A. All spectral reflectances were sampled from 400 to 700 nm at 10 nm steps.

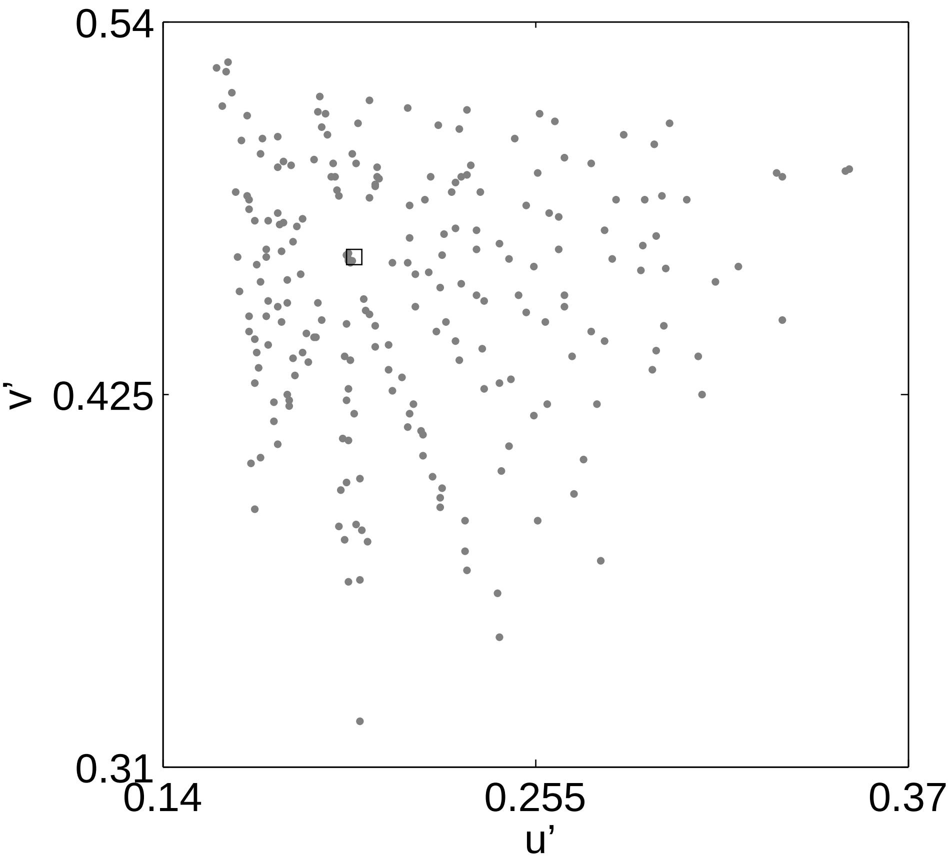


Figure 4.1: CIE u'v' coordinates of the entire set of 226 experimental surfaces under illuminant CIE D65 (open square).

4.3 General procedure

Throughout this work, the operational approach developed by Craven & Foster (1992), or slight modifications, were used. This paradigm is supposed to investigate color constancy in situations with temporal abrupt illuminant changes and was applied in a number of other studies (e. g. Foster et al, 1992; Nascimento & Foster, 1997; Amano et al., 2005). Each image was a Mondrian pattern composed of 7x7 adjacent rectangular surfaces of equal size against a dark background (Figure 4.3). The pattern (but not the background) was rendered homogeneously under one experimental illuminant. It subtended 10.5 degrees of visual angle, vertically and horizontally. The stimulus presentation in each trial consisted of two temporal intervals. In the first interval, a Mondrian pattern was rendered under a standard illuminant. In the second interval, the same Mondrian was presented, but the illuminant underwent one of two types of changes. For the uniform illuminant change, the illuminant was shifted along a certain color axis. For the non–uniform illuminant change, the same uniform illuminant change was first applied. In addition, a change in surfaces occurred. It was the goal of the non–uniform illuminant shift to render a picture for the second interval that cannot be created from the Mondrian in the first interval through a naturally occurring uniform illuminant shift. To an observer, the uniform illuminant change would appear as a pure *change in illuminant* between the two images, while the non–uniform illuminant change would be best interpreted as a *change in surfaces*. Figure 4.2 depicts two examples of illuminant and surface changes. It can be seen that a uniform illuminant change was performed in both conditions. Without a uniform illuminant change in the surface change condition, an additional cue would have been given to the observer because, between the images, there would have been an overall chromaticity shift in the illuminant change condition, but not in the surface change condition. With this uniform illuminant change in both conditions, there was the same average chromaticity shift. The intervals lasted one second each and were presented immediately after each other.

After the presentation of the two images, observers were to decide whether an occurring change between the two images was due to a change in illuminant or a change in surfaces. They were to give their answers by pressing one of two buttons on a response box. There was no time constraint, but all observers gave their judgments almost immediately after presentation. After the response, the next stimuli were calculated, leading to a total duration of about 4s per trial. Figure 4.3 depicts the procedure of a typical stimulus presentation.

For each experiment, observers had to participate in several sessions. Within sessions, observers made several judgments in each experimental condition. The duration of the sessions differed, but never lasted longer than 45 minutes with short intervening breaks. The first session of each experiment was regarded as a practice session and was not included in the analysis.

In Experiment 1, a set of daylight illuminants, along with the set of 226 Munsell papers, served as experimental stimuli to measure color constancy along the daylight axis, with additional changes in light intensity. In Experiments 2 and 3, daylights as well as non–daylights and the same set of Munsell papers were used to examine whether the degree of color constancy is different under differently colored illuminants. In Experiment 4, one daylight and one non–daylight illuminant was used. The set of surfaces was split into four differently colored subsets to investigate the role of surface collection for

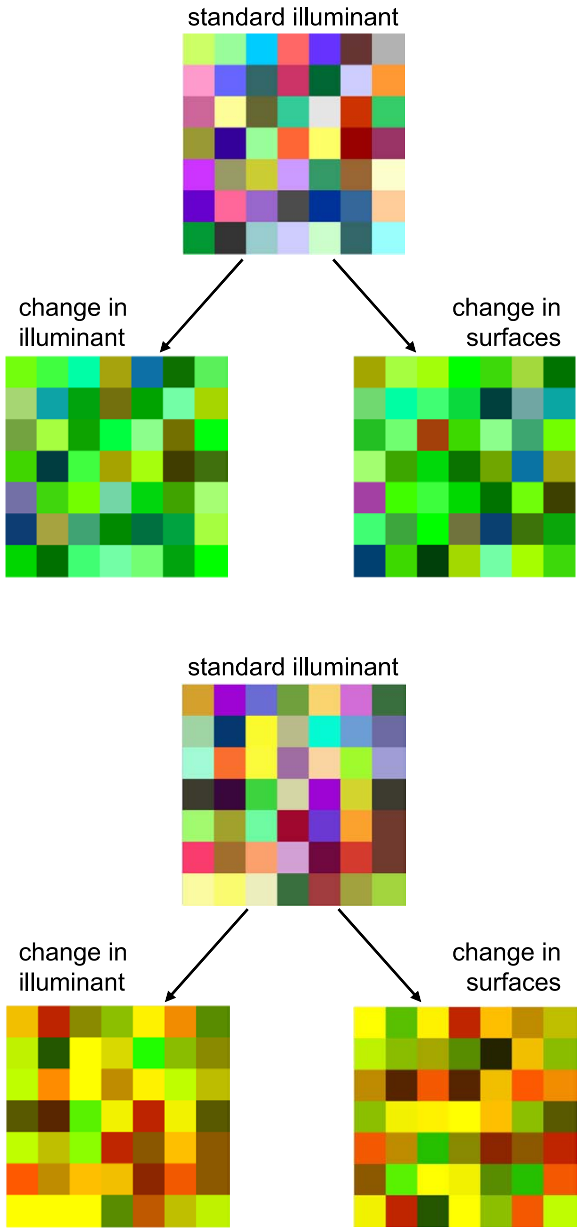


Figure 4.2: Two examples of illuminant and surface changes. At first, the Mondrian is always rendered under the standard illuminant (center Mondrians). After that, either a change in illuminant (left Mondrians) or a change in surfaces (right Mondrians) occurs.

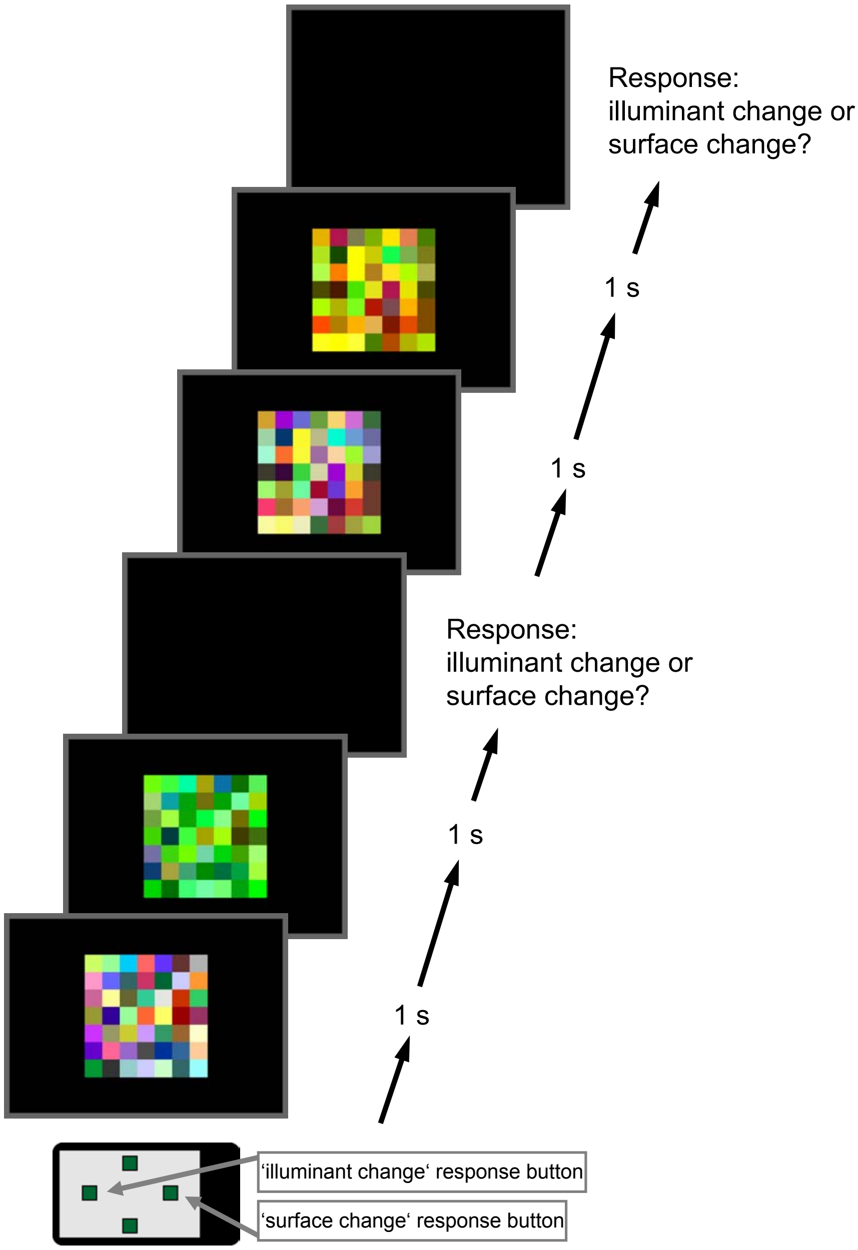


Figure 4.3: Stimulus presentation (two trials). Two equal Mondrians rendered under different illuminants were presented immediately after each other. In addition to this illuminant change, an additional change in surfaces was introduced in half of the trials. After each trial, observers were asked to decide whether a pure change in illuminant or a change in surfaces occurred.

color constancy.

4.4 Data Analysis

In the paradigm used in this work, observers had to discriminate between illuminant changes and surface changes. In this sense, it can be interpreted as a signal detection paradigm. Uniform illuminant changes that occurred in all trials were considered as noise, whereas additional non–uniform illuminant changes were considered as the signal to detect. A Hit was therefore a correctly classified surface change, and a False Alarm was an illuminant change that was classified as a surface change. A classical discrimination index d' was computed from the difference of the z–transformed Hit Rates (HR) and False–Alarm Rates (FAR):

$$d' = z(HR) - z(FAR)$$

The discrimination index d' was the measure for the degree of color constancy in this paradigm.

Chapter 5

Experiments

5.1 Experiment 1: The role of luminance in illuminant changes

Luminance plays an important role in our environment. Luminance of illuminants, say daylights, can vary drastically depending on daytime and weather conditions. When the sun gets covered by a cloud, for example, luminance decreases considerably. Thus, when investigating illuminant changes, not only chromaticity but also luminance of illuminants should be considered.

Most previous studies about color constancy either did not involve luminance changes or did not control them systematically. Werner & Walraven (1982) examined successive color constancy and found an effect of luminance on the achromatic locus, but they used center–surround stimuli rather than Mondrian patterns. Brainard et al. (1997) controlled luminance in a simultaneous matching paradigm and found no effect on observers' settings. They conducted their experiments in a room with real illuminants and surfaces to simulate natural viewing conditions. In studies investigating surface color constancy in situations with rapid temporal illuminant changes using the operational approach of this work, luminance was held constant or was not controlled at all (e. g. Craven & Foster, 1992; Nascimento, 1995; Nascimento & Foster, 1997, 2000).

The following experiment is conducted for two reasons. First, the experimental setup which was adopted from Craven & Foster (1992) and used throughout this work has to be validated. For this purpose, I will try to replicate the findings of Craven and Foster's Experiment 3. They found that discrimination performance decreased with uniform illuminant change magnitude and increased with non–uniform illuminant change magnitude. Second, the role of luminance in illuminant changes is to be investigated. The question is whether a change in luminance, in addition to a change in illuminant chromaticity, affects the degree of simultaneous color constancy in situations with rapid temporal illuminant changes. Since luminance generally changes in this type of everyday situation, the degree of color constancy is to remain roughly the same. The experiment is run under three conditions. The chromaticity change condition is designed for the replication. The luminance change condition serves as a control condition to assess observers' discrimination performance for scenes where illuminant changes consist solely of luminance changes. The chromaticity+luminance change condition involves illuminant changes where both chromaticity and luminance change. This condition is to be compared to the chromaticity change condition in order to investigate the influence of the additional luminance change on discrimination performance.

5.1.1 Methods

Observers

Three observers participated in this experiment, CA (the author), SW, and EH. All had normal color vision as assessed by Ishihara color plates (Ishihara, 1917). All observers, except the author (CA), were naïve about the purpose of the experiment.

Experimental stimuli

Two daylights were used as initial illuminants, D_1 (x=0.250, y=0.255) and D_2 (x=0.370, y=0.376). The surfaces that the Mondrian patterns were composed of were drawn randomly without replacement from the pool of 226 spectral reflectances. There were three conditions: chromaticity change, luminance change, and chromaticity+luminance change. In the chromaticity change condition, both images were on an average luminance of 4 cd/m^2, but individual surfaces varied around this value (0.65 to 8.81 cd/m^2). In luminance change and chromaticity+luminance change conditions, average luminance of the first image was 4 cd/m^2 (0.65 to 8.81 cd/m^2), and average luminance of the second picture was 16 cd/m^2 (2.62 to 35.24 cd/m^2). In the luminance change condition, illuminant chromaticity was held constant.

Procedure

The first image was a Mondrian illuminated randomly either by illuminant D_1 or D_2. For the uniform illuminant change, the CIE x–coordinate of the initial illuminant was shifted by 0.03, 0.06, or 0.09 CIE x–units[1], respectively, the shift being positive for initial illuminant D_1 and negative for initial illuminant D_2. For the non–uniform illuminant change, the same uniform illuminant change was applied. In addition, the illuminant of a random half of the patches was shifted positively by either 0.01, 0.02, or 0.03 CIE x–units and negatively for the remaining half. The magnitudes of all shifts were randomly drawn for each trial. There were 216 trials in each session, divided into three blocks with short intervening breaks. Observers made about 60 judgments in each condition, i. e. for each combination of initial illuminant, uniform illuminant shift and non-uniform illuminant shift.

5.1.2 Results

Figure 5.1 shows the results for each participant in the chromaticity change condition. Rows represent data for single observers while columns represent data for trials where initial illuminant was D_1 or D_2, respectively. Within each panel, data points depict discrimination performance d' as a function of uniform and non–uniform illuminant change. Magnitude of uniform illuminant change is coded by blue diamonds, pink squares, and yellow triangles, representing changes of Δx=0.03, Δx=0.06, and Δx=0.09, respectively. Magnitude of non–uniform illuminant changes Δx=0.01, Δx=0.02, and Δx=0.03 is shown on the x–axis. Overall performance is above chance for all observers. It decreases as a function of magnitude of uniform illuminant change and increases as a function of magnitude of non–uniform illuminant shift. This becomes evident once we regard uniform illuminant shift

[1]Since the daylight locus is approximately a line in the CIE xy chromaticity diagram, illuminant shifts are labeled for convenience by their x–coordinates. The y–coordinates may be calculated using the respective algorithms in Wyszecki & Stiles (1982).

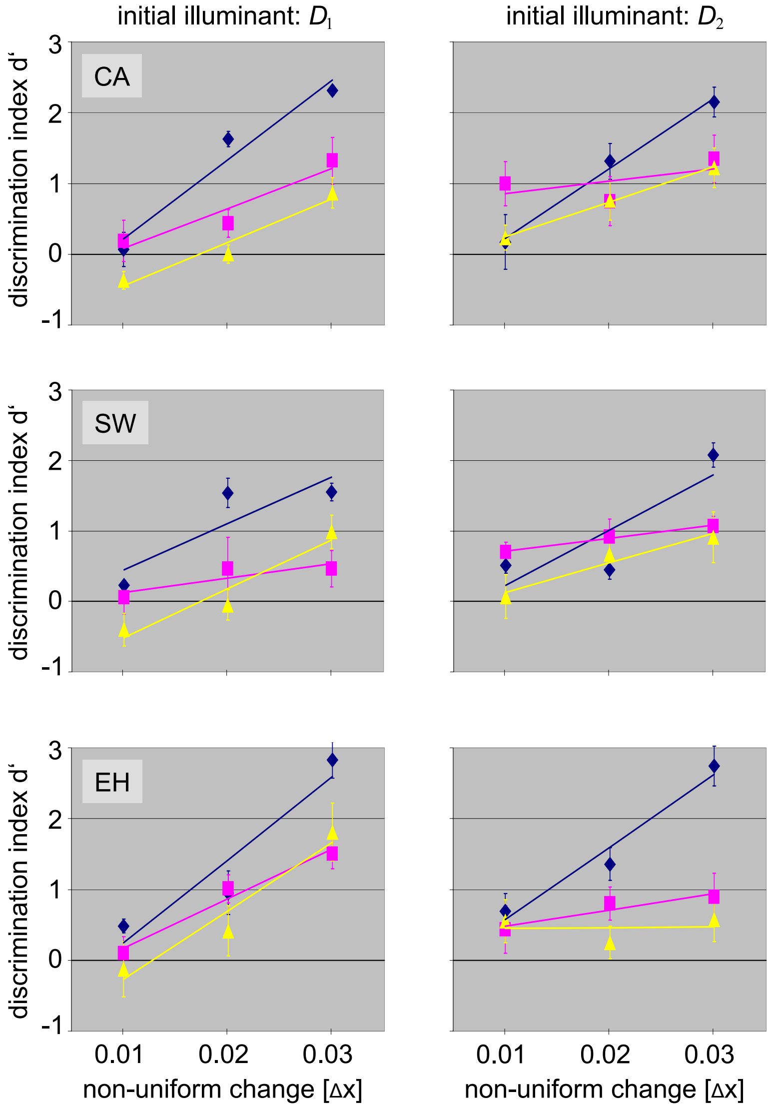


Figure 5.1: Results for the chromaticity change condition. Columns represent data for initial illuminants D_1 and D_2. Discrimination performance d' is plotted as a function of uniform and non–uniform illuminant change. Magnitude of uniform illuminant change is coded by blue diamonds, pink squares, and yellow triangles representing changes of Δx=0.03, Δx=0.06, and Δx=0.09, respectively. Magnitude of non–uniform illuminant change is shown on the x–axis. Error bars show $\pm$ 1 SEM.

as noise and non–uniform illuminant change as signal in this psychophysical discrimination paradigm. Performance then is a function of the signal–to–noise ratio. The result pattern is very similar to that obtained in Experiment 3 of Craven & Foster (1992), thus their results could be replicated. The authors did not provide a statistical analysis of their data. The analysis of this replication, however, is included in the comparison analysis with the chromaticity+luminance condition below.

Figure 5.2 shows discrimination performance of each participant in the luminance change condition, which served as a control condition in order to assess performance when solely luminance but not chromaticity changed. A within–subject two–way ANOVA was conducted. There is an effect of initial illuminant for observer CA ($F=13.61$, $MSE=0.19$, $p=0.01$), a marginal effect for SW ($F=6.12$, $MSE=0.81$, $p=0.07$), but no effect for EH ($F=0.39$, $MSE=0.75$, $p=0.57$). Discrimination performance increases significantly as a function of magnitude of non–uniform illuminant change for all three observers (CA: $F=15.46$, $MSE=0.31$, $p=0.001$; SW: $F=20.69$, $MSE<0.01$, $p<0.01$; EH: $F=38.25$, $MSE=0.08$, $p<0.01$). There is also a significant interaction for CA ($F=5.15$, $MSE=0.39$, $p=0.03$) and SW ($F=15.92$, $MSE<0.01$, $p<0.01$), but not for EH ($F=0.13$, $MSE=0.03$, $p=0.88$).

Figure 5.3 shows the discrimination performance for each participant in the chromaticity+luminance change condition. Data coding is the same as in Figure 5.1. Discrimination, again, increases as a function of magnitude of non–uniform illuminant change. However, the effect of uniform illuminant change seems not as evident as in the chromaticity change condition. In Figure 5.4, data from Figures 5.1 and 5.3 was replotted in a scatterplot for better comparison of chromaticity change condition and chromaticity+luminance change condition in order to examine a possible effect of luminance on perfor-

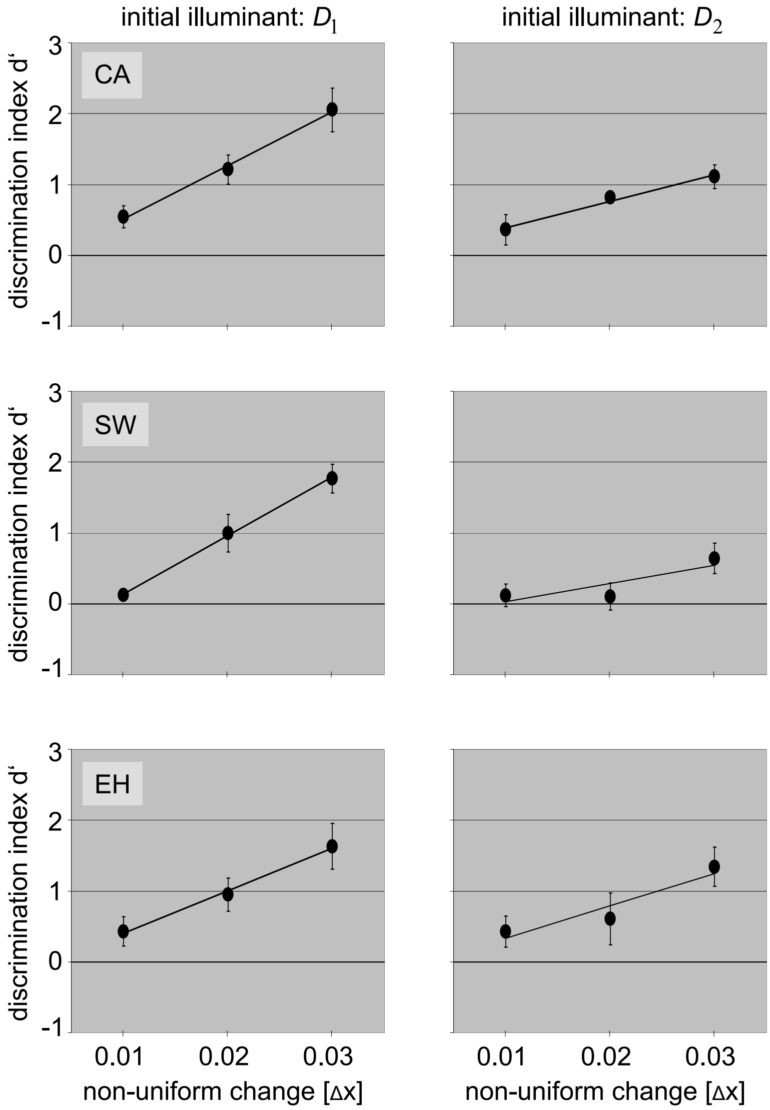


Figure 5.2: Results for the luminance change condition. Columns represent data for initial illuminants D_1 and D_2. Discrimination performance d' is plotted as a function of non–uniform illuminant change. Error bars show ± 1 SEM.

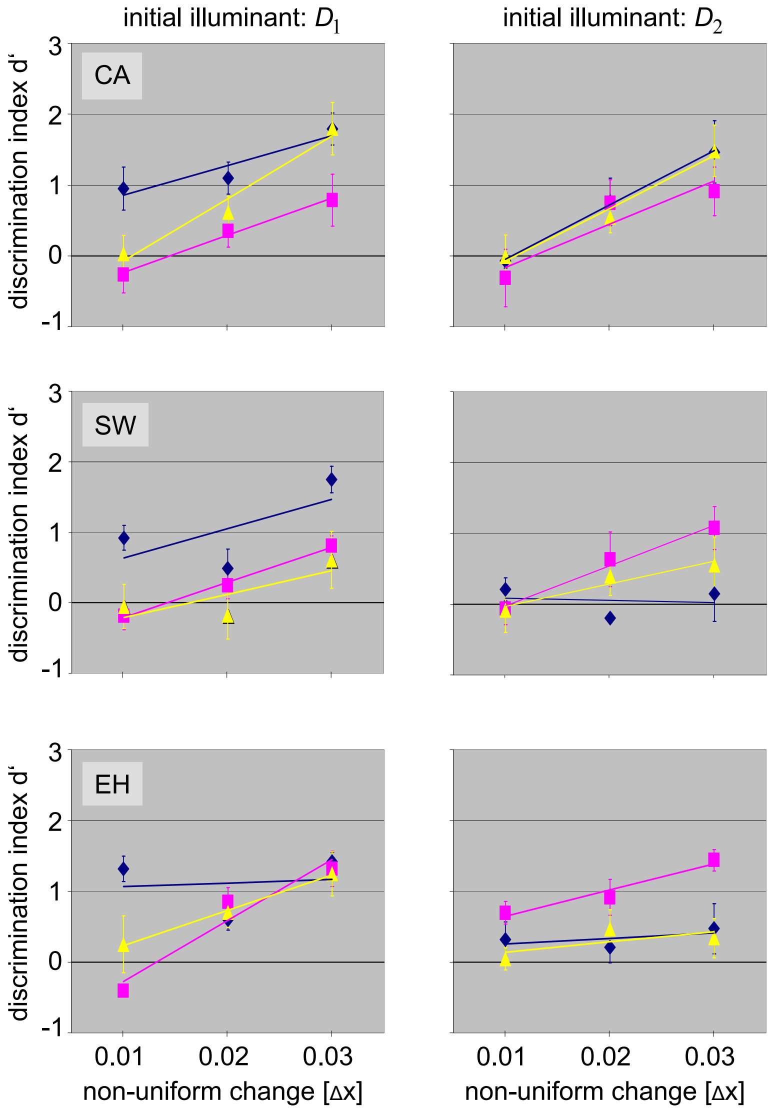


Figure 5.3: Results for the chromaticity+luminance change condition. Columns represent data for initial illuminants D_1 and D_2. Discrimination performance d' is plotted as a function of uniform and non–uniform illuminant change. Magnitude of uniform illuminant change is coded by blue diamonds, pink squares, and yellow triangles representing changes of Δx=0.03, Δx=0.06, and Δx=0.09, respectively. Magnitude of non–uniform illuminant change is shown on the x–axis. Error bars show ± 1 SEM.

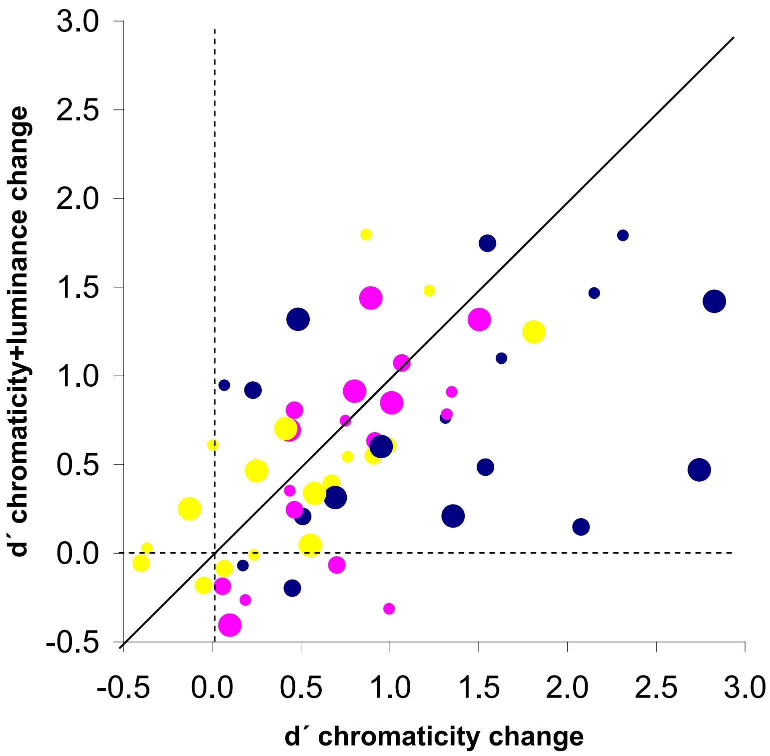


Figure 5.4: Comparison of performances in chromaticity change and chromaticity+luminance change conditions. Each data point from Figure 5.1 is plotted against its corresponding data point from Figure 5.3. Magnitude of uniform illuminant change is coded by colors, blue, pink, and yellow, representing changes of Δx=0.03, Δx=0.06, and Δx=0.09, respectively. Magnitude of non–uniform illuminant shift is coded by size, small, medium, and large, representing shifts of Δx=0.01, Δx=0.02, and Δx=0.03, respectively.

mance. Each data point from Figure 5.1 is plotted against its corresponding data point from Figure 5.3. Magnitude of uniform illuminant shift is coded by colors, blue, pink, and yellow, representing shifts of Δ x=0.03, Δx=0.06, and Δx=0.09, respectively. Magnitude of non–uniform illuminant shift is coded by size, small, medium, and large, representing shifts of Δx=0.01, Δx=0.02, and Δx=0.03, respectively. The correlation between data of the two conditions is medium (r=0.55). If corresponding performances for all possible combinations of uniform and non–uniform illuminant changes were equal in both conditions, all data points would fall on the diagonal. There are clear deviations from that. However, data points scatter rather evenly around the diagonal, indicating similar mean performances in both conditions across observers and illuminant changes. There are three major outliers, one medium and two large blue circles on the right, indicating some better performance in the chromaticity change condition when signal–to–noise ratio is high and the task is rather easy.

A within–subject 4–way ANOVA with the factors condition, initial illuminant, uniform illuminant change magnitude, and non–uniform illuminant change magnitude was conducted to investigate discrimination performance d' of each observer. For all observers performance across conditions do not differ (CA: F=0.08, MSE=1.60, p=0.80; SW: F=2.18, MSE=1.31, p=0.24; EH: F=3.21, MSE=0.25, p=0.15). There is also no effect of initial illuminant (CA: F=0.01, MSE=0.58, p=0.93; SW: F=3.68, MSE=0.34, p=0.15; EH: F=0.53, MSE=0.46, p=0.51). An effect of uniform illuminant change magnitude was found for observer EH (F=8.25, MSE=0.54, p=0.01) and marginally for observer SW (F=4.27, MSE=0.69, p=0.01), but not for observer CA (F=2.05, MSE=0.99, p=0.19). However, there is a large effect of non–uniform illuminant change magnitude for all observers

(CA: $F=37.55$, $MSE=0.38$, $p<0.01$; SW: $F=17.32$, $MSE=0.22$, $p=0.003$; EH: $F=30.48$, $MSE=0.32$, $p<0.01$). A significant interaction of condition and uniform illuminant change magnitude was found for observer EH ($F=10.24$, $MSE=0.35$, $p=0.01$), a marginal interaction for observer CA ($F=3.60$, $MSE=0.45$, $p=0.08$), and no interaction for observer SW ($F=0.15$, $MSE=0.06$, $p=0.86$). A significant interaction of condition and non–uniform illuminant change magnitude was found for observer EH ($F=7.28$, $MSE=0.07$, $p=0.03$), but not for observers CA ($F=0.34$, $MSE=0.07$, $p=0.72$) and SW ($F=0.26$, $MSE=0.20$, $p=0.78$). All in all, discrimination performance was similar across chromaticity change and chromaticity+luminance change conditions.

5.1.3 Discussion

Two major results stand out. First, Experiment 3 of Craven & Foster (1992) could be replicated, thus validating the experimental setup used in this work. Discrimination performance increases with increasing signal–to–noise ratio, determined by uniform and non–uniform illuminant change magnitudes. Similar results were also found in another replication by Nascimento (1995). The results show that observers are able to reliably discriminate between an illuminant change and a change in surface material in a scene. This is an important feature in everyday life, since, for example, we have to be able to tell whether or not objects in a scene retain their color when they are rapidly illuminated in succession by two different lights. Second, color constancy is not impaired if a luminance change in addition to a chromaticity change is introduced.

Werner & Walraven (1982) examined successive color constancy and found an effect of luminance. However, they used simple center–surround stimuli instead of Mondrian patterns. Brainard et al. (1997) investigated color constancy in a simultaneous situation using real–world stimuli. He did not find an effect of luminance on observers' settings. The findings, that luminance changes do not have a major impact on the degree of color constancy in a simultaneous matching paradigm as well as in the present paradigm, may contribute to the view that luminance and chromaticity are processed differently in the visual system and that these processes are largely independent from one another (see Kaiser & Boynton, 1996). The present results suggest that this seems further to account for processes responsible for color constancy. It was shown that discrimination performance deteriorates with increasing uniform illuminant change magnitude in this paradigm. With an additional change in luminance, this magnitude was further increased. However, the effect of such an additional luminance change is at best small. It is an important feature of the visual system to maintain color constancy in the present situation where an additional change in luminance is involved because most illuminant changes in our environment are a combined change in chromaticity and luminance. However, it is not clear if the present results generalize to successive and simultaneous color constancy situations. Further research has to be done on this issue to draw firm conclusions.

5.2 Experiment 2: The role of color direction in illuminant changes

Illuminant colors in our environment can vary widely in color space. Daylight varies from blue to white to yellow, but many scenes are not at all or at least not solely illuminated directly by it. Depending on the reflectance properties of a scene, the color of the direct daylight illuminant can be shifted in different directions (Figure 4.1). Thus, we are surrounded by variously colored illuminants, which all have to be considered for color constancy.

There is a number of studies which compared the degree of color constancy along the daylight axis and along other color axes. Most studies examined successive color constancy using either asymmetric color matching or achromatic adjustment. Lucassen & Walraven (1996) found better constancy in the blue direction than in the yellow direction. Brainard (1998) found only slight differences in color constancy along several color axes. Rüttiger et al. (2001) measured color constancy along the daylight axis and the red–green cardinal directions in color space. They found better color constancy along the red–green axis. Delahunt & Brainard (2004a, 2004b) conducted the currently most promising study regarding the issue of color direction. They used achromatic adjustment and a CRT–rendered three–dimensional room in order to investigate color constancy in blue and yellow daylight color directions and orthogonal red and green color directions. They found rather good constancy along blue and green axes, mediocre constancy along the yellow axis, and rather bad constancy along the red axis. Until now, no study has focussed on the role of illuminant direction in a simultaneous color constancy situation. However, Bäuml (1999a) compared observers' apparent and surface color settings in a simultaneous situation and found them to be similar in a qualitative way. Foster et al. (2003) and Amano et al. (2003) investigated color constancy under rapid temporal illuminant changes using a discrimination paradigm similar to the one used in this work. They found similar performance in the green and blue direction.

The following experiment was carried out for two reasons. First, previous studies produced mixed results. This might be due to individual observer differences in the degree of color constancy along different color axes. Such an observer effect might also be apparent in the operational paradigm used in this work. This experiment tries to overcome this by using five observers. Second, Delahunt and Brainard (2004a, 2004b) found an effect of color direction on the degree of successive color constancy while using a larger number of seven observers. It is not clear if this pattern shows up in this discrimination paradigm as well. No experiment using the present paradigm considered this issue directly. However, if the effect of color direction is an intrinsic feature of the visual system, a similar pattern should show up in the present paradigm. The results of this experiment might then help to see how closely related they are to results of successive color constancy paradigms, regarding the relative amount of visual adjustment under different illuminant changes.

This experiment consists of two parts, Experiment A and Experiment B. Experiment A uses the four illuminants formerly used by Delahunt & Brainard (2004a, 2004b) in order to make the results comparable to their study. Experiment B uses four additional illuminants to examine the pattern of color constancy performance along different color axes in more detail.

5.2.1 Methods

Observers

Five observers participated in this experiment, CA (the author), EH, OK, SW, and TD. All had normal color vision as assessed by Ishihara color plates (Ishihara, 1917). All observers, except the author (CA), were naïve about the purpose of the experiment.

Experimental stimuli

CIE D65 was used as the initial illuminant. For Experiment A, the four illuminants used by Delahunt & Brainard (2004a, 2004b) served as test illuminants. Figure 5.5 (upper panel) and Table 5.1 show their chromaticity coordinates in CIE u'v' color space. This space is approximately perceptually uniform, so equal Euclidean distances in the diagram roughly represent equal perceptual distances. The distance from the initial illuminant to each test illuminant is 60 CIELab ΔE^* units, so the test illuminants are named Blue60, Yellow60, Red60, and Green60. The spectral power distributions of Blue60, Yellow60, and Red60 were constructed using the daylight basis functions, Green60 was constructed using monitor basis functions.

For Experiment B, four additional illuminants were used. Their CIE u'v' chromaticity coordinates were constructed to lie, respectively, exactly between illuminants used in Experiment A, with an equal distance of 60 CIELab ΔE^* units from the D65 illuminant. They were labelled RY60, YG60, GB60, and BR60. Figure 5.5 (lower panel) and Table 5.1 show their chromaticity coordinates in CIE u'v' color space. The spectral power distribution of RY60 and BR60 were constructed using the daylight basis functions, YG60 and GB60 were constructed using monitor basis functions. The surfaces which the Mondrian patterns were composed of were drawn randomly without replacement from the pool of 226 spectral reflectances. The average luminance of the images was held constant at 4 cd/m^2, but individual surfaces varied from 0.65 to 8.81 cd/m^2.

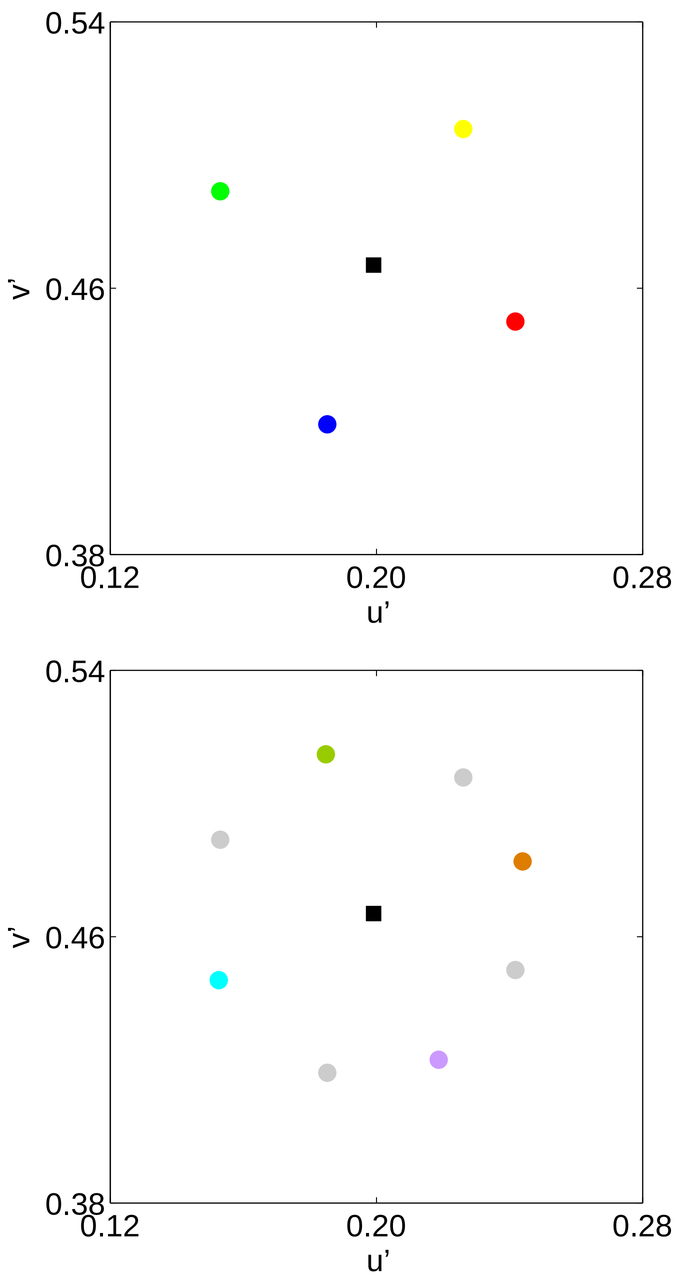


Figure 5.5: CIE u'v' chromaticity coordinates of test illuminants and standard illuminant CIE D65 (black square). Upper panel: Illuminants for Experiment A (Blue60, Yellow60, Red60, Green60). Lower panel: Illuminants for Experiment B (RY60, YG60, GB60, BR60); for comparison illuminants of Experiment A are depicted in grey.

Table 5.1: Experimental illuminants used throughout this work. Distance of each test illuminant from standard illuminant CIE D65 in CIELab ΔE^* units and CIE u'v' chromaticity coordinates are tabled.

Illuminant	Distance	CIE u'	CIE v'
D65	—	0.199	0.467
Blue60	60 ΔE^*	0.185	0.419
Yellow60	60 ΔE^*	0.226	0.508
Red60	60 ΔE^*	0.242	0.450
Green60	60 ΔE^*	0.153	0.489
RY60	60 ΔE^*	0.242	0.484
YG60	60 ΔE^*	0.183	0.512
GB60	60 ΔE^*	0.155	0.450
BR60	60 ΔE^*	0.219	0.427
Red30	30 ΔE^*	0.221	0.460
RY30	30 ΔE^*	0.221	0.477
Yellow30	30 ΔE^*	0.212	0.489
YG30	30 ΔE^*	0.190	0.492
Green30	30 ΔE^*	0.174	0.479
GB30	30 ΔE^*	0.175	0.459
Blue30	30 ΔE^*	0.192	0.445
BR30	30 ΔE^*	0.210	0.446
Red85	85 ΔE^*	0.260	0.443
RY85	85 ΔE^*	0.263	0.489
Yellow85	85 ΔE^*	0.237	0.525
YG85	85 ΔE^*	0.179	0.535
Green85	85 ΔE^*	0.134	0.498
GB85	85 ΔE^*	0.133	0.439
Blue85	85 ΔE^*	0.179	0.399
BR85	85 ΔE^*	0.227	0.405

Procedure

The first Mondrian pattern was always illuminated by CIE D65. The illuminant of the second pattern was randomly drawn from the respective pool of four test illuminants. Between images either an illuminant change or a surface change occurred randomly. In illuminant change trials, the second Mondrian was simply illuminated by one of the test illuminants. In the surface change condition, the same illuminant change occurred, but additionally chromaticity coordinates of a random quarter of the surfaces were then shifted in the illuminant change direction, a second quarter in the opposite direction, and a third and fourth quarter in the two orthogonal directions, respectively. The magnitude of these shifts was 0.03 units in CIE u'v' space. There were 200 trials per session, divided into three blocks with short intervening breaks. Experiments A and B were carried out successively. In each experiment, each observer made 300 judgments per illuminant direction.

5.2.2 Results

Figure 5.6 shows the results of Experiment A for each of the five observers, as well as mean results over observers. Discrimination index d' is plotted as a function of illuminant direction. A one–way ANOVA was conducted for the five observers to examine discrimination performance across different illuminant changes. There is an effect of illuminant direction on the degree of visual adjustment for observers CA ($F=6.13$, $MSE=0.17$, $p<0.01$), OK ($F=4.48$, $MSE=0.22$, $p=0.02$), and SW ($F=9.12$, $MSE=0.24$, $p<0.01$), but not for observers EF ($F=1.14$, $MSE=0.34$, $p=0.37$) and TD ($F=1.47$, $MSE=0.42$, $p=0.26$). Plots show different patterns of performance over subjects. Color constancy in the yellow direction, for instance, exceeds constancy

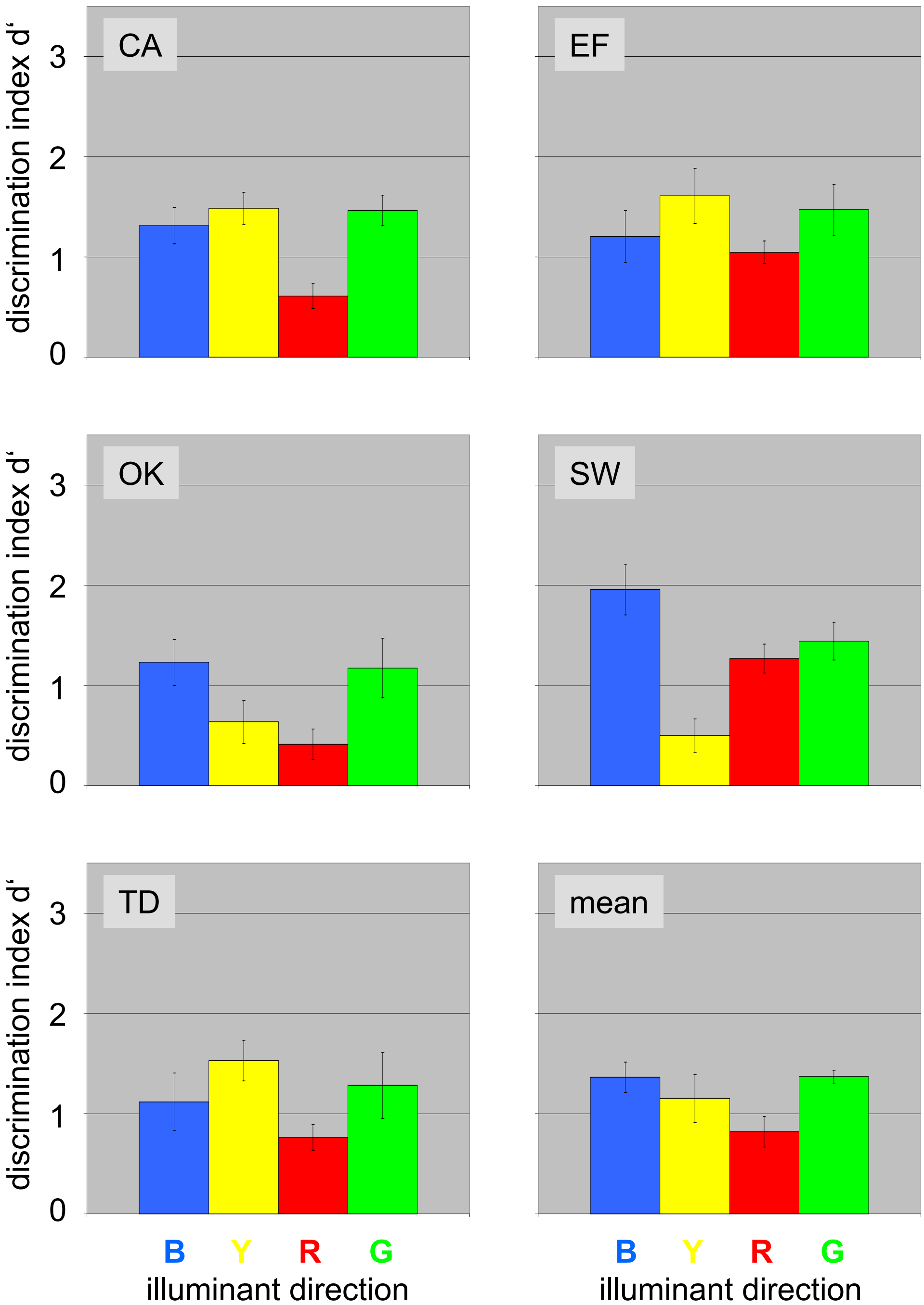


Figure 5.6: Results for the five observers and mean results over observers. Discrimination index d' is plotted as a function of illuminant direction (B=Blue60, Y=Yellow60, R=Red60, G=Green60). Error bars show ± 1 SEM.

in the blue direction for observers CA, EF, and TD, but the opposite is true for observers OK and SW. There is also a larger variation in performance in the red direction across observers, while performance in blue and green directions are rather stable across observers. A re–analysis of the data with observer as a factor was carried out. The factors are observer (CA, EF, OK, SW, TD) and illuminant direction (Blue60, Yellow60, Red60, Green60). The replication is repeated measurements for each observer. There is a marginal effect of observer (F=2.52, MSE=0.82, p=0.07), indicating some differences in performance across observers. There is again an effect of illuminant direction (F=6.27, MSE=0.32, p<0.01). The significant interaction (F=3.00, MSE=0.80, p=0.03) confirms differences in the performance patterns across observers, which are visible in Figure 5.6. The lower right panel of Figure 5.6 shows the effect of illuminant direction over observers. There is comparatively high performance in blue and green directions, mediocre performance in the yellow direction, and rather low performance in the red direction.

To examine whether False Alarm rates of individual observers as well as of the mean vary across conditions, these are listed in Table 5.2. It can be seen, that False Alarm rates vary widely with illuminant direction. However, there is no evidence that they correlate with discrimination performance. For instance, observer CA has approximately equal discrimination indices of about 1.5 under the yellow and green illuminant, but rather different False Alarm rates of 0.07 and 0.25. In turn, he has similar False Alarm rates of 0.30 and 0.31 under the blue and red illuminant, but rather different discrimination indices of about 1.3 and 0.6. Analysis of the data of the other observers as well as of the mean produces similar results.

Results for each observer participating in Experiment B, as well as mean performance over observers, are shown in Figures 5.7–5.12. Upper panels

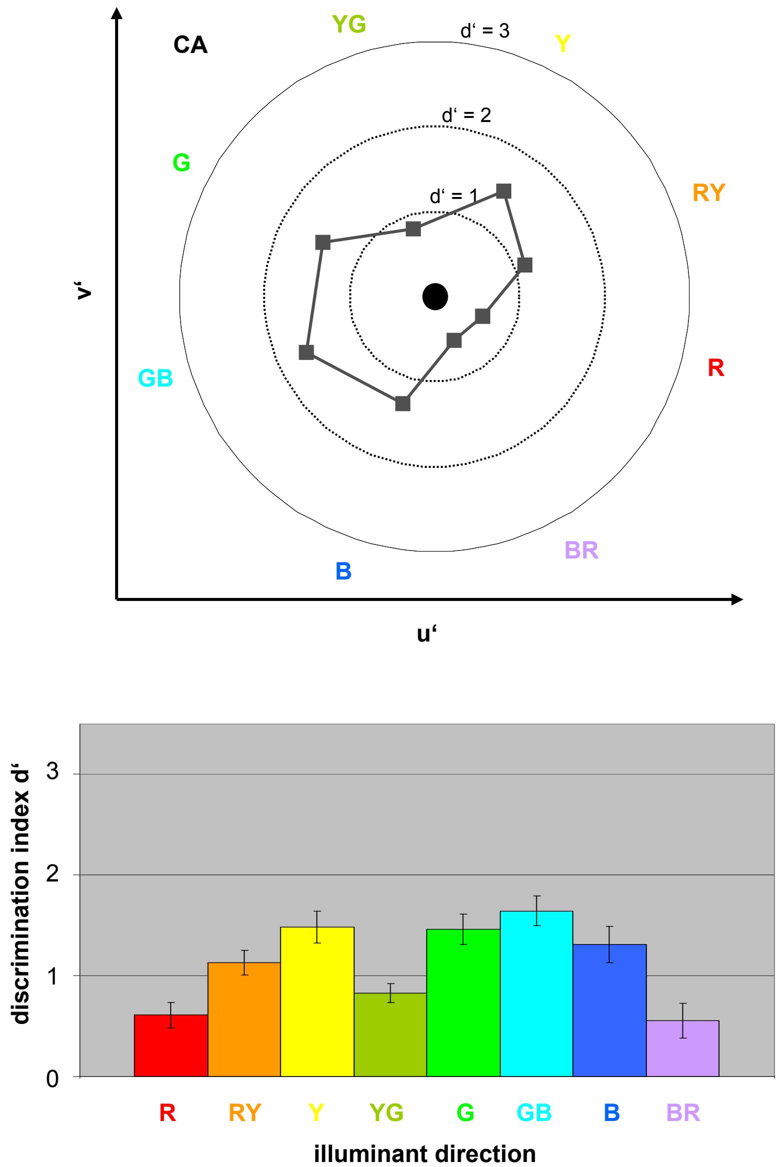


Figure 5.7: Results for observer CA. Upper panel: Polar plot within CIE u'v' coordinate system. The filled circle represents u'v' coordinates of CIE D65, direction from the center represents color direction in CIE u'v' space, and distance from the center represents discrimination index d'. Lower panel: Bar plot for the same data. Illuminant shift magnitude is 60 ΔE^* units. Error bars show $\pm$ 1 SEM. Data from Experiment A is reprinted for comparison.

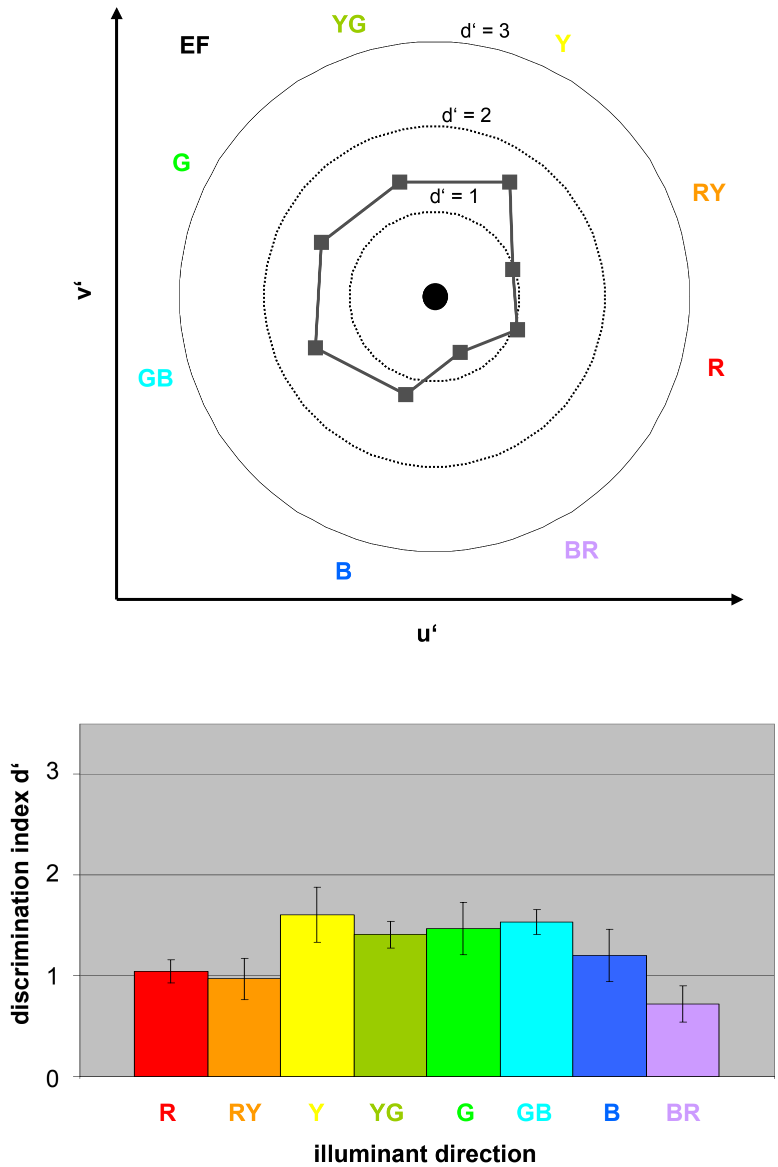


Figure 5.8: Results for observer EF. Upper panel: Polar plot within CIE u'v' coordinate system. The filled circle represents u'v' coordinates of CIE D65, direction from the center represents color direction in CIE u'v' space, and distance from the center represents discrimination index d'. Lower panel: Bar plot for the same data. Illuminant shift magnitude is 60 ΔE^* units. Error bars show $\pm$ 1 SEM. Data from Experiment A is reprinted for comparison.

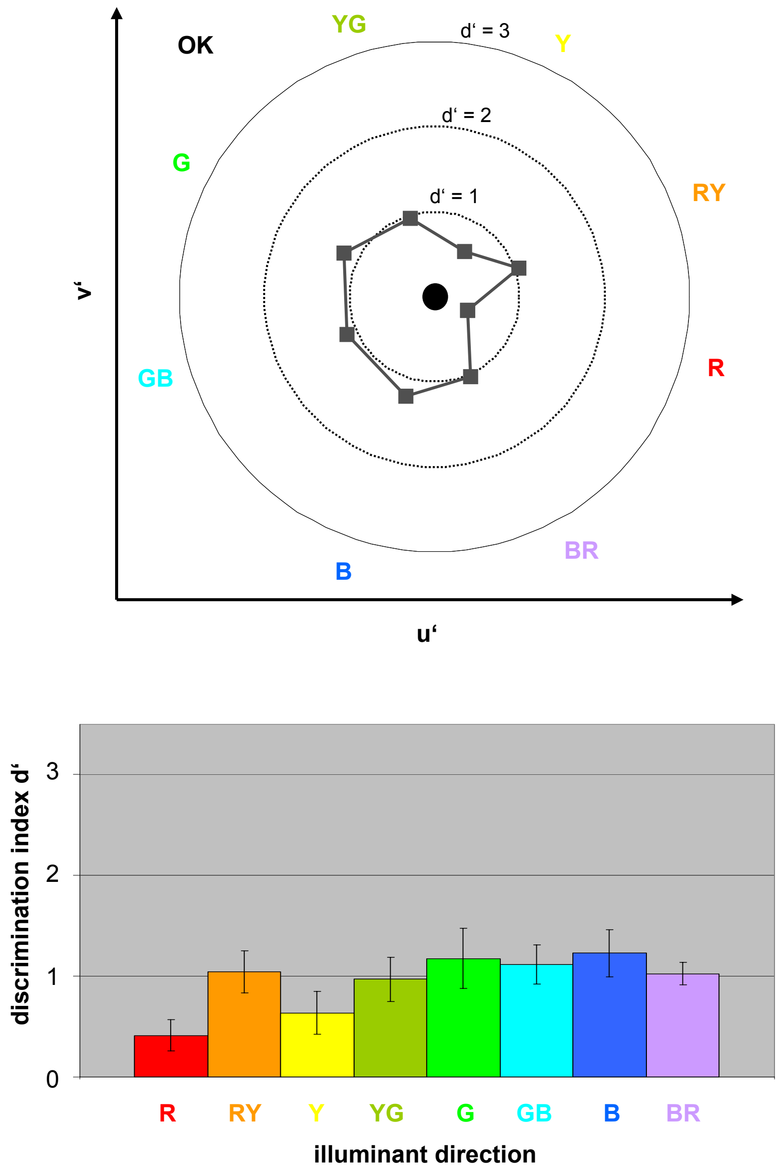


Figure 5.9: Results for observer OK. Upper panel: Polar plot within CIE u'v' coordinate system. The filled circle represents u'v' coordinates of CIE D65, direction from the center represents color direction in CIE u'v' space, and distance from the center represents discrimination index d'. Lower panel: Bar plot for the same data. Illuminant shift magnitude is 60 ΔE^{*} units. Error bars show $\pm$ 1 SEM. Data from Experiment A is reprinted for comparison.

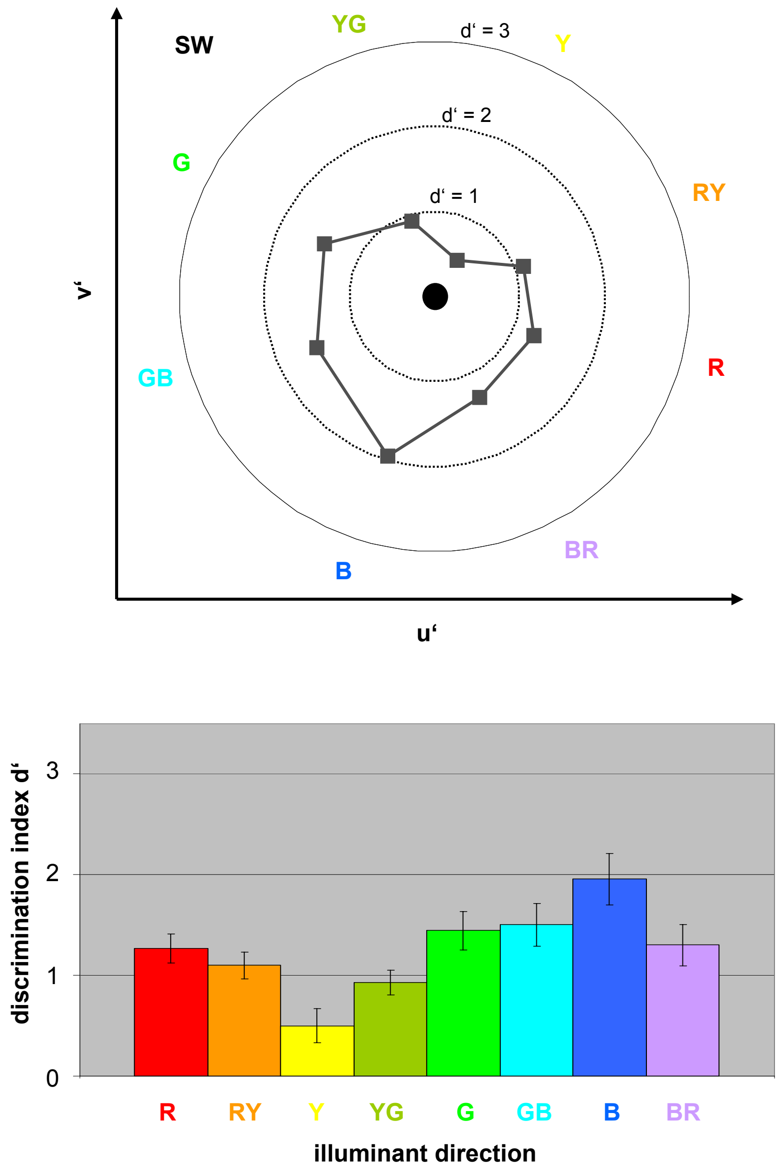


Figure 5.10: Results for observer SW. Upper panel: Polar plot within CIE u'v' coordinate system. The filled circle represents u'v' coordinates of CIE D65, direction from the center represents color direction in CIE u'v' space, and distance from the center represents discrimination index d'. Lower panel: Bar plot for the same data. Illuminant shift magnitude is 60 ΔE^* units. Error bars show $\pm$ 1 SEM. Data from Experiment A is reprinted for comparison.

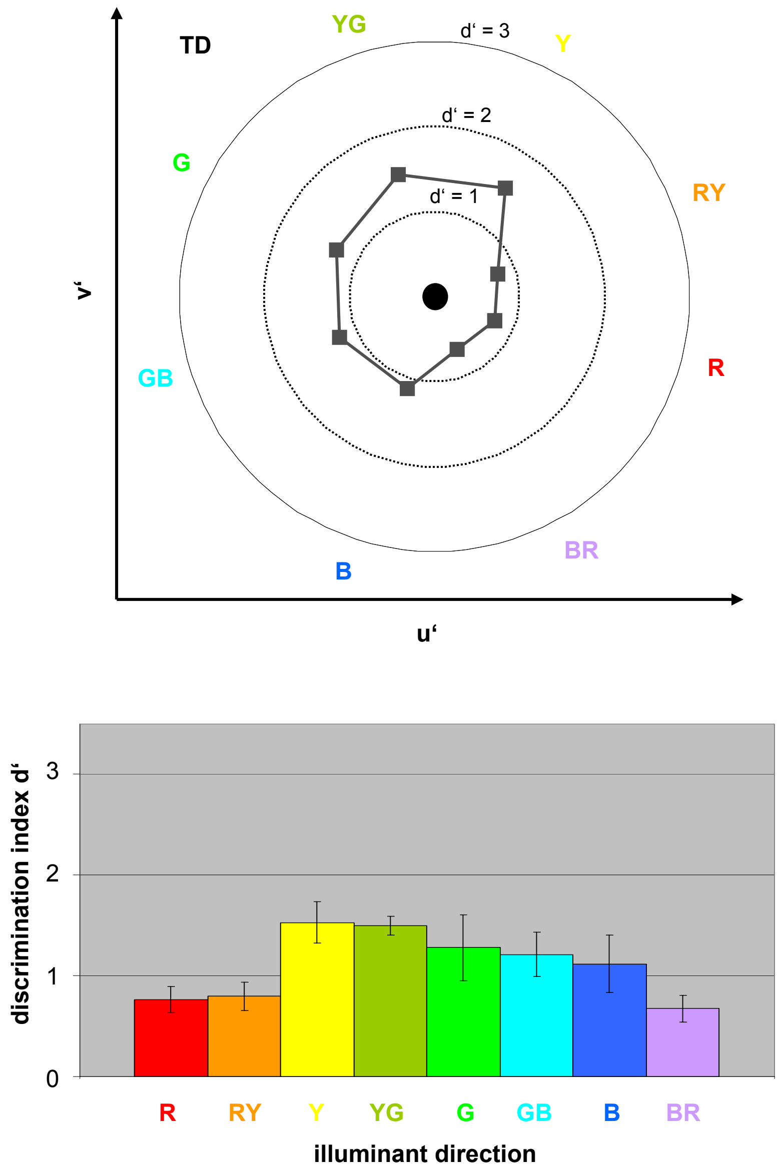


Figure 5.11: Results for observer TD. Upper panel: Polar plot within CIE u'v' coordinate system. The filled circle represents u'v' coordinates of CIE D65, direction from the center represents color direction in CIE u'v' space, and distance from the center represents discrimination index d'. Lower panel: Bar plot for the same data. Illuminant shift magnitude is 60 ΔE^* units. Error bars show $\pm$ 1 SEM. Data from Experiment A is reprinted for comparison.

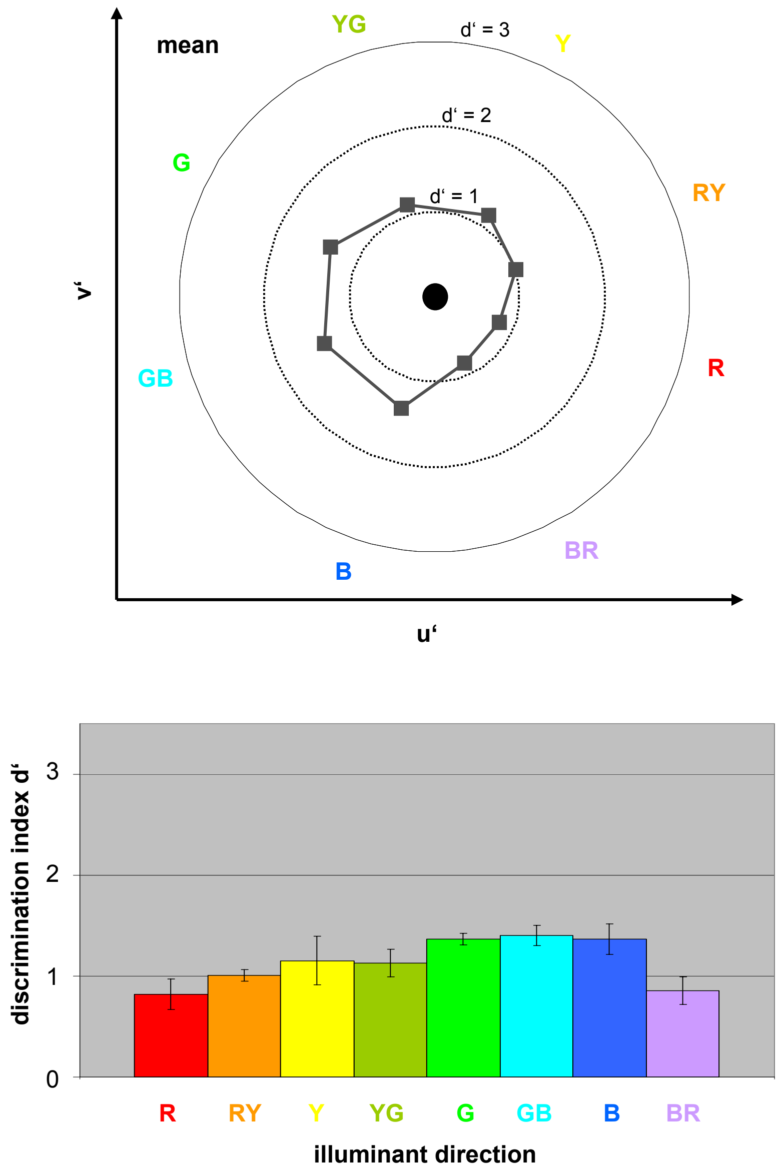


Figure 5.12: Mean results over observers. Upper panel: Polar plot within CIE u'v' coordinate system. The filled circle represents u'v' coordinates of CIE D65, direction from the center represents color direction in CIE u'v' space, and distance from the center represents discrimination index d'. Lower panel: Bar plot for the same data. Illuminant shift magnitude is 60 ΔE^* units. Error bars show $\pm$ 1 SEM. Data from Experiment A is reprinted for comparison.

Table 5.2: False Alarm rates across illuminant directions of Experiment 2A for individual observers as well as for the mean.

Observer	Blue	Yellow	Red	Green
CA	0.30	0.07	0.31	0.25
EF	0.70	0.09	0.60	0.05
OK	0.29	0.17	0.29	0.15
SW	0.42	0.02	0.10	0.03
TD	0.59	0.09	0.59	0.06
mean	0.46	0.09	0.38	0.11

show data in a polar plot within Cartesian CIE u'v' coordinates. The center of the plot represents the chromaticity coordinates of D65 in CIE u'v' space. The distance of each data point from the center depicts discrimination index d', while the direction of each data point from the center is equal to the illuminant change direction from the standard to the respective test illuminant in CIE u'v' color space. Lower panels show bar plots similar to Figure 5.6 of Experiment A. Plots include data from Experiment A. The plots show some observer differences in the overall pattern of color constancy in different illuminant directions. A one–way ANOVA for the five observers was conducted over data from both Experiments A and B to capture the effect of illuminant direction (Red60, Red–Yellow60, Yellow60, Yellow–Green60, Green60, Green–Blue60, Blue60, Blue–Red60) on discrimination performance. There is a significant effect of illuminant direction for each observer (CA: $F=7.22$, $MSE=0.15$, $p<0.01$; EF: $F=2.34$, $MSE=0.25$, $p=0.05$; OK: $F=2.72$, $MSE=0.18$, $p=0.02$; SW: $F=5.08$, $MSE=0.22$, $p<0.01$; TD: $F=2.64$, $MSE=0.25$, $p=0.03$). To capture differences across observers, a re–analysis of the data with observer as an additional factor was carried out. Similar to Experiment A, there is a marginal effect of observer ($F=2.18$,

Table 5.3: False Alarm rates across illuminant directions of Experiment 2B for individual observers as well as for the mean.

Observer	RY	YG	GB	BR
CA	0.15	0.10	0.16	0.52
EF	0.55	0.03	0.31	0.86
OK	0.15	0.31	0.15	0.22
SW	0.24	0.03	0.09	0.36
TD	0.38	0.07	0.13	0.75
mean	0.29	0.11	0.17	0.54

MSE=0.33, p=0.11), as well as a large effect of illuminant direction (F=7.86, MSE=0.20, $p<0.01$), and a high interaction (F=2.74, MSE=0.21, $p<0.01$). Figure 5.12 shows mean performances over observers. The graph (upper panel) is approximately a circle which is widened towards the blue–green direction and flattened in the red direction. The bar plot (lower panel) confirms the irregularities in terms of a smooth slope towards blue and green and a decline in the red direction.

As for Experiment A, False Alarm rates of individual observers as well as of the mean are examined and listed in Table 5.3. False Alarm rates again vary widely with illuminant direction. However, there is again no evidence that they correlate with discrimination performance.

5.2.3 Discussion

The purpose of this study was to find out if the degree of visual adjustment depends on the color direction of a rapid temporal illuminant change, and if results from studies using successive color constancy paradigms generalize to this type of color constancy situation. In general, observers were again able to reliably discriminate illuminant changes from surface changes. However, different discrimination performances were found depending on illuminant color direction. Foster et al. (2003) and Amano et al. (2003) found similar constancy in the blue and green direction using a discrimination paradigm similar to the one used in this work. Similar results were obtained here. It was shown that False Alarm rates vary widely across illuminant directions but do not correlate with discrimination performance. Therefore, False Alarm rates do not help explaining the different discrimination indices across conditions.

It is an interesting question whether the results found in situations with rapid temporal illuminant changes generalize to successive color constancy situations. In a successive paradigm, Lucassen & Walraven (1996) found better constancy along the blue than along the yellow axis. This finding is consistent with the present results. Brainard (1998) found approximately equal constancy in several color directions. However, he employed only two observers, which led to a reduced experimental power. Rüttiger et al. (2001) found better constancy along the red–green axis than along the daylight axis. Their results are difficult to compare to the present findings since performance is not split into semi–axes like neutral–green and neutral–red. However, they in a way contradict the present results. When performance in the blue and yellow direction and in the red and green direction is combined, then constancy along the daylight axis exceeds that along the red–green axis in the present experiment. Delahunt & Brainard (2004a, 2004b) found high color constancy in the blue and green direction, mediocre constancy in the yellow direction, and rather low constancy in the red direction using seven subjects. They replicated their results several times and found them reliable. Their results are consistent with the present results. Moreover, the marginal effect of individual differences could be replicated. It seems that the performance irregularities found here compare reasonably to patterns obtained in successive color constancy situations.

The predominance of performance in blue and green illuminant directions is not easy to explain. In our natural environment, a rapid illuminant change to the blue side occurs frequently when the sun is covered by a cloud. A change to the yellow side occurs only during short periods at dusk and dawn (Delahunt, 2001). Thus, taking D65 as the standard illuminant, the probability of an illuminant change in the blue direction is higher than a change in the yellow direction. This might explain the higher performance in the blue direction relative to the yellow direction. The predominance of the green direction might be explained by an evolutionary approach. It was shown in section 3.1 that real–world scenes are mostly illuminated by non–daylight illumination which arises from mutual reflections at surfaces. For this reason, in forest areas, overall illumination is shifted towards green (Endler, 1993). Given that our visual system developed in forest areas, it might be argued that performance is rather high in the green direction.

In Experiment B, four additional illuminants were used. The degree of visual adjustment in these directions integrate smoothly in the pattern of Experiment A. Performance in the green–blue direction, for instance, is about the same as performance in the green and in the blue direction. Such patterns can also be seen at single–observer level. Thus, the irregularity of performance along different color axes has some systematic nature. Overall, there is best performance when illuminant changes are in greenish and bluish directions.

Altogether, the results of the related studies from other color constancy paradigms are consistent with the present results. Two results stand out.

First, color direction of illuminant changes plays some role for color constancy. There is a predominance of performance in greenish and bluish directions over yellowish and reddish directions. Second, there is evidence that the same result patterns account for the present situation as well as for successive color constancy situations. This becomes particularly obvious when comparing the present results with those of Delahunt & Brainard (2004a), for the same illuminants and a quite large number of observers were used in both studies. The mechanisms of the two types of color constancy show similar performance patterns across different illuminant directions.

5.3 Experiment 3: The role of color direction under various signal–to–noise ratios

The previous experiment showed significant differences in performance along different illuminant color directions. However, the experiment's signal–to–noise ratio based the surface change magnitude of 0.03 units in CIE u'v' space, and the illuminant change magnitude of 60 CIELab ΔE^{*} units, is arbitrary. Considering that CIELab and CIELuv color spaces are not exactly perceptually uniform, there is some possibility that the obtained effects result from perceptually unequal illuminant change magnitudes. If the effect is intrinsic to the color direction of illuminant changes, the pattern of performance should be similar when using different signal–to–noise ratios in the experiment. To investigate this issue, I repeated the previous experiment, this time increasing and decreasing the noise component in the paradigm by altering uniform illuminant change magnitudes.

5.3.1 Methods

Observers

Three observers from Experiment 2 participated in this experiment, CA (the author), SW, and TD. All had normal color vision as assessed by Ishihara color plates (Ishihara, 1917). All observers, except the author (CA), were naïve about the purpose of the experiment.

Experimental stimuli

CIE D65 was used as the initial illuminant. 16 new test illuminants were introduced. Their CIE u'v' chromaticity coordinates were constructed to lie in the same directions as the illuminants from Experiment 2. Eight of them had a distance of 30 CIELab ΔE^* units (Red30, RY30, Yellow30, YG30, Green30, GB30, Blue30, BR30), and eight had a distance of 85 CIELab ΔE^* units (Red85, RY85, Yellow85, YG85, Green85, GB85, Blue85, BR85) from the D65 illuminant. Figure 5.13 shows all test illuminants along with the test illuminants from Experiment 2 for comparison. CIE u'v' chromaticity coordinates of the illuminants are listed in Table 5.1. Illuminants Red30, RY30, Yellow30, Blue30, BR30, as well as Red85, RY85, Blue85, and BR85 were constructed using daylight basis functions, YG30, Green30, GB30, as well as Yellow85, YG85, Green85, and GB85 were constructed using monitor basis functions. Surfaces were drawn randomly without replacement from the pool of 226 spectral reflectances. The average luminance of the images was held constant at 4 cd/m^2, but individual surfaces varied from 0.65 to 8.81 cd/m^2.

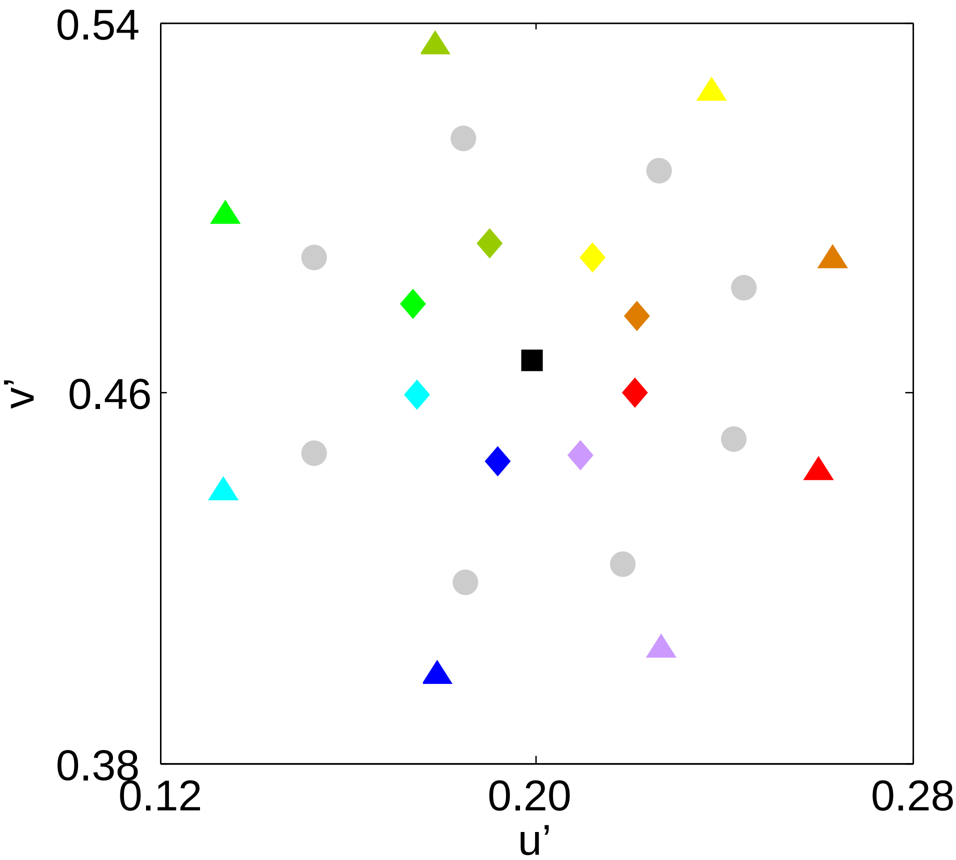


Figure 5.13: CIE u'v' chromaticity coordinates of test illuminants. Diamonds depict the eight illuminants which had a distance of 30 CIELab ΔE^* units (Red30, RY30, Yellow30, YG30, Green30, GB30, Blue30, BR30), and triangles the eight illuminants which had a distance of 85 CIELab ΔE^* units (Red85, RY85, Yellow85, YG85, Green85, GB85, Blue85, BR85) from initial CIE D65 illuminant (black square). For comparison, CIELab $\Delta E^* = 60$ illuminants are depicted in grey.

Procedure

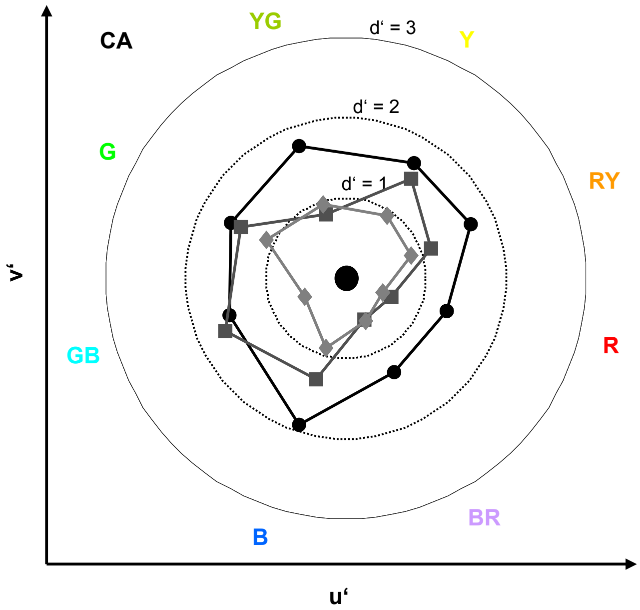
The first Mondrian pattern was always illuminated by CIE D65. Within sessions, the illuminant of the second pattern was drawn from exactly one of four pools with four test illuminants each. The first pool consisted of Red30, Yellow30, Green30, and Blue30, the second of RY30, YG30, GB30, and BR30. The third and fourth pool consisted of the respective $\Delta E^* = 85$ illuminants. Illuminants were drawn randomly from each pool. The selection of the pools of test illuminants were counterbalanced over sessions. Between images, either an illuminant change or a surface change occurred randomly. In illuminant change trials, the second Mondrian was simply illuminated by one of the test illuminants. In the surface change condition, the same illuminant change occurred, but additionally chromaticity coordinates of a random quarter of the surfaces was shifted in the illuminant change direction, a second quarter in the opposite direction, and a third and fourth quarter in the two orthogonal directions, respectively. The magnitude of these shifts was 0.03 units in u'v' space. There were 200 trials per session, divided into three blocks with short intervening breaks. Each observer made 300 judgments for each of the 16 illuminant changes.

5.3.2 Results

Figures 5.14–5.17 show discrimination performance d' of the three observers, as well as the mean over observers. In each figure, data is depicted in a polar plot and a bar plot similar to Experiment 2B (Figures 5.7–5.12). In the polar plots, black circles and light grey diamonds show performance under 30 ΔE^* and 85 ΔE^* illuminant changes, respectively. For comparison, performance under 60 ΔE^* illuminant changes is also shown (dark grey squares).

In bar plots, plain bars and dotted bars represent performance in conditions with illuminant change magnitudes of 30 ΔE^* and 85 ΔE^* units, respectively. Checkered bars show results under 60 ΔE^* illuminant changes for comparison.

A within–subject two–way ANOVA was conducted for the three observers, with factors illuminant color direction (Red, Red–Yellow, Yellow, Yellow–Green, Green, Green–Blue, Blue, Blue–Red) and uniform illuminant change magnitude ($\Delta L^* = 30, 60, 85$). For each observer, there is a significant effect of illuminant color direction (CA: F=6.04, MSE=0.17, p<0.01; SW: F=12.19, MSE=0.20, p<0.01; TD: F=11.99, MSE=0.12, p<0.01) and of uniform illuminant change magnitude (CA: F=74.16, MSE=0.10, p<0.01; SW: F=166.20, MSE=0.11, p<0.01; TD: F=53.87, MSE=0.10, p<0.01). The interaction of the factors is significant for observers CA (F=2.52, MSE=0.12, p<0.01) and TD (F=2.37, MSE=0.22, p<0.01) and marginally significant for SW (F=1.70, MSE=0.18, p=0.08). One–way ANOVAs for each observer, separately for the two illuminant shift magnitudes $\Delta L^* = 30$ and $\Delta L^* = 85$, respectively, reveal an effect of illuminant color direction. In the $\Delta L^* = 30$ condition, the effect was significant for observer SW (F=6.42, MSE=0.17, p<0.01) and TD (F=8.68, MSE=0.14, p<0.01), and marginally for CA (F=2.03, MSE=0.12, p=0.08). In the $\Delta L^* = 85$ condition, there was a significant effect for all observers (CA: F=2.41, MSE=0.14, p=0.04, SW: F=5.10, MSE=0.16, p<0.01, TD: F=3.48, MSE=0.18, p<0.01). To capture possible observer differences, a re–analysis of the data was done with observer as an additional factor. The three–way ANOVA was conducted with factors observer (CA, SW, TD), illuminant direction (Red, Red–Yellow, Yellow, Yellow–Green, Green, Green–Blue, Blue, Blue–Red), and uniform illuminant change magnitude ($\Delta L^* = 30, 60, 85$). There are significant observer



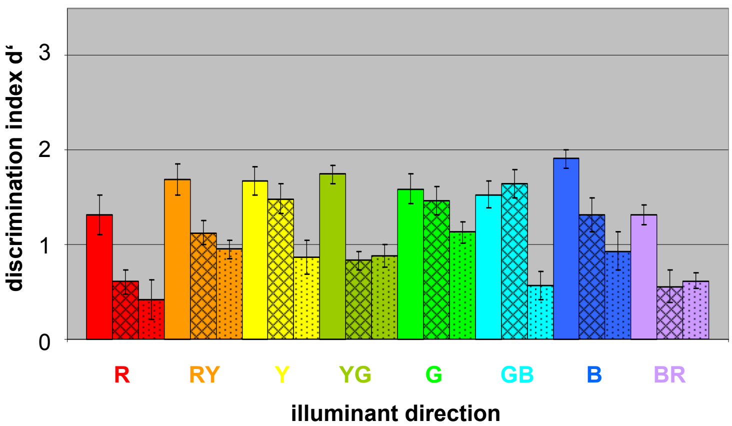


Figure 5.14: Results for observer CA. Upper panel: Polar plot within CIE u'v' coordinate system. The filled circle represents u'v' coordinates of CIE D65, direction from the center represents color direction in CIE u'v' space, and distance from the center represents discrimination index d'. Lower panel: Bar plot for the same data. Illuminant shift magnitude of 30 ΔE^* units is indicated by black circles and plain bars, and magnitude of 85ΔE^* units by light grey diamonds and dotted bars. For comparison, data from the previous experiment with 60 ΔE^* units (dark grey squares and checkered bars) is reprinted. Error bars show ± 1 SEM.

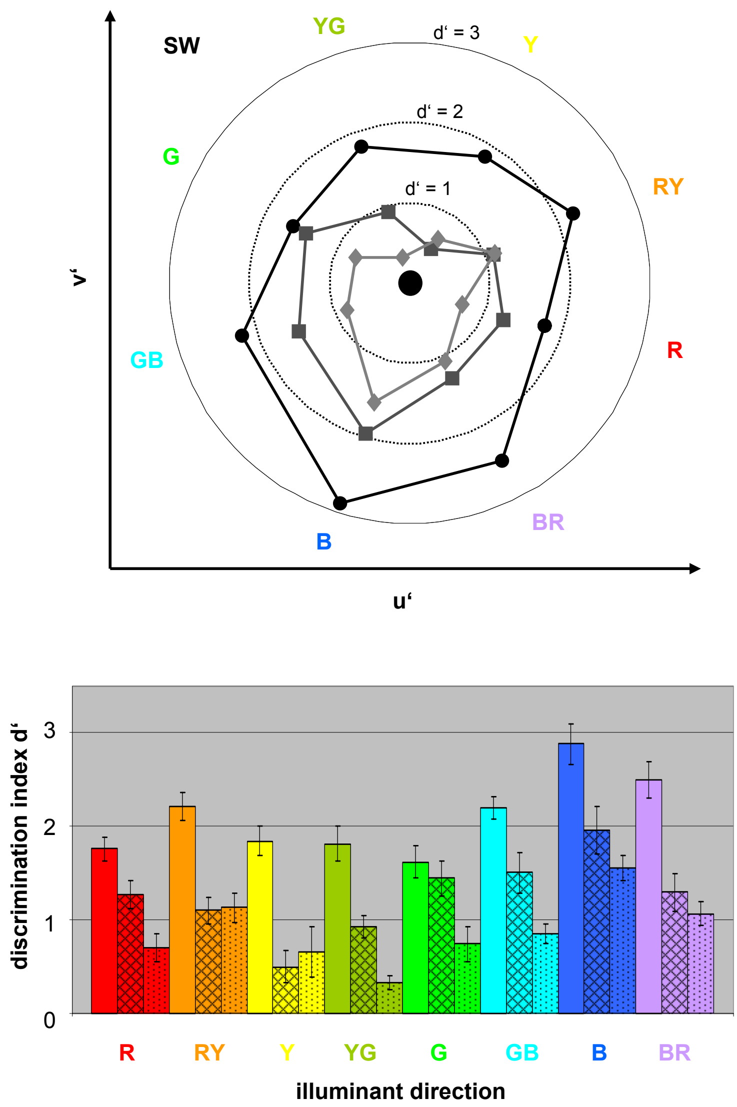
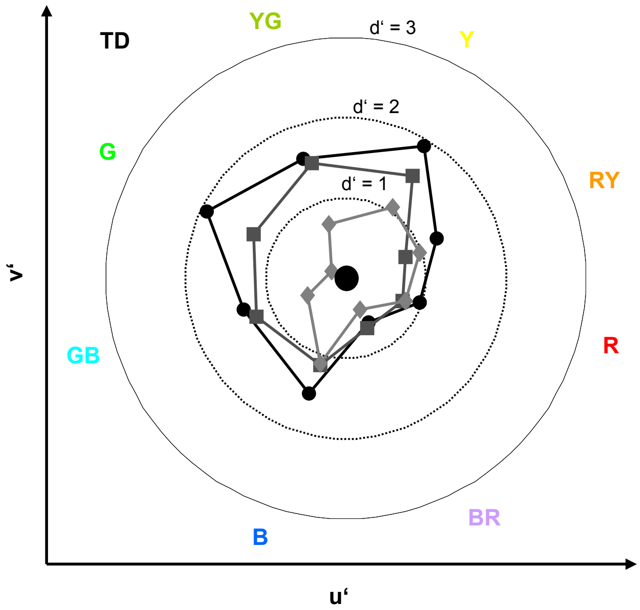


Figure 5.15: Results for observer SW. Polar plot within CIE u'v' coordinate system. The filled circle represents u'v' coordinates of CIE D65, direction from the center represents color direction in CIE u'v' space, and distance from the center represents discrimination index d'. Lower panel: Bar plot for the same data. Illuminant shift magnitude of 30 ΔE^* units is indicated by black circles and plain bars, and magnitude of 85ΔE^* units by light grey diamonds and dotted bars. For comparison, data from the previous experiment with 60 ΔE^* units (dark grey squares and checkered bars) is reprinted. Error bars show $\pm$ 1 SEM.



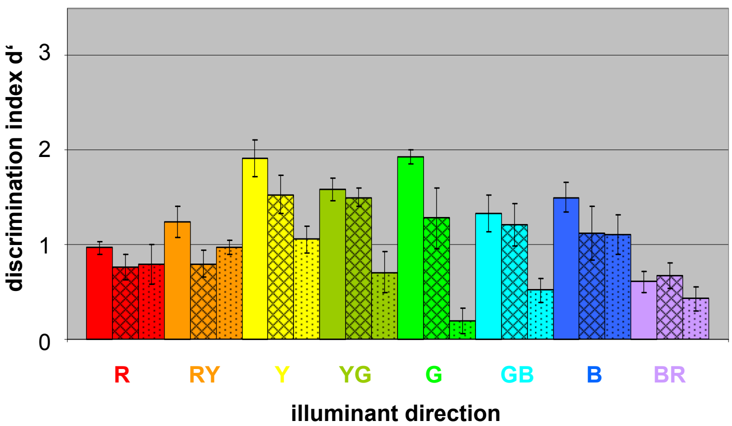


Figure 5.16: Results for observer TD. Polar plot within CIE u'v' coordinate system. The filled circle represents u'v' coordinates of CIE D65, direction from the center represents color direction in CIE u'v' space, and distance from the center represents discrimination index d'. Lower panel: Bar plot for the same data. Illuminant shift magnitude of 30 ΔE^* units is indicated by black circles and plain bars, and magnitude of 85ΔE^* units by light grey diamonds and dotted bars. For comparison, data from the previous experiment with 60 ΔE^* units (dark grey squares and checkered bars) is reprinted. Error bars show $\pm$ 1 SEM.

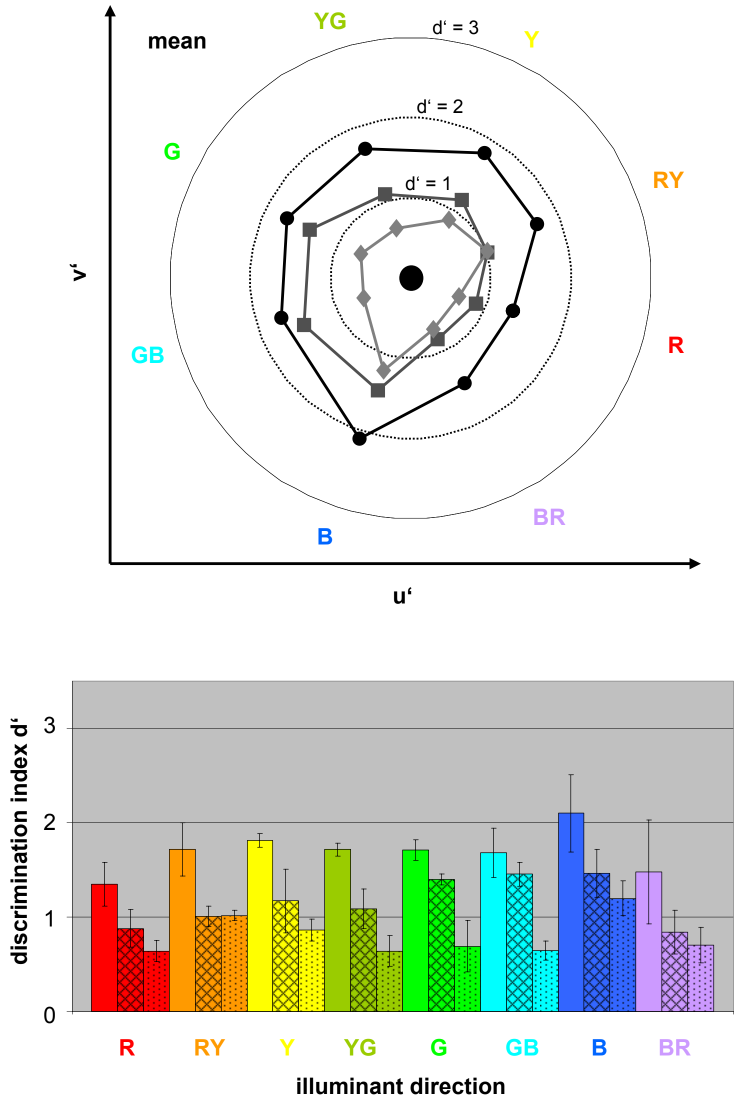


Figure 5.17: Mean results over observers. Polar plot within CIE u'v' coordinate system. The filled circle represents u'v' coordinates of CIE D65, direction from the center represents color direction in CIE u'v' space, and distance from the center represents discrimination index d'. Lower panel: Bar plot for the same data. Illuminant shift magnitude of 30 ΔE^* units is indicated by black circles and plain bars, and magnitude of 85ΔE^* units by light grey diamonds and dotted bars. For comparison, data from the previous experiment with 60 ΔE^* units (dark grey squares and checkered bars) is reprinted. Error bars show $\pm$ 1 SEM.

differences (F=45.41, MSE=0.10, p<0.01) along with significant effects of illuminant direction (F=10.42, MSE=0.19, p<0.01), and uniform illuminant change magnitude (F=246.15, MSE=0.12, p<0.01). There is also a high interaction of observer and illuminant direction (F=9.71, MSE=0.15, p<0.01) and of illuminant change magnitude and illuminant direction (F=3.02, MSE=0.13, p=0.01). For a better insight, Figure 5.18 replots data of Figure 5.17 and shows differences in mean discrimination performance over observers under illuminant change magnitudes $\Delta L^* = 30$ and $\Delta L^* = 85$. It is evident that

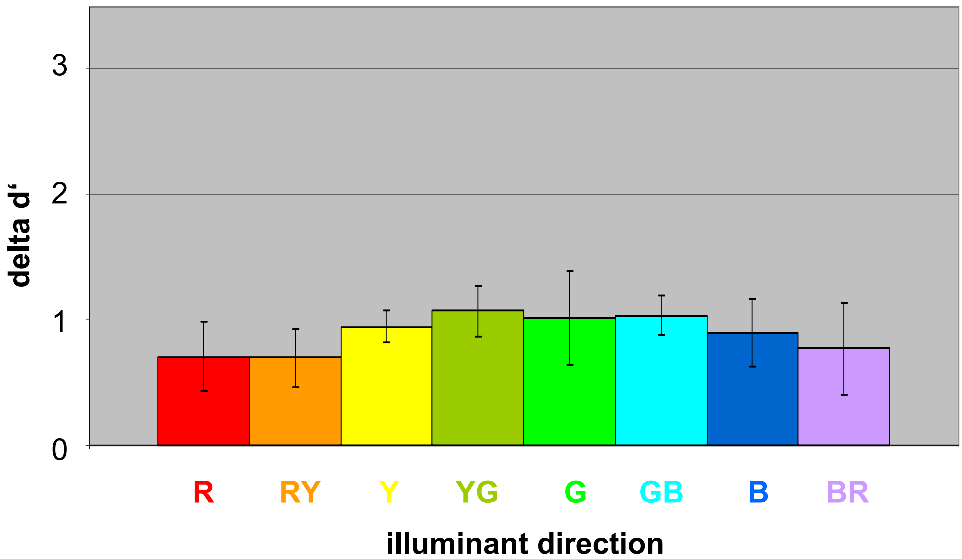


Figure 5.18: Differences between performances in 30 ΔE^* and 85 ΔE^* conditions over observers. Error bars show ± 1 SEM.

performance differences are quite similar across illuminant directions. This shows that performance patterns for these two magnitudes are approximately equal.

5.3.3 Discussion

The purpose of the experiment was to investigate if the performance pattern from Experiment 2 depends solely on non–linearities of color space or if it is intrinsic to color direction of illuminant changes. If the latter was true, the pattern should remain stable across changes in illuminant change magnitude, i. e. across changes in signal–to–noise ratios in this paradigm. It was shown that within subjects there was some variation in the performance patterns over different illuminant shift magnitudes. However, these variations have no systematic nature. This is particularly evident from mean results over observers. Result patterns from 30 ΔE^* and 85 ΔE^* conditions are rather similar. However, compared to the pattern of the 60 ΔE^* condition the effect of illuminant direction is slightly reduced. This may result from certain floor and ceiling effects in these conditions. Particularly, performance in the green and green–blue direction deteriorates to some extent. Performance in the blue direction, on the other hand, is highest in all three conditions and performance in the red direction is always rather low. Overall, the pattern remained rather stable under changes in signal–to–noise ratios in the experiment. There is evidence now, that, in this discrimination paradigm, the effect of color direction in illuminant changes on the degree of color constancy is not due to perceptual non–linearities of color space, but is an attribute of the visual system.

5.4 Experiment 4: The role of surface collection in illuminant changes

A color constant visual system is able to maintain object colors despite changes in surrounding illumination. Since we encounter different environments in everyday life, this feature must hold across a variety of scenes. In section 3.1, we made a distinction between urban scenes, where spectral reflectances are rather equally distributed in color space with mean chromaticities clustering along the daylight locus, and rural scenes, where reflectances are distributed more in the green area, with means lying to the green side of the daylight locus. By far the fewest reflectances fall to the red side of the daylight locus. From our daily experience, our visual system compensates well for illuminant changes mostly independent of scene surface composition. However, it has been shown in Experiments 2 and 3 that there are also irregularities in color constancy under illuminant changes with different color directions which are hardly recognized in everyday life. Therefore, there is some possibility that surface collection also influences the degree of visual adjustment to an illuminant.

There is some research on this issue in successive color constancy situations. Bäuml (1994, 1999b) found some differences in observers' settings under different surface collections with diverse mean chromaticities. Brainard (1998) used differently colored backgrounds and found differences in achromatic loci. However, when surface collections differ mainly in luminance, rather than in mean chromaticity, no such effect can be found (Bäuml, 1995). Furthermore, in the studies of Bäuml (1994, 1995), slight observer differences were found. Bäuml (1999a) investigated appearance and surface color in simultaneous situations. He found almost no differences between color matches when collections differed only in luminance, but found some when collections differed in mean chromaticity. He also found a slight interaction of illuminant direction and surface collection in both conditions.

There is no color constancy research investigating a possible influence of surface collection in situations where illumination changes temporally and rapidly. It is also unclear whether there is an interaction of surface collection and color direction of illuminant change. It is the purpose of the next experiment to fill this gap. Two possible outcomes can be expected. First, Experiment 2 showed that the amount of visual adjustment is related to the distribution of illuminants in our natural environment. If degrees of color constancy are also related to the distribution of surfaces in our environment, then a pattern should show up with high constancy under green, medium under yellow and blue, and low constancy under red collections. Second, if the visual system processes illuminants and surfaces separately, and the degree of color constancy only depends on the color direction of the illuminant change, then the amount of visual adjustment should be similar under each surface collection.

5.4.1 Methods

Observers

Four observers participated in this experiment, AW, BD, CA (the author), and HM. All had normal color vision as assessed by Ishihara color plates (Ishihara, 1917). All observers except the author (CA) were naïve about the purpose of the experiment.

Experimental stimuli

As experimental illuminants, Blue60 and Red60 (Figure 5.5, Table 5.1) from Experiment 2 were chosen. As experimental surfaces, the whole set of 226 reflectances was split into four slightly overlapping subsets (Figure 5.19) to obtain surface collections containing mainly red, yellow, green, and blue surfaces. Each collection contained 61 different surfaces. As a fifth collection, the whole set of 226 surfaces was used (Figure 4.1). It served as a neutral collection. The average luminance of the images was held constant at 4 cd/m^2, but individual surfaces varied from 0.65 to 8.81 cd/m^2.

Procedure

The first Mondrian pattern was always illuminated by CIE D65. The illuminant of the second pattern was either test illuminant Blue60 or Red60. Between images, either an illuminant change or a surface change occurred randomly. In illuminant change trials, the second Mondrian was simply illuminated by one of the test illuminants. In the surface change condition, the same illuminant change occurred, but additionally chromaticity coordinates of a random quarter of the surfaces were then shifted along the Blue axis, a second quarter along the Yellow axis, a third quarter along the Red axis, and a fourth along the Green axis. The magnitude of these shifts was 0.03 units in CIE u'v' space. The surfaces which the Mondrian patterns were composed of were drawn randomly, without replacement, from one of the five surface collections, also chosen randomly for each trial. There were 250 trials per session, divided into three blocks with short intervening breaks. Within sessions, only one of the test illuminants was used.

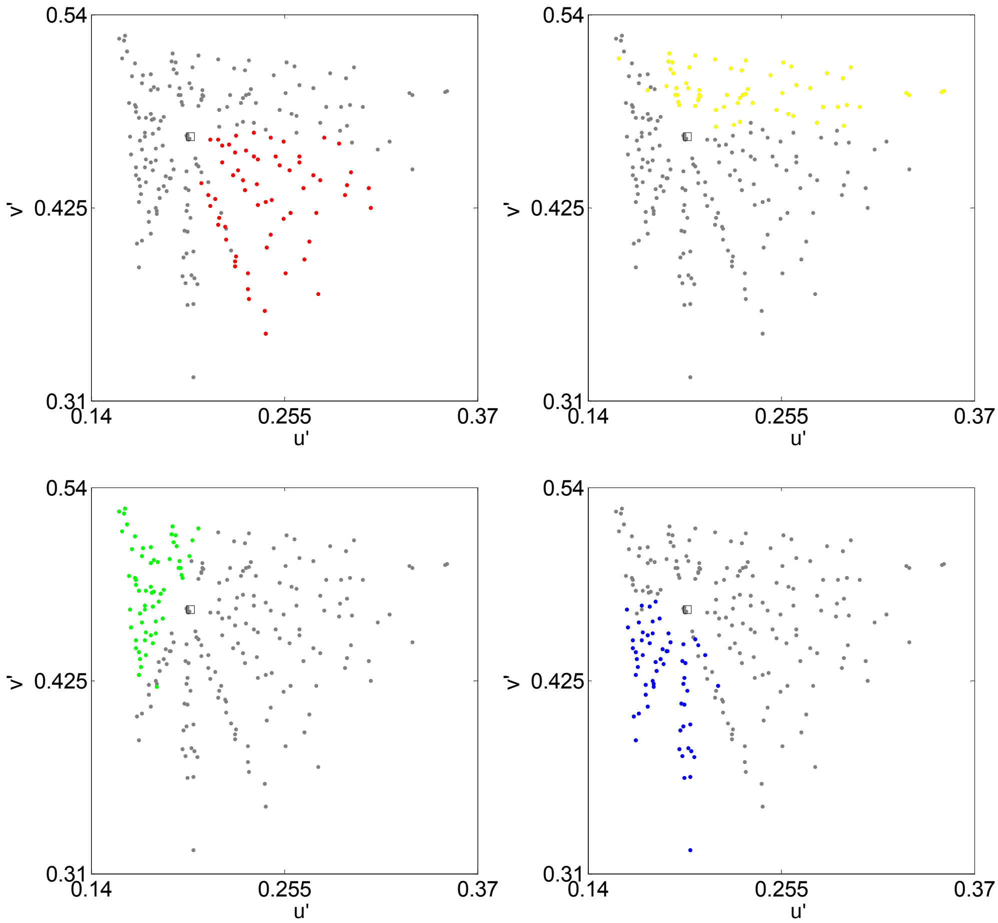


Figure 5.19: Experimental surface collections. In each panel, the CIE u'v' coordinates of a single collection (Red, Yellow, Green, Blue), illuminated by D65 (open square), are depicted in the respective color. For comparison, coordinates of the remainder of the entire surface set is shown in light grey in each panel.

5.4.2 Results

Figure 5.20 shows discrimination performance d' for observers AW, BD, and CA, and Figure 5.21 for observer HM, as well as mean results over observers, and results collapsed over observers and illuminant directions.

A two-way ANOVA with factors illuminant direction (Blue, Red) and surface collection (Neutral, Red, Yellow, Green, Blue) shows, for each of the four observers, effects of illuminant direction and surface collection. The effect of illuminant direction is significant for observer AW (F=95.91, MSE=0.16, p<0.01), BD (F=11.03, MSE=0.18, p=0.02), and CA (F=7.40, MSE=0.17, p=0.04), but not for HM (F=3.11, MSE=0.16, p=0.14). For each observer, overall performance is higher in the blue direction than in the red direction. There is also a significant effect of surface collection for observer AW (F=23.75, MSE=0.23, p<0.01), BD (F=38.11, MSE=0.27, p<0.01), and HM (F=6.82, MSE=0.40, p<0.01), and marginally for CA (F=2.34, MSE=0.08, p=0.09). Observers BD and CA have highest overall performance under the green collection, and observers AW and HM under the green and blue collection. Results under the neutral surface collection are directly comparable to Experiment 2A on the role of illuminant direction (Figure 5.6). Observer CA participated in both experiments and replicated his results. There is a significant interaction of illuminant direction and surface collection for all four observers (AW: F=2.93, MSE=0.27, p=0.05; BD: F=11.73, MSE=0.23, p<0.01; CA: F=7.04, MSE=0.17, p<0.01; HM: F=3.90, MSE=0.30, p=0.02). Figures 5.20 and 5.21 show, for each observer, a rather stable performance under the green and blue collections across illuminant changes. However, performance under the neutral, red, and yellow collections deteriorates for each observer when illuminant direction is changed from blue to red.

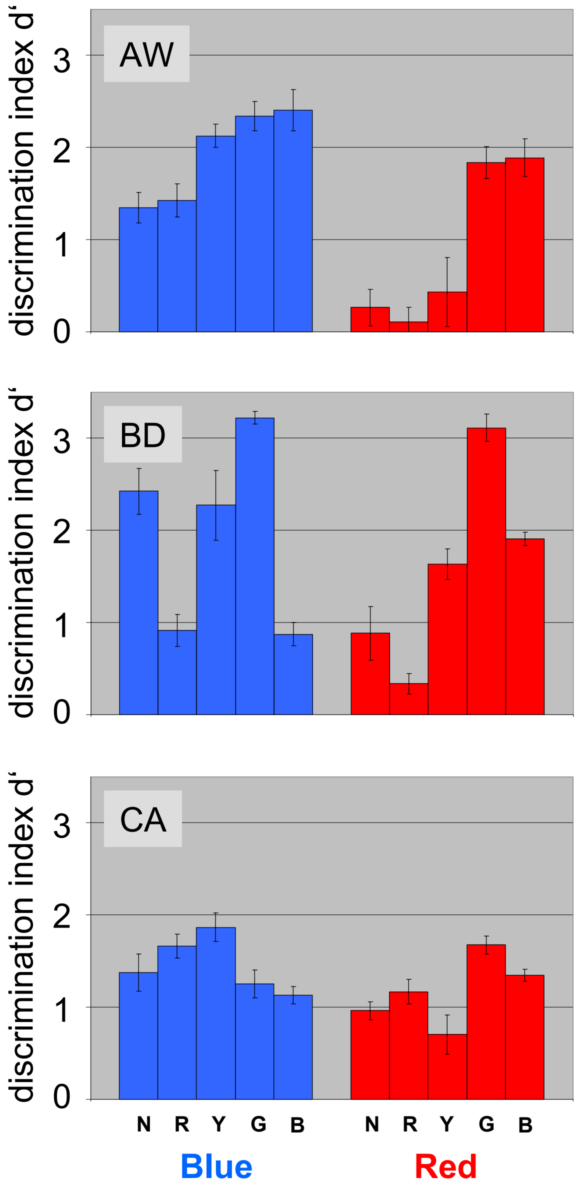


Figure 5.20: Results for observers AW, BD, and CA. In each panel the two bar groups show performance in illuminant directions Blue and Red. Within each bar group, performance under the five surface collections (Neutral, Red, Yellow, Green, Blue) is shown. Error bars show ± 1 SEM.

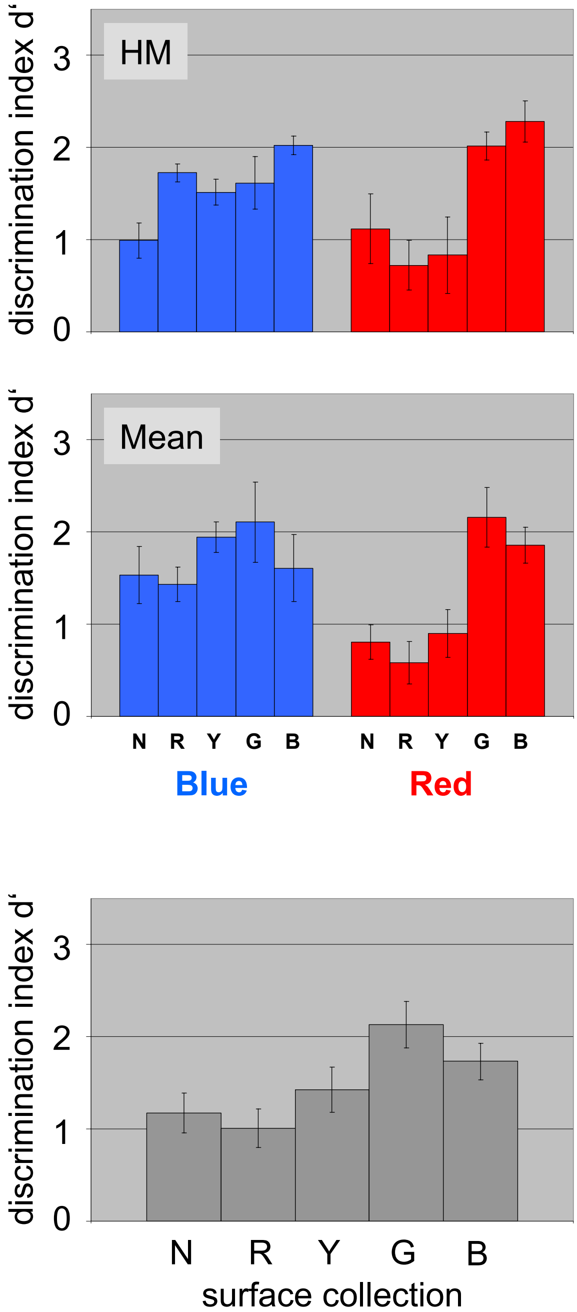


Figure 5.21: Results for observer HM (upper panel), depicted as in Figure 5.20, results for data collapsed over observers (middle panel), and for data collapsed over both observers and illuminant directions (bottom panel). Error bars show ± 1 SEM.

The middle panel of Figure 5.21 shows mean performance collapsed over observers where this effect becomes particularly obvious. Performances under the neutral collection again replicated results from Experiment 2 (Figure 5.6, lower right panel). To capture the effect of observer differences, data was re-analyzed with a 3-way ANOVA with factors observer (AW, BD, CA, HM), illuminant direction (Blue, Red), and surface collection (Neutral, Red, Yellow, Green, Blue). Besides the expected effects of illuminant direction ($F=88.61$, $MSE=0.15$, $p<0.01$) and surface collection ($F=44.10$, $MSE=0.22$, $p<0.01$), there are again significant observer differences ($F=7.62$, $MSE=0.28$, $p<0.01$). The significant interaction of illuminant direction and surface collection ($F=17.69$, $MSE=0.23$, $p<0.01$) confirms the visual examination of Figure 5.21 (middle panel). A significant interaction of illuminant direction and observer, already found in Experiments 2 and 3, is also found here ($F=12.45$, $MSE=0.17$, $p<0.01$), along with a significant variation of surface collection with observer ($F=11.82$, $MSE=0.25$, $p<0.01$).

The lower panel of Figure 5.21 shows results of the same data collapsed over observers and illuminant directions. The declining order of performance under surface collection is Green, Blue, Yellow, Neutral, and Red. The pattern looks rather similar to the pattern obtained for respective illuminant directions in Experiment 2 (Figure 5.6, lower right panel). For instance, performance is high under the green surface collection, as well as in the green illuminant direction, and performance is rather low under the red collection, as well as in the red illuminant direction. A two-way ANOVA with factors observer (AW, BD, CA, HM) and surface collection (Neutral, Red, Yellow, Green, Blue) confirms the effect of surface collection ($F=17.22$, $MSE=0.57$, $p<0.01$), besides effects of observer ($F=5.32$, $MSE=0.41$, $p=0.04$) and a significant interaction of the factors ($F=19.58$, $MSE=0.28$, $p<0.01$).

Table 5.4: False Alarm rates across test illuminants (Blue, Red) and across surface collections (N=Neutral, R=Red, Y=Yellow, G=Green, B=Blue) of Experiment 3 for individual observers as well as for the mean under each test illuminant. The overall mean is calculated by collapsing data over both observers and test illuminants.

Observer	Blue-N	Blue-R	Blue-Y	Blue-G	Blue-B
AW	0.59	0.39	0.13	0.07	0.07
BD	0.19	0.02	0.45	0.02	0.02
CA	0.44	0.03	0.08	0.16	0.02
HM	0.62	0.03	0.16	0.35	0.02
mean Blue	0.46	0.12	0.21	0.15	0.03

Observer	Red-N	Red-R	Red-Y	Red-G	Red-B
AW	0.86	0.44	0.80	0.09	0.14
BD	0.70	0.02	0.11	0.04	0.03
CA	0.46	0.11	0.49	0.03	0.04
HM	0.72	0.73	0.73	0.22	0.28
mean Red	0.69	0.33	0.53	0.09	0.12

overall mean	0.57	0.22	0.37	0.12	0.08

Table 5.4 lists False Alarm rates of individual observers the mean to investigate whether they vary across condition and correlate somehow with discrimination performance. It can be clearly seen that False Alarm rates vary widely across surface collections but do not correlate with discrimination indices. For instance, observer BD under the blue illuminant has rather similar discrimination performance of about 1.3 under the neutral and yellow collection but rather different False Alarm rates of 0.19 and 0.45. In turn, False Alarm rates of 0.02 both under the red and green collection do not correlate with rather different discrimination indices of about 0.9 and 3.2.

5.4.3 Discussion

This experiment was designed to investigate the role of surface collection on the degree of surface color constancy in situations with rapid, temporal illuminant changes. Observers could reliably discriminate illuminant changes from surface changes in a variety of scenes and illuminants. An effect of illuminant direction was found with better performance in the blue direction than in the red direction. This result is consistent with findings earlier in this work (Experiments 2 and 3). There was also an effect of surface collection on performance. This effect varied somewhat between observers and interacted with illuminant direction. When data is collapsed over observers, this interaction becomes particularly apparent. While performance under green and blue collections remains quite stable, performance under the other collections deteriorate when illuminant direction changes from Blue to Red. When data is further collapsed over illuminant directions, a decline of performance under different surface collections can be observed, the order being Green, Blue, Yellow, Neutral, Red. This pattern reminds of results previously found in this work (Experiment 2), where performance under different illuminant directions was quite similar, with performance being highest in green and blue directions, mediocre in the yellow direction, and low in the red direction. There seems to be some evidence that the visual system, regarding the degree of color constancy, adjusts to the light incident at the eye, i. e. the product of illuminant and surface properties. For instance, color constancy under a neutral surface collection when illuminant changes in the blue direction is comparable to constancy under a blue surface collection when illuminant changes in blue, red and probably other color directions.

It was investigated whether False Alarm rates vary across conditions and correlate with discrimination performance. It could be shown that, indeed, False Alarm rates vary widely across surface collections. However, they do not correlate with discrimination performance. The same result was obtained in Experiment 2 for varying illuminant directions. False Alarm rates, therefore, do not predict differences in discrimination performance under changing illuminant directions and surface collections.

When relating these results to findings from studies concerning successive and simultaneous color constancy situations using similar illuminants and surface collections, some similarities become apparent. Better performance under the blue than the red illuminant was also found by Delahunt & Brainard (2004a, 2004b). Some effect of surface collection, when varied in mean chromaticity, was also found by Bäuml (1994, 1995, 1999b, 1999a) and Brainard (1998). However, Bäuml (1995) did not find this effect when varying the surface collection mainly in luminance rather than chromaticity. In Experiment 1 of this work, it was shown that luminance of an illuminant does not have a major impact on discrimination performance. These two findings support the assumption that the visual system adjusts to the product of illumination and surface reflectance, rather than separately (but see Bäuml (1994) for strong effects of surface collection which are separable from effects of illumination). Slight effects of surface collection and an interaction were also found by Bäuml (1999b, 1999a) and Brainard (1998).

Different degrees of constancy under different surface collections can be related to the distribution of surfaces in our environment. As mentioned above, mean chromaticities of urban surface collections lie near the daylight locus (Nascimento et al., 2002). However, chromaticities of rural surface collections lie on average to the green side of the daylight locus (e. g. Webster & Mollon, 1997; Nascimento et al., 2002). In addition, reddish surfaces are relatively rare in rural environments. Based on these data, color constancy performance under a particular surface collection correlates somehow with the frequency of those surfaces in rural environments.

The close entanglement of the roles of illuminant direction and surface collection on the degree of color constancy on the one hand, and correlation of color constancy and frequency of surfaces in natural environments on the other hand, is not surprising when we consider how non-daylight illumination arises. It is the product of the surface reflectance and the impinging light on this surface. As a conclusion the frequency of colors of indirect illuminations correlate with the colors of surfaces by which they arise. Reddish illuminants, for instance, are rather rare because reddish surfaces are rather rare in natural environments.

Chapter 6

General Discussion

Summary of results

In this chapter, a series of four experiments was run to systematically investigate the role of color direction of illuminant changes and surface collection on the degree of color constancy in situations with rapid temporal illuminant changes. In Experiment 1, the experimental setup was evaluated. It was found that luminance in illuminant changes only plays a minor role for the degree of color constancy. In Experiment 2, it was found that the degree of color constancy depends on the color direction of illuminant changes. Best performance was in greenish and blueish directions, and worst performance in reddish directions. In Experiment 3, different illuminant change magnitudes were tested to reassess the performance pattern obtained and exclude the possibility that the irregularities found are due to non–linearities of color space. As a result, the overall pattern stayed rather stable across illuminant change magnitudes. In Experiment 4, the role of surface collection for color constancy was investigated. Performance was highest under the green collection, and deteriorated under the other collections blue, yellow, and red in declining order. Furthermore, there was an interaction of illuminant direction and surface collection.

The role of illuminants and surface collections

The motivation of this study was to investigate the roles of illuminant color direction and surface collection on the degree of color constancy under rapid temporal illuminant changes. For this purpose, the paradigm of Craven & Foster (1992) was applied, in which observers had to discriminate changes in illuminant from changes in surfaces within a scene. It is shown that the degree of color constancy in situations with rapid temporal illuminant changes depends on the color direction of these illuminant changes. This is true for changes of chromaticity, but not for changes in luminance which has almost no effect on color constancy. Overall, performance was best for greenish and bluish color directions, medium for yellowish directions, and worst for reddish directions. The surface collection also plays some role on the degree of simultaneous color constancy. The results resemble the pattern for the effect of illuminant direction. Performance was best for the collection with on average green reflectances, medium for collections with on average blue and yellow reflectances, and worst for the collection consisting of on average red reflectances. However, the effect varied somehow with illuminant direction indicating an interaction of the two effects.

Two conclusions can be drawn from the experiments provided in this work. First, the visual system shows color constancy in situations with rapid temporal illuminant changes. This holds true, however to different extents, for a considerable range of daylight and non–daylight illuminants and several color–biased scene compositions. This type of color constancy is important for everyday life, since we frequently encounter situations where the illuminant changes rather rapidly, e. g. when an additional light source is switched on or when the sun gets screened by a cloud. Second, the degree of color constancy in the present paradigm seems to depend on the combination of illuminant direction and surface collection, so the visual system seems to adjust to some product of the two.

Relation to successive and simultaneous color constancy

Previous color constancy research focussed on successive and simultaneous color constancy situations. In successive situations, illumination changes rather slowly. It is common belief by now that visual adjustment is mediated by some adaptational process at receptor site in this situation (Kaiser & Boynton, 1996). In simultaneous color constancy paradigms, where illumination changes spatially, those adaptational processes are to a large extent excluded. Nonetheless, even when observers are asked to make surface color matches, the visual system adjusts in terms of receptor signal scaling very similar to adaptational processes, suggesting a close relation of apparent color and surface color mechanisms (Bäuml, 1999a). In this sense, there is a connection between successive and simultaneous color constancy situations.

This work provides a third paradigm derived from Craven & Foster (1992), where illumination changes rapidly in a temporal manner. All results obtained in this work are consistent with or can easily be embedded in findings from studies concerning successive and simultaneous color constancy. In successive color constancy situations, for instance, Brainard (1998) found a slight effect of illuminant direction. Lucassen & Walraven (1996) found better constancy in the blue illuminant direction than in the yellow direction. Delahunt & Brainard (2004a, 2004b) found best performance in green and blue directions, medium performance in the yellow direction, and worst performance in the red direction. Regarding the role of surface collection in successive color constancy situations, an effect was found for collections with rather different mean chromaticity coordinates (Bäuml, 1994, 1999b), but no effect for collections differing mainly in mean luminance (Bäuml, 1995). Brainard (1998) also found small differences in adjustment for differently colored backgrounds. Overall, the results of this work are consistent with the results of the studies concerning successive color constancy. Bäuml (1999a) found an effect for surface collections with varying chromaticity, but no effect for collections with varying luminance only in a simultaneous color matching paradigm. The results of this work also show an effect of surface collection with varying mean chromaticity. He also showed that observers' appearance and surface color matches are similar in a qualitative way suggesting similar constancy patterns along different color directions, and under different surface collections in successive color constancy and in simultaneous color constancy situations. In addition, he found a slight interaction of illuminant direction and surface collection in both apparent and surface color situations. An interaction was found in the present study as well. As a conclusion, this paradigm is also related to simultaneous color constancy.

Despite reflecting rather different situations, all three paradigms seem to be related with respect to which results they produce. However, in contrast to this paradigm, the settings produced by matching paradigms, which are used for successive and simultaneous color constancy experiments, provide additional information about the way of visual adjustment. It was shown that simple von Kries and illuminant linearity models fitted on those data describe the characteristics of visual adjustment rather well. Moreover, these models are rather robust against influences of illuminant direction and surface collection. This leads indeed to detectable but small effects. The data analysis of the paradigm used here involves paired comparison and appears like a magnifying lens on the effects of illuminant direction and surface collection for these model data. Therefore, it provides a detailed view on the influence of these two factors.

Individual observer differences

In the present study, some observer differences were found. For instance, when different illuminant directions were tested, some observers had better performance under the yellow illuminant than under the red illuminant and vice versa. Differences could also be observed when testing color constancy under different surface collections. It is not easy to explain this effect. When the role of illuminant direction and surface collection was investigated using successive and simultaneous color matching paradigms, observer differences were found as well (e. g. Delahunt, 2001; Bäuml, 1999a). However, many studies focussed on the characteristics of visual adjustment by fitting rather robust models to the data, so that effects of illuminant direction and surface collection were often small and could have been neglected for this purpose. For this reason, observer differences were not large enough to be focussed on. On the other hand, it is obviously important to involve far more than just two or three or five observers in experiments to obtain reliable results on individual differences, when the issue of illuminant direction and surface collection is supposed to be examined. However, such a detailed analysis of observer differences is beyond the scope of this work.

Why does color constancy depend on illuminant color direction and surface collection?

This work shows that the degree of color constancy depends on the color direction of the illuminant change and on the color bias of the scene composition. How can these effects be explained? The reason why performance is better under the blue than under the yellow illuminant might be due to the probability of daylight changes in everyday environment. In this work, CIE D65 was used as the standard illuminant which is regarded as neutral in color and typical for a mixture of sunlight and scattered skylight. In our natural environment, rapid illuminant changes to the blue side of D65 occur frequently when the sun gets shaded by a cloud. Changes to the yellow side occur only during rather brief periods at dusk and dawn. The visual system might adjust better to blue illuminant changes because it is more often confronted with these kind of changes (Delahunt, 2001).

An explanation of the rather high performance in the green illuminant direction, especially compared to that in the red direction, may be provided by an evolutionary approach. It has been shown that in forested areas almost the entire illumination is, due to mutual reflections, shifted towards green to yellow–green (Endler, 1993). Given that our visual system has evolved in such environments, this comparatively high degree of color constancy is not surprising. Moreover, the visual system seems to have developed towards certain goals. Old World primates, which are one of the few mammals to have trichromatic color vision similar to that of humans, live in environments where some vital tasks are to be fulfilled in order to ensure survival of the species. One of such tasks is to identify edible fruit against green foliage (Allen, 1879). Osorio & Vorobyev (1996) showed empirically that trichromacy is superior to dichromacy in such a task. Regan, Julliott, Simmen, Vinot, Charles–Dominique, & Mollon (2001) found that the responsivity functions of the photoreceptors in trichromatic primates are well–matched to succeed in this task. Another task is to discriminate emotional states, socio–sexual signals and threat displays of conspecifics. Changizi, Zhang, & Shimojo (2006) showed that sensitivities of medium– and long–wavelength receptors in trichromatic primates are optimized to accomplish this task. These studies focus at the characteristics of photoreceptors and found evidence that they evolved towards accomplishing certain vital tasks in the environment. Color constancy mechanisms, which facilitate perceiving constant object colors, might as well have evolved adjusting to certain environmental conditions, like living in forest areas illuminated by mostly greenish light. However, forested areas nowadays do not have such a high significance for humans anymore. The high performance in the blue and in the green direction may stem from lifetime and evolutionary experiences, respectively. However, these types of experience are entwined and it is speculative from which source of experience in detail the present results arise.

The second factor which influences the degree of color constancy in the present work is the surface collection. Roughly similar to the effect of illuminant direction, performance is best under the green surface collection and worst under the red collection. It was mentioned in chapter 3 that mean reflectances of urban scenes cluster roughly along the daylight locus, whereas mean reflectances of rural scenes are shifted towards the yellow–green area

(Nascimento et al., 2002; Hendley & Hecht, 1949). By far the least reflectances can be found in the red area. Again, the results obtained here may be explained by an evolutionary approach. This parallel is not surprising since non–daylight illuminants, like green, arise from mutual reflections on mainly greenish surfaces. This fact implies that the frequency of illuminant colors correlates somehow with the occurrence of surface colors within a scene. For instance, very few surfaces are reddish in forests, so reddish illumination is also rather rare.

Perspectives

Effects of illuminant color direction and surface collection were found in the present discrimination paradigm, but in appearance and surface color matching paradigms as well. However, the size and the meaningfulness of these effects depend on the issue to be investigated. When discrimination performance is compared, as done in this work, the effects are obvious. When it is the main interest to examine the characteristics of visual adjustment by fitting models to data, the effects are less obvious and to first approximation may even be neglected. Therefore, models of color constancy, like illuminant linearity, seem to be very robust against such effects. These models are very simple and, anyway, provide a good description of how the visual system adjusts to illuminant changes. Illuminant linearity states that receptor scalings resulting from an illuminant change depend linearly on this change. If illuminant linearity holds, then, in a matching paradigm, color matches for two different illuminant changes provide data to predict the match for any third illuminant change that is a linear combination of the two. This seems plausible under the assumption that the amount of visual adjustment is equal under all illuminant changes. This work shows, however, that this is not the case. If the degree of color constancy under two different illuminants, say a red and a blue one, is rather different then the prediction of a match under a blue-red illuminant might be bad. It would be interesting to examine the effects of illuminant direction on the illuminant linearity model in detail. Depending on the size of the influence, a decision should be made whether the effects should be incorporated into existing models. This may be a challenge for future research.

Matching paradigms and the operational discrimination paradigm are rather different approaches to the issue of color constancy, and each one has pros and cons. Matching paradigms produce more information, especially for evaluating models for visual adjustment as described above, since matches are made in a two– or three–dimensional color space. However, matching tasks are rather time–consuming and demand adjustment of a color by operating sliders or the like. This is a very unnatural procedure which is hardly related to any task regarding color judgment in our daily life, and therefore requires some time for training. Discrimination tasks, in turn, seem rather natural for they have to be accomplished in everyday life. When colors of a scene change, one has to judge whether this is due to a change in illuminant or to a change in objects. Furthermore, discrimination tasks have shown to be rather easy for observers to accomplish, and require, if at all, only a few minutes of training. As shown in this work, a discrimination paradigm provides a detailed view on differences in visual adjustment depending on illuminant direction or surface collection. However, the information one gets from a discrimination paradigm is very limited. It is not possible to explain the characteristics of visual adjustment processes as it is possible with data from matching paradigms.

Both matching and discrimination paradigms provide information which contribute to the understanding of color constancy. As described above, they are able to benefit from each other. Therefore, it is necessary to consider results from both paradigms and integrate them to expand the view on the phenomenon of color constancy.

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Appendix A

This Appendix consists of one table and three figures. Table A1 lists CIE u'v' chromaticity coordinates of the 226 experimental surfaces and the surface collection to which each individual surface belonged. Figures A1 and A2 show, respectively, the daylight and monitor basis functions used for modelling experimental illuminants. Figure A3 shows the reflectance basis functions used for modelling experimental surfaces.

Table A1: All 226 experimental surfaces. CIE u'v' chromaticity coordinates of surfaces illuminated by CIE D65 as well as membership to surface collections are listed.

Surface collections			
Surface	u'	v'	Collection
1	0,197	0,468	Neutral
2	0,199	0,466	Neutral
3	0,198	0,465	Neutral
4	0,197	0,466	Neutral
5	0,197	0,467	Neutral
6	0,198	0,469	Neutral
7	0,197	0,468	Neutral
8	0,244	0,471	Neutral
9	0,237	0,476	Neutral
10	0,231	0,476	Yellow, Neutral
11	0,227	0,474	Yellow, Neutral
12	0,217	0,473	Yellow, Neutral
13	0,277	0,475	Yellow, Neutral
14	0,280	0,485	Yellow, Neutral
15	0,263	0,479	Yellow, Neutral
16	0,259	0,481	Yellow, Neutral
17	0,292	0,474	Yellow, Neutral
18	0,302	0,485	Yellow, Neutral
19	0,294	0,486	Yellow, Neutral
20	0,289	0,485	Yellow, Neutral
21	0,331	0,492	Yellow, Neutral
22	0,329	0,493	Yellow, Neutral
23	0,352	0,495	Yellow, Neutral
24	0,351	0,494	Yellow, Neutral
25	0,252	0,483	Yellow, Neutral
26	0,272	0,496	Yellow, Neutral
27	0,264	0,498	Yellow, Neutral
28	0,256	0,493	Yellow, Neutral
29	0,238	0,487	Yellow, Neutral
30	0,292	0,502	Yellow, Neutral
31	0,296	0,508	Yellow, Neutral
32	0,283	0,505	Yellow, Neutral
33	0,229	0,487	Yellow, Neutral

Surface	u'	v'	Collection
34	0,232	0,492	Yellow, Neutral
35	0,234	0,493	Yellow, Neutral
36	0,230	0,490	Yellow, Neutral
37	0,221	0,485	Yellow, Neutral
38	0,216	0,483	Yellow, Neutral
39	0,261	0,509	Yellow, Neutral
40	0,256	0,512	Yellow, Neutral
41	0,249	0,504	Yellow, Neutral
42	0,235	0,495	Yellow, Neutral
43	0,223	0,492	Yellow, Neutral
44	0,232	0,507	Yellow, Neutral
45	0,234	0,513	Yellow, Neutral
46	0,225	0,508	Yellow, Neutral
47	0,207	0,492	Yellow, Neutral
48	0,206	0,490	Yellow, Neutral
49	0,207	0,495	Yellow, Neutral
50	0,207	0,492	Yellow, Neutral
51	0,206	0,489	Yellow, Neutral
52	0,204	0,486	Yellow, Neutral
53	0,216	0,513	Yellow, Neutral
54	0,200	0,496	Yellow, Neutral
55	0,199	0,499	Green, Yellow, Neutral
56	0,204	0,516	Green, Yellow, Neutral
57	0,200	0,508	Green, Yellow, Neutral
58	0,187	0,497	Green, Yellow, Neutral
59	0,193	0,496	Green, Yellow, Neutral
60	0,192	0,492	Green, Yellow, Neutral
61	0,193	0,492	Green, Yellow, Neutral
62	0,194	0,488	Green, Yellow, Neutral
63	0,194	0,486	Green, Yellow, Neutral
64	0,189	0,507	Green, Yellow, Neutral
65	0,188	0,512	Green, Yellow, Neutral
66	0,189	0,517	Green, Yellow, Neutral
67	0,190	0,511	Green, Yellow, Neutral
68	0,191	0,505	Green, Yellow, Neutral
69	0,176	0,495	Green, Yellow, Neutral
70	0,158	0,514	Green, Yellow, Neutral
71	0,165	0,503	Green, Yellow, Neutral
72	0,171	0,504	Green, Yellow, Neutral
73	0,170	0,499	Green, Yellow, Neutral
74	0,177	0,497	Green, Yellow, Neutral
75	0,180	0,495	Green, Yellow, Neutral
76	0,157	0,526	Green, Yellow, Neutral
77	0,161	0,518	Green, Yellow, Neutral
78	0,166	0,511	Green, Yellow, Neutral
79	0,176	0,504	Green, Yellow, Neutral
80	0,160	0,527	Green, Yellow, Neutral
81	0,160	0,524	Green, Yellow, Neutral
82	0,167	0,482	Green, Yellow, Neutral
83	0,173	0,479	Green, Yellow, Neutral
84	0,176	0,477	Green, Yellow, Neutral
85	0,177	0,478	Green, Yellow, Neutral
86	0,182	0,476	Green, Yellow, Neutral
87	0,183	0,479	Green, Yellow, Neutral
88	0,162	0,487	Green, Yellow, Neutral
89	0,167	0,485	Green, Yellow, Neutral
90	0,176	0,481	Green, Yellow, Neutral
91	0,166	0,486	Green, Yellow, Neutral
92	0,169	0,478	Green, Yellow, Neutral
93	0,169	0,465	Green, Yellow, Neutral
94	0,172	0,467	Green, Yellow, Neutral
95	0,177	0,469	Blue, Green, Neutral
96	0,180	0,472	Blue, Green, Neutral
97	0,163	0,467	Blue, Green, Neutral
98	0,172	0,470	Blue, Green, Neutral
99	0,164	0,457	Blue, Green, Neutral
100	0,170	0,459	Blue, Green, Neutral
101	0,169	0,442	Blue, Green, Neutral
102	0,172	0,449	Blue, Green, Neutral
103	0,176	0,452	Blue, Green, Neutral
104	0,179	0,453	Blue, Green, Neutral
105	0,183	0,462	Blue, Green, Neutral
106	0,167	0,444	Blue, Green, Neutral
107	0,173	0,454	Blue, Green, Neutral
108	0,179	0,460	Blue, Green, Neutral
109	0,167	0,449	Blue, Green, Neutral
110	0,169	0,428	Blue, Green, Neutral
111	0,170	0,433	Blue, Green, Neutral
112	0,173	0,440	Blue, Green, Neutral
113	0,177	0,447	Blue, Green, Neutral
114	0,169	0,438	Blue, Green, Neutral
115	0,179	0,421	Blue, Green, Neutral
116	0,185	0,435	Blue, Neutral
117	0,187	0,442	Blue, Neutral
118	0,187	0,443	Blue, Neutral
119	0,189	0,448	Blue, Neutral
120	0,188	0,453	Blue, Neutral
121	0,176	0,410	Blue, Neutral
122	0,179	0,423	Blue, Neutral
123	0,181	0,430	Blue, Neutral
124	0,183	0,438	Blue, Neutral
125	0,184	0,443	Blue, Neutral
126	0,168	0,389	Blue, Neutral
127	0,171	0,405	Blue, Neutral
128	0,174	0,417	Blue, Neutral
129	0,179	0,424	Blue, Neutral
130	0,181	0,436	Blue, Neutral
131	0,167	0,403	Blue, Neutral
132	0,174	0,422	Blue, Neutral
133	0,200	0,385	Blue, Neutral
134	0,201	0,399	Blue, Neutral
135	0,199	0,419	Blue, Neutral
136	0,198	0,426	Blue, Neutral

Surface	u'	v'	Collection
137	0,198	0,435	Blue, Neutral
138	0,197	0,446	Blue, Neutral
139	0,203	0,379	Blue, Neutral
140	0,202	0,383	Blue, Neutral
141	0,197	0,398	Blue, Neutral
142	0,195	0,411	Blue, Neutral
143	0,197	0,423	Blue, Neutral
144	0,196	0,436	Blue, Neutral
145	0,201	0,368	Blue, Neutral
146	0,196	0,380	Blue, Neutral
147	0,195	0,396	Blue, Neutral
148	0,198	0,410	Blue, Neutral
149	0,201	0,324	Blue, Neutral
150	0,198	0,367	Blue, Neutral
151	0,195	0,384	Blue, Neutral
152	0,218	0,422	Blue, Neutral
153	0,210	0,440	Blue, Neutral
154	0,206	0,446	Blue, Neutral
155	0,204	0,449	Blue, Neutral
156	0,203	0,451	Neutral
157	0,202	0,454	Neutral
158	0,223	0,399	Neutral
159	0,220	0,412	Neutral
160	0,214	0,430	Red, Neutral
161	0,210	0,433	Red, Neutral
162	0,206	0,439	Red, Neutral
163	0,234	0,370	Red, Neutral
164	0,226	0,393	Red, Neutral
165	0,220	0,413	Red, Neutral
166	0,216	0,419	Red, Neutral
167	0,211	0,426	Red, Neutral
168	0,234	0,376	Red, Neutral
169	0,226	0,396	Red, Neutral
170	0,220	0,406	Red, Neutral
171	0,216	0,415	Red, Neutral
172	0,244	0,350	Red, Neutral
173	0,234	0,386	Red, Neutral
174	0,226	0,390	Red, Neutral
175	0,244	0,363	Red, Neutral
176	0,244	0,401	Red, Neutral
177	0,239	0,427	Red, Neutral
178	0,230	0,441	Red, Neutral
179	0,228	0,447	Red, Neutral
180	0,218	0,452	Red, Neutral
181	0,256	0,386	Red, Neutral
182	0,247	0,408	Red, Neutral
183	0,244	0,429	Red, Neutral
184	0,239	0,439	Red, Neutral
185	0,224	0,444	Red, Neutral
186	0,267	0,394	Red, Neutral
187	0,255	0,418	Red, Neutral
188	0,248	0,429	Red, Neutral
189	0,232	0,435	Red, Neutral
190	0,275	0,373	Red, Neutral
191	0,270	0,405	Red, Neutral
192	0,259	0,421	Red, Neutral
193	0,237	0,455	Red, Neutral
194	0,226	0,458	Red, Neutral
195	0,218	0,462	Red, Neutral
196	0,216	0,465	Red, Neutral
197	0,211	0,465	Red, Neutral
198	0,267	0,437	Red, Neutral
199	0,252	0,450	Red, Neutral
200	0,239	0,453	Red, Neutral
201	0,232	0,459	Red, Neutral
202	0,222	0,462	Red, Neutral
203	0,274	0,422	Red, Neutral
204	0,272	0,444	Red, Neutral
205	0,258	0,447	Red, Neutral
206	0,250	0,455	Red, Neutral
207	0,291	0,432	Red, Neutral
208	0,276	0,441	Red, Neutral
209	0,264	0,452	Red, Neutral
210	0,307	0,424	Red, Neutral
211	0,293	0,438	Red, Neutral
212	0,305	0,436	Red, Neutral
213	0,264	0,456	Red, Neutral
214	0,255	0,464	Red, Neutral
215	0,247	0,467	Red, Neutral
216	0,237	0,469	Red, Neutral
217	0,227	0,468	Red, Neutral
218	0,295	0,446	Red, Neutral
219	0,288	0,463	Red, Neutral
220	0,279	0,467	Red, Neutral
221	0,262	0,469	Neutral
222	0,311	0,459	Neutral
223	0,295	0,464	Neutral
224	0,288	0,470	Neutral
225	0,331	0,448	Neutral
226	0,318	0,464	Neutral

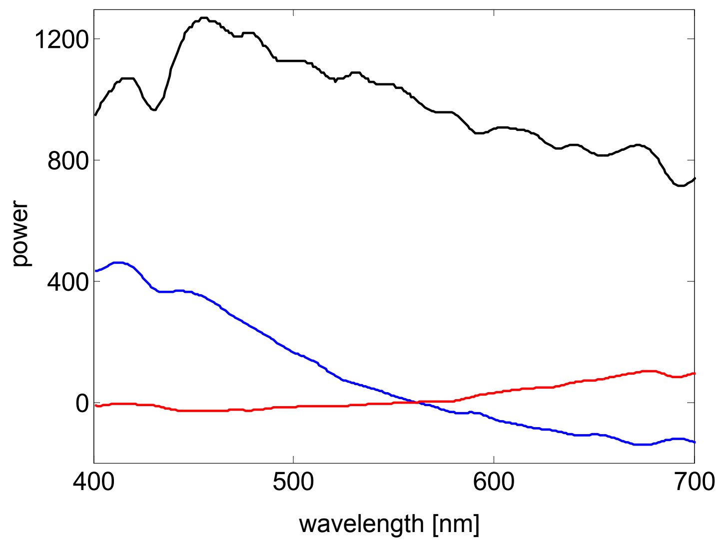

Figure A1: Daylight basis functions from which experimental illuminants were modelled.

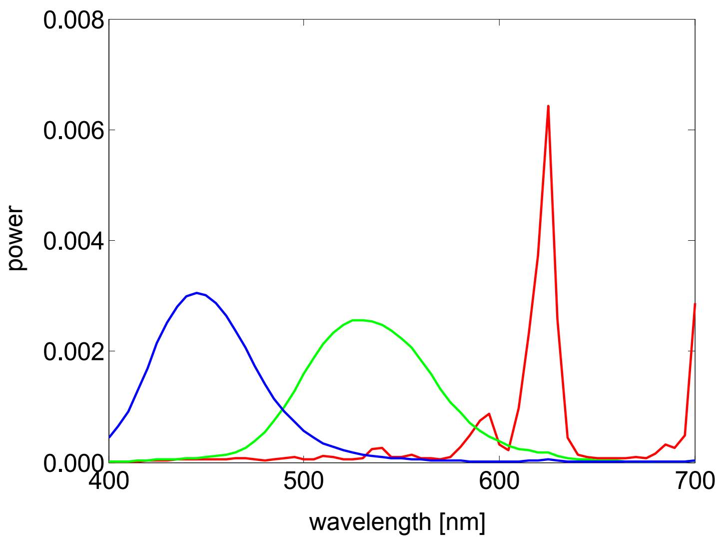

Figure A2: Monitor basis functions as provided by Delahunt & Brainard (2004a). These basis functions were used to model experimental illuminants which lied outside of the daylight model.

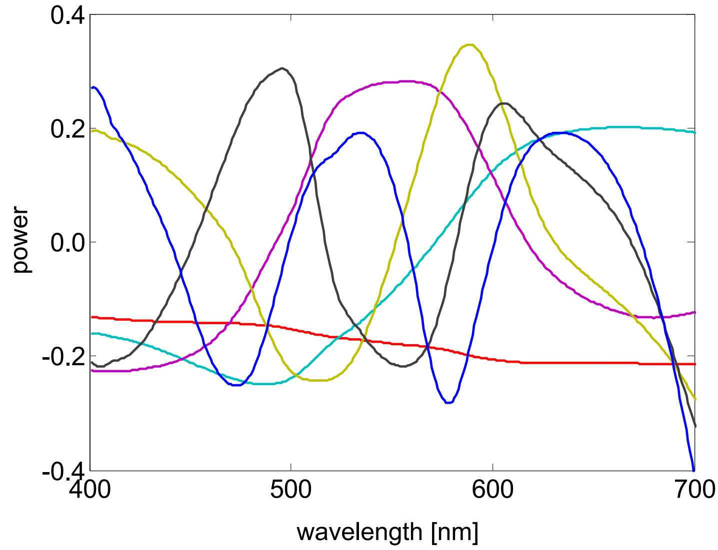

Figure A3: Reflectance basis functions derived by Kelly et al. (1943). These basis functions were used to model experimental surfaces.

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