Chapter 6
Color Constancy and Contextual Effects on Color Appearance

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Abstract Color is a useful cue to object properties such as object identity and state (e.g., edibility), and color information supports important communicative functions. Although the perceived color of objects is related to their physical surface properties, this relationship is not straightforward. The ambiguity in perceived color arises because the light entering the eyes contains information about both surface reflectance and prevailing illumination. The challenge of color constancy is to estimate surface reflectance from this mixed signal. In addition to illumination, the spatial context of an object may also affect its color appearance. In this chapter, we discuss how viewing context affects color percepts. We highlight some important results from previous research, and move on to discuss what could help us make further progress in the field. Some promising avenues for future research include using individual differences to help in theory development, and integrating more naturalistic scenes and tasks along with model comparison into color constancy and color appearance research.

Keywords Color perception • Color constancy • Color appearance • Context • Psychophysics • Individual differences

6.1 Introduction

Color is a useful cue to object properties such as object identity and state (e.g., edibility), and color information supports important communicative functions [1]. Although the perceived color of objects is related to their physical surface properties,

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this relationship is not straightforward. In this chapter, we focus on how viewing context and illumination affect color percepts.

The development of the Young-Helmholtz trichromatic theory, according to which color sensations rely on three mechanisms with sensitivities in different parts of the electromagnetic spectrum, was essentially complete more than a century ago [2, 3]. Most research efforts in color vision thereafter have either been directed towards obtaining a better understanding of (a) the physiology and genetics underlying the trichromatic theory (also see Chaps. 1, 3, and 4) or (b) the many aspects of color perception which are beyond the explanatory scope of trichromatic theory. Many significant advances have been made in the first line of research: after the trichromatic theory was corroborated with direct measurement of retinal photoreceptors [4], our understanding of the early processing of color signals has evolved to the stage where treatment of color blindness seems realistic in the near future [5, 6]. This chapter is about central aspects of the second line of research, namely color constancy and the context-dependence of perceived color. Here, progress has been more modest, despite intense and often quite ingenious research efforts. For that reason, we organize this chapter around the question of why progress has been so slow and what might be done to remedy it rather than providing a comprehensive state-of-the art review of the literature (for those, see Refs. [7–10]).

We start by reviewing the problem of color constancy and context effects on color appearance, and then move on to review commonly used methods. We further discuss a few more novel methods that hold much promise in advancing the field. We conclude the chapter by laying out some outstanding questions and suggestions for future research.

6.2 Contextual Effects on Color Appearance

Contextual effects on color perception have traditionally been studied under two relatively separate rubrics: color constancy and color induction/color appearance. In general, studies in color constancy aim to understand how constant descriptors of surface color are extracted from variable sensory signals, whereas studies in color induction aim to understand how changes in background properties affect the color appearance of a target stimulus. In fact, many studies could be classified under either rubric, making the distinction rather arbitrary. But because studies in the two traditions often differ in how fundamental problems are formulated, we introduce them separately. However, we do not make a hard distinction between the two rubrics when discussing methodology and theoretical approaches later in the chapter.

6.2.1 Color Constancy

Imagine stepping out on the patio with your favorite cup in hand; the surface color of the cup does not appear to change even though the illumination impinging on the cup changes quite dramatically. This ability to perceive stable object colors in varying illumination is called color constancy. Although seemingly effortless, constancy involves complex visual processing: as the illumination on the cup changes, the light reflected to the eye from the cup changes as well; there is no unique signal for any given surface color (Fig. 6.1 illustrates this for a clover). In order to use object color as a cue to object identity, the visual system faces the challenge of parsing the retinal light signal into object and illumination components ("inverse optics" [11]). This mathematically underdetermined estimation problem cannot be solved without constraints, for instance from prior knowledge about the nature of surfaces and illuminants [12].

Although vision scientists agree to some extent about the nature of the computational problem, there is little agreement about whether the visual system actually inverts the calculation (and estimates reflectance and illumination) (e.g., [13–16]), or rather bypasses the inverse problem by using heuristics or image cues to make decisions about color [17–19]. The first computational models solved the inverse problem by assuming certain regularities in the visual scene, for instance

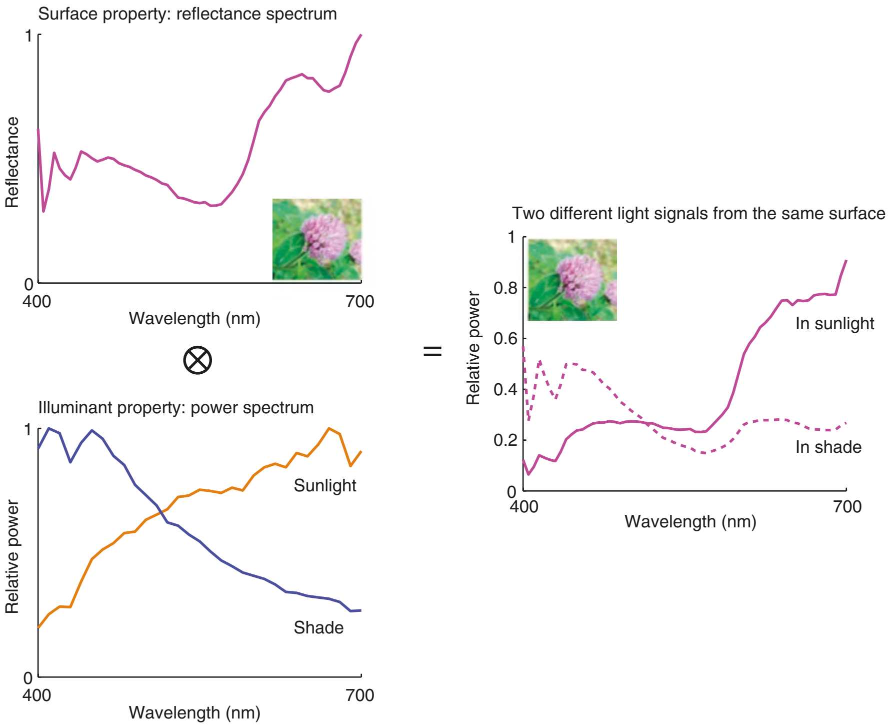

Fig. 6.1 Color constancy is hard because the light reflected off a surface depends both on the reflectance properties of the surface and the light illuminating the surface. The *upper left panel* shows the reflectance of a clover as a function of wavelength. The *lower left panel* shows the power spectrum of two different daylight illuminants: direct sunlight and skylight (shade). The light reflected to the eyes off a clover, shown in the *right panel*, depends on whether the clover is illuminated by sunlight or skylight. In order to perceive the surface color accurately, the visual system has to estimate the surface reflectance from the combined light signal

that the mean chromaticity of a scene is neutral or at least known [20], or that illumination changes more slowly across a visual scene than surface reflectance [21–23]. Another class of models relied on the fact that natural surface reflectances and daylight illuminants can be represented with a limited number of basis functions, greatly simplifying the inverse calculation (e.g., [20, 24, 25]). These models showed that the illuminant in relatively simple scenes can be estimated and thus discounted based on cues from mean chromaticity across the scene [20], specular highlights on surfaces [24, 26], and mutual illumination [27].

Of course, that these models work for some visual scenes does not mean that they accurately model human color constancy, but they have been useful in developing experimental hypotheses. In a seminal study, Kraft and Brainard [28] tested three common theoretical assumptions: that color constancy is determined by adaptation to mean luminance; adaptation to local contrast; or adaptation to the brightest surface in the scene. Their results were not consistent with any single mechanism, but rather with a combination of several mechanisms. In a series of studies taking advantage of computer rendering techniques, Maloney and colleagues tested the role of different image cues for color constancy. They found that observers used information from several cues, such as highlights, cast shadows, and depth cues when estimating surface color [18, 29–31].

Color constancy is usually quantified by measuring changes in color appearance caused by a change in viewing context. Reduced to a two-dimensional world, this can be something like the simultaneous contrast illusion in Fig. 6.2a. In the top panel, the surrounds affect perceived lightness of the target: the two physically identical middle-gray patches look either dark or light depending on the surround. In the chromatic case depicted in the middle panel of Fig. 6.2a, the two physically identical targets appear either bluish or yellowish depending on the surround. One can measure the magnitude of the context effect on target color appearance and use mathematical methods to quantify the “compensation” for the difference in surrounds in terms of color constancy (*color constancy index*, see Ref. [8]). As the stimuli in Fig. 6.2a (top and middle) are very simple compared to natural scenes, contemporary studies commonly use more complex backgrounds (Fig. 6.2a, bottom) or computer renderings of three-dimensional scenes (Fig. 6.2b). The idea behind all of these visual displays is the same, however: the overall color difference between the two sides of the display simulates an illumination change, and the extent to which the observer compensates for this difference when judging target color appearance is a measure of color constancy.

Contextual effects on color perception have been extensively quantified during the past century with scenes similar to the ones depicted in Fig. 6.2a, and we now have some understanding about the regularities of color perception in such scenes. To a first approximation, observers are able to partially compensate for illumination changes when judging object color appearance across illumination variation, especially with more “natural” tasks and realistic displays (for a comprehensive review, see Ref. [8]). However, the degree of color constancy depends on the instructions and task [34, 35], the display, and the realism of the stimuli in ways that are not well-understood (for a review, see Ref. [7]). In order to uncover the mechanisms of color constancy, it is important to develop general models that predict both successes and failures of color constancy in a broad range of experimental situations.

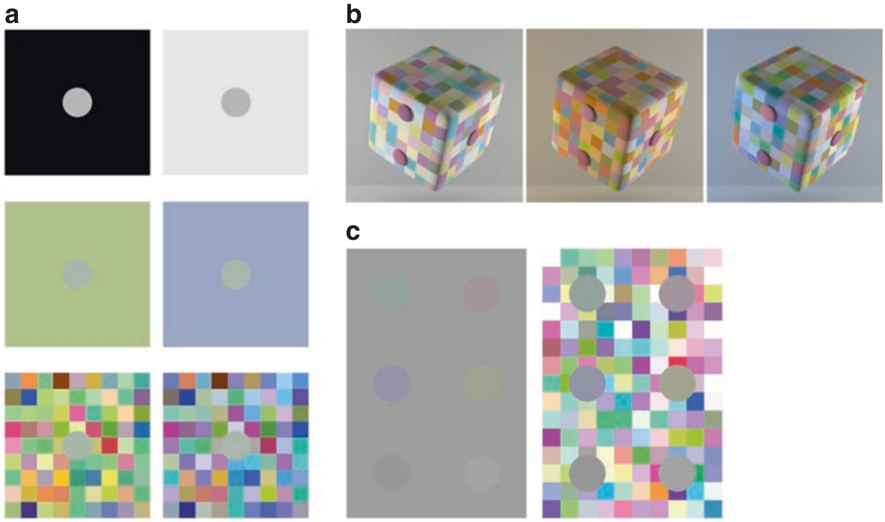

Fig. 6.2 Typical displays used in the study of color constancy and color induction. (**a**) A demonstration of the classical simultaneous brightness/color contrast illusion. The two central disks are identical in terms of reflected light, but viewing them embedded in different surrounds make their colors appear different. *Top*: achromatic; *middle*: chromatic; *bottom*: chromatic with different spatial properties in the targets and surrounds. (**b**) Here, the observer's task is to choose the button on the left side of a cube that matches the button on the right side. The cube on the *left* is illuminated by a standard light on both sides; the two other cubes are illuminated by a standard light on the right and a yellowish (*center*) or bluish (*right*) light on the left. Figure reproduced with permission of Association for Research in Vision and Ophthalmology from [32] via Copyright Clearance Center. (**c**) A demonstration of Brown and MacLeod's [33] gamut expansion effect. The six colored disks embedded in the uniform grey surround (*left*) are printed in the same ink as the six disks embedded in the variegated surround (*right*), yet they appear more saturated (or colorful). This demonstrates that target color appearance is influenced by the variance of surround colors even with the same average surround color

6.2.2 *Color Induction*

Stimulus context plays a crucial role in enabling the organism to solve the problem of color constancy. It has been proposed that observers derive information about the illuminant from the surround [36], and some models achieve color constant representations from edge contrasts between a target and its surround (e.g., [37, 38]). Accordingly, several authors have suggested that color constancy and various effects of context on color appearance are essentially two sides of the same coin. Both von Helmholtz [12] and Hering [39] agreed on this point, although their theories were rather different [40, 41].

Helmholtz famously proposed that the simultaneous contrast effect is produced by an error of judgement (or "unconscious inference"), where the target is mistakenly assumed to be illuminated with a light having the color of the surround (also see Fig. 4 in Ref. [42]). Due to the discounting of the illumination, the perceived color of the target shifts in a direction opposite in color space to the color of the surround. Thus, a grey target appears greenish if embedded in a red surround, bluish if embedded in a yellow surround, and so on (for a computational implementation of this idea, see Ref. [16]). Hering, on the other hand, explained both color constancy and simultaneous contrast in terms of lateral inhibition between neighboring receptors at the retina. Helmholtz and Hering's ideas have been hugely influential and most current theories of color constancy and simultaneous contrast can be regarded as modern incarnations of their theories. Consequently, their shared basic assumption that simultaneous contrast is due to mechanisms subserving color constancy is broadly adopted in the field [43–47]. Indeed, the stimuli and tasks in experiments on simultaneous color constancy and simultaneous contrast are often quite similar or even identical.

A priori, though, any given observable induction effect may be due to a host of different mechanisms, subserving different functional goals (or even be spandrels serving no particular functional purpose at all [48]). The widespread idea that simultaneous contrast is a side effect of mechanisms correcting for the influence of the prevailing illumination is therefore by no means necessary. For instance, it has been proposed that mechanisms are involved that serve to counteract intraocular glare [49] or to infer the color of transparent media [50]. Importantly, if such alternative mechanisms contribute, empirical measurements of the effect would not directly reflect the pure effect of constancy mechanisms correcting for the prevailing illumination. More specifically, the transparency mechanism discussed by Ekroll and Faul [50] seems to be triggered only when the surround is uniform in the vicinity of the target. Thus, experiments using variegated surrounds such as in Fig. 6.2b, c may provide a better, uncontaminated estimate of the effect due to mechanisms correcting for the illuminant [51].

6.2.3 Type I and Type II Constancy

An interesting challenge to the popular idea that both simultaneous contrast and color constancy are simply due to mechanisms encoding difference (contrast) information at the borders between surfaces [45, 52–54] is the observation that when an object moves across a multicolored background, we hardly ever experience the strong changes in its perceived color that this idea would predict [53, 55]. This observation of a "natural background independence" has led researchers to propose that in addition to the mechanisms that provide color constancy across illumination changes (Type I constancy), the visual system also possesses mechanisms providing color constancy across background changes (Type II constancy) [53, 56]. According to Whittle, the initial coding of color based on differences at edges (presumed to take place in the retina or early visual cortex) is counteracted by a subsequent stage of processing in which the differences at edges are integrated across space, much as in the Retinex model by Land and McCann [23]. While retinal processing can be understood as mathematical differentiation of the retinal image, later processing is essentially conceived of as mathematical integration. The concatenation of these two operations yields the original image up to an unknown additive constant (which could be determined based on some kind of anchoring rule, see Gilchrist et al. [17]). Thus, perfect integration would lead to Type II constancy (background independence). From this perspective, simultaneous contrast effects (a failure of background independence) are to be understood as failures of integration [53]. Indeed, the Retinex model, which integrates luminance across edges, does not "see" the classical simultaneous contrast illusion.

It has been proposed that the integration process depends on perceptual mechanisms that classify edges in the visual input as reflectance edges or illumination edges: It would make sense for the processes responsible for the computation of surface color to integrate only across reflectance edges and to disregard illumination edges [57]. In a certain sense, this differentiation-integration perspective redefines the problem of understanding color perception. From this perspective, color constancy and strong simultaneous contrast effects are not very mysterious. Rather, the central problem becomes to understand exactly how the postulated integration and edge classification processes work [53, 57]. As pointed out by Koffka ([58], cited in Ref. [57]), "a complete answer to this question would probably supply the key to the complete theory of color perception in the broadest sense." It should be pointed out, however, that the problematic observation of "a natural background independence" is also amenable to an alternative explanation. There is evidence that simultaneous color contrast is sometimes considerably stronger for the uniform backgrounds typically used in many studies than in more naturalistic variegated backgrounds [43, 51, 59], and as pointed out by Evans ([60], p. 210) uniform backgrounds come "close to being contrary to the laws of nature." Thus, strong simultaneous contrast effects may be the result of the activation of special-purpose mechanisms [50, 61] rather than general principles of retinal coding. An informal observation consistent with this proposal is that when an object moves in front of different uniform surfaces (such as a bird crossing the clouds of the twilight sky), quite strong simultaneous contrast effects can be observed (see also [43]). From this perspective, the often-made implicit or explicit assumption that "the centre-surround configuration is a particularly important one" [53] may be misleading.

6.3 How Are Contextual Effects on Color Perception Quantified?

6.3.1 Current Situation in the Field

Although the amount of literature on color constancy and color induction is nothing short of daunting, our understanding of the fundamental mechanisms and processes in contextual color perception is still far from complete. As one delves deeper into the literature, the lack of convergence into general quantitative models becomes tangible [53]. There also remains disagreement about fundamental theoretical issues; for instance, whether the perceptual representation of surface color is equivalent to the physical property "surface reflectance," and whether illumination is explicitly represented [48, 62, 63].

Another important issue is to what extent color perception can be understood independently from other aspects of perception such as material properties, scene layout, depth relationships, and perceptual organization in general [61, 64–76]. It is also unclear what the relevant dimensions of color experience are [50, 60, 77–82]. On a more practical level, there is much debate about what is the best way to characterize color constancy, and whether it is even possible to measure it in "objective" or artifact-free ways. Many different methods have been employed in the past [83], but they may often provide conflicting results [53, 84]. An unfortunate consequence of these issues is that it is not always clear which results should be incorporated into theories, and which are artifacts of inadequate measurement methods or misleading assumptions about the phenomenal structure of color experience.

In the following, we briefly review the most popular classic methods, along with a few interesting more novel approaches.

6.3.2 Classic Methods

6.3.2.1 Asymmetric Color Matching

Asymmetric matching has traditionally been a popular method to measure color constancy and color induction [34, 85]. Here, the observer is presented with two target patches embedded in different surrounds and asked to adjust the color coordinates of one of the targets such that it appears identical to the other one. The difference between the color coordinates of the two targets at the perceptual match can then be taken as a measure of the combined effect of the two surrounds on the color appearance of the targets. To quantify the amount of color constancy, the observed color match is often compared to a perfectly color constant match, whereby the ratio between the two matches indicates the degree of color constancy (*color constancy index*). A further option is to infer the observer's illuminant estimate from the color match and use this to quantify color constancy [86]. This approach has the advantage of offering a direct link to computational models of constancy that estimate the illuminant.

It would often be more interesting to measure the effect of each surround on the color appearance of a target separately, rather than the combined effect of the two surrounds. Unfortunately, there seems to be no principled way for decomposing the measured combined effect into single surround-specific effects without relying on theoretical assumptions. An easy and popular, but potentially questionable way out of this dilemma is to posit that some particular surround is functionally neutral (i.e., that it has no effect on the perceived color of targets embedded in it). That way, the effect of any surround of interest can be directly measured by adjusting targets in the functionally neutral surround to match those presented in the surround of interest. It is often assumed that a completely dark surround or phenomenologically neutral surrounds (i.e., surrounds that appear achromatic) are functionally neutral, but this is a purely theoretical assumption that may well be incorrect [87]. For instance, one often speaks of a completely dark surround as "no surround," but the absence of physical stimulation does not imply that such a surround is functionally neutral. If, for instance, the difference between target and surround is the essential determinant of the target's perceived color [46, 47], a completely dark surround affects perceived color in essentially the same way as any other surround by contributing to the critical target-surround difference.

To gain a clearer idea of the inherent ambiguity of asymmetric matching data, a simple formal consideration may be helpful. Models of color appearance typically posit a three-dimensional color code [88], i.e., a function f of the tristimulus vectors[1] t, s of the target T and the surround S which yields a triplet of numbers representing the perceived color of the target. Any such model predicts that two targets T_1, T_2 embedded in surrounds S_1, S_2 should match whenever $f(t_1, s_2)=f(t_2, s_2)$. However, since any other color code $h:=g(f)$ obtained by concatenation of the function f with an arbitrary invertible function g makes exactly the same predictions, many rather different models of color appearance are compatible with the same set of matching data. This makes it evident that the shape of the function relating target coordinates to color appearance for targets in a certain surround cannot be inferred from asymmetric matching data. Once it is known (say, based on scaling or threshold data, see Sect. 6.3.2.5) for one surround, however, the matching data can be used to infer it for another surround [90].

It is also important to realize that the direction of the induction effect produced by a surround cannot be inferred from matching data without making (potentially incorrect) assumptions about what constitutes a functionally neutral surround.

6.3.2.2 Asymmetric Matching with Haploscopically Superimposed Displays

Based on an idea of Hering [91], Whittle [47, 53] pioneered the use of a special matching paradigm in which one target-surround stimulus is presented separately to each eye such that, through binocular fusion, the observer experiences the two targets to be matched as embedded in the same surround, although their monocular surrounds are different (haploscopically superimposed displays, HSD). An important advantage of this technique is that the subjective matching problems often reported in experiments using conventional side-by-side displays seem to be absent or at least significantly reduced. This technique also tends to produce much stronger induction effects than experiments with side-by-side displays [92]. Whittle [54] argued that this is because the results obtained with these techniques reflect the consequences of retinal mechanisms that essentially only register color differences at edges more directly than the results obtained with conventional side-by-side matching: The weaker effects

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[1] Colorimetric specification of a light stimulus is often made in terms of tristimulus values, which are the intensity values of three reference lights needed to match the test light. Different systems, such as the [R,G,B] and [X,Y,Z] of the Commission Internationale de L'éclairage (CIE) are based on different choices of the three reference lights, but they are essentially equivalent: different tristimulus values are related to each other by a linear transform. The tristimulus vector of a light is often just referred to as its "color," but this is potentially misleading, since the perceived color depends on context as well (see [89] for a good introduction to color measurement)

obtained with conventional matching are attributed to secondary mechanisms of integration counteracting the effects of the primary difference coding. However, alternative explanations of the special results obtained with these techniques are also possible: as the observer's eyes receive different input from the two hemifields, the haploscopic matching results could be attributed to strong temporal adaptation in each hemifield rather than to simultaneous contrast per se ([87], p. 125).

6.3.2.3 Achromatic Settings

In this technique, the observer is asked to adjust the chromaticity of a target embedded in a surround such that it appears achromatic (e.g., [93, 94]). Compared to asymmetric matching, this method has the advantage of obviating the need for presenting a second comparison target (and surround) which may influence the perceived color of the target [95]. Apart from that, however, results obtained with this method suffer from the same fundamental ambiguity as the results from asymmetric color matching. This is because the interpretation and modeling of achromatic matches implicitly or explicitly involves the comparison with targets that would appear achromatic when presented in another surround (typically gray or black). But note that this ambiguity is a problem only if the goal is to understand the quality of color appearance, instead of quantifying how constantly observers judge color appearance across illuminant changes [93].

An important disadvantage of achromatic settings is that measurements can only be made for a small subset of all possible colors (those that appear achromatic in a given surround). Given the large nonlinearities sometimes observed in asymmetric color matching experiments [51, 96–101], it does not appear advisable to draw general conclusions based only on achromatic settings.

6.3.2.4 Unique Hue Settings

The method of unique hue settings [102] is based on a central notion of opponent color theory, namely that the four unique hues red, green, yellow, and blue[2] have special properties that make them particularly useful as landmarks in color space [39, 103]. Unique hue settings have the advantage that measurements can be made not only for targets that appear achromatic in a given surround, but also for targets that appear unique red, green, blue, or yellow (see also [104] for the related method of unique hue scaling, and see also Chap. 5 about between-individual variation in unique hues). A disadvantage, however, is that interpretation and modeling requires even more assumptions than achromatic settings because the set of colors that appear in a given unique hue is a two-dimensional manifold. Like achromatic settings, unique hue settings can be regarded as a limited form of implicit asymmetric matching. Hence, this technique also suffers from the aforementioned fundamental ambiguity of asymmetric matching data.

[2] So called because they cannot be divided further into component hues; see Chap. 5.

6.3.2.5 Threshold and Scaling Measurements

Context does not only influence color appearance, but also the discriminability of colors [105–108]. Color discrimination may be measured with threshold measurements and various supra-threshold scaling techniques [109, 110] and in some cases threshold measurements and scaling techniques seem to yield consistent results [108]. In theory, much of the aforementioned inherent ambiguity of asymmetric matching data can be resolved based on corresponding data from discrimination experiments. Specifically, threshold or scaling measurements can be used to estimate the derivative of the color code $f(t,s)$ (target color appearance in a given surround) with respect to t (the color coordinates of the target), which cannot be determined based on asymmetric matching. Therefore, employing both appearance and discrimination measurements in conjunction [90, 111, 112] can be particularly useful for constraining models of color appearance.

6.3.3 Critical Assumptions in Measuring and Modeling Color Appearance

The methods described above for measuring color appearance, and the modeling of the resulting data typically rely on a host of critical (implicit or explicit) assumptions that warrant consideration. We have already discussed the assumption that certain surrounds are often assumed to be "functionally neutral" and now briefly scrutinize two other potentially questionable assumptions.

6.3.3.1 The Continuity Assumption

Virtually all models of color appearance implicitly assume that perceived color (represented by a color code) is a continuous function of the color coordinates of the target and the surround. There is some evidence to suggest that this assumption, sometimes referred to as Grassmann's second law [113], is not generally valid. Rather, there is often a discontinuity in color appearance when the target color coordinates reach the coordinates of the surround, at least when the surround is uniform [47, 50, 51, 114]. This phenomenon, sometimes called "crispening," is related to the observation that color discrimination is best for target colors close to the surround color [106].

6.3.3.2 The Compensation Assumption

The core idea behind the asymmetric matching method is that the observer compensates the net effect of the surrounds on the perceived colors of the targets by adjusting the tristimulus values of one of the targets. As the observer can adjust three variables, this should be possible provided that the space of perceived colors is three-dimensional.

But if this space has more than three dimensions, it should be difficult to establish a subjectively satisfactory match. A priori, the perceived color of a target embedded in a simple uniform surround depends on six variables, namely the tristimulus values of the target plus those of the surround and hence the space of perceived colors could theoretically be up to six-dimensional even in this simple case [60]. Empirically, the evidence for or against the validity of the three-dimensionality assumption is mixed. While many studies do not mention any matching problems, other studies suggest that the problems can be quite dramatic [85, 115, 116]. Interestingly, subjective matching problems seem to be absent using the special viewing conditions of haploscopically superimposed displays [53, 92]. A general hypothesis that could account for the mixed results is that matching is possible for some combinations of target and surround colors, but not for others. For instance, subjective matching problems are often particularly evident when the contrast between target and surround is small [51] or when the two targets have a different contrast polarity [54].

6.3.4 Performance-Based Measures

Although the matching methods described above have various advantages, they are rather far-removed from everyday color tasks (compare matching two color patches in hue and saturation to selecting ripe tomatoes in the market). One potential issue with matching methods is that such an artificial task might not tap into real-world constancy mechanisms. For instance, observers might choose a variety of strategies to accomplish an asymmetric match, introducing variability unrelated to the experimental manipulation.

Due to these issues, an increasing number of laboratories use performance-based measures to characterize color constancy. Although these methods vary in many regards, they all measure observers' ability to recognize surface colors when the illuminant or viewing context is varied, rather than asking observers to match colors. Of course, the choice of task depends on the goal of the experiment; if the variable of interest is *perceptual appearance*, other methods are more suitable. But performance-based tasks are useful for quantifying how well and under what conditions observers are able to *identify surface colors* across context changes, which is useful for understanding real-world color constancy mechanisms.

6.3.4.1 Color Identification and Color Selection

In color identification and selection tasks, observers are asked to identify surfaces across illuminant changes. Because observers are not required to adjust or match colors, they often find this more intuitive. Color selection tasks are also arguably closer to everyday demands on color constancy than classic adjustment tasks; if the function of color constancy is to infer relevant object properties, such as ripeness, the outcome of the constancy process should lead to a successful selection of the target item amongst similar "distractors."

In one of the first performance-based color constancy studies, Bramwell and Hurlbert [92] used a task where observers saw a target under one simulated illuminant and were asked to pick the matching surface from a set of possible matches displayed under a different illuminant. Constancy was quantified as the distance between the true reflectance match and the match picked by the observer. The task was easy for observers and yielded measures of both color constancy and color discrimination, unlike classic matching methods.

Zaidi and colleagues [117–119] developed a method along similar lines but using real objects and illuminants. In their influential studies, observers saw four objects under two different illuminations, and were asked to pick the odd object out. By comparing observers' choices with different strategies—for instance reflectance matching and color contrast matching—Zaidi et al. showed that observers used a suboptimal strategy based on color similarity when identifying objects, instead of a more complicated reflectance estimation or "inverse-optics" approach.

Recently, Radonjić et al. [32] developed a color selection task with a similar principle to the paradigm of Zaidi and colleagues. Their use of rendered stimuli (see Fig. 6.2b) affords more flexibility in the choice of stimuli, and thus more accurate measurements of color constancy. Analyzing the selection data with a variant of maximum likelihood difference scaling, Radonjić et al. showed that observers were very color constant with complex, 3D stimuli (similar to the ones in Fig. 6.2b), but poor with simple, 2D stimuli. In a follow-up study with an even more naturalistic block-sorting task, Radonjić et al. [120] found good color constancy that was robust to manipulations of scene complexity (i.e., number of surfaces in the scene) and local contrast.

6.3.4.2 Color Naming and Categorization

One can also study the influence of context by asking subjects to categorize the color of targets in different contexts [121–125]. This has the same advantage as achromatic or unique hue settings: There is no need to display a comparison stimulus, which may influence the measurements. Color naming also has the advantage over achromatic adjustments that it can yield information about several landmarks in color space [121]. A well-known limitation is that humans are able to discriminate many more colors than they have color names for [83]. One way to overcome this issue is to use stimulus sets that span a large portion of color space and to model constancy for a group of stimuli simultaneously [121, 122, 126].

Color naming is similar to typical forced-choice paradigms in that it requires observers to categorize stimuli instead of making matches across contexts. In an early study, Jacobs and Gaylord [127] measured adaptation to spectral narrow-band lights and found color naming to be as accurate as asymmetric matching for measuring adaptation effects but more intuitive for observers. Later studies have found similar results for color constancy [124, 125, 128]. In a series of studies, Gegenfurtner and colleagues studied how the structure of color space changes under varying illumination by using a combination of color naming and mathematical modeling. They found the structure of color space to be largely stable, with small transformations in category boundaries explained by relatively simple linear models [121, 126]. By using Munsell chips with known surface reflectances, Olkkonen et al. [122] were further able to compare how consistently individual observers named surface colors across illuminants with how consistently different observers named the same surfaces under one illuminant. They found across-illuminant naming consistency to be similar to across-observer naming consistency; in other words, those surface colors that remained stable across illuminants also reached high inter-observer agreement under a baseline illuminant.

6.3.4.3 Priming

The Helmholtzian view that unconscious inference is necessary for achieving color constancy from "raw sensations" at the retina has often been taken as a given by color scientists (see [78], for further discussion). Norman et al. [129] investigated this assertion with a clever priming task, where they used metacontrast masking to display subliminal color primes to observers. Norman et al. tested whether a prime matched with the mask in terms of reflected light (proximal properties) or reflectance (distal properties) differentially facilitated the subsequent color categorization of the mask. They found that categorization was facilitated more when the prime matched the mask in terms of reflectance rather than in reflected color. This led Norman and colleagues to conclude that object color is initially represented in terms of its surface reflectance, and not the reflected color. This is notably inconsistent with the common notion that the earliest processing stages represent proximal stimulus qualities that need to be processed in order to arrive at a representation of surface color [12, 130].

6.3.4.4 Operational Color Constancy

Based on the observation that color constancy in the laboratory is often poor (e.g., [34, 131]), Foster and colleagues have advocated a more operational definition of color constancy (also see Ref. [132]). Their approach agrees with the observation that although the color appearance of objects often changes with the illuminant (a sheet of white paper often looks yellower under sunlight than in shade), we do not perceive the surface material as having changed; rather, we are able to distinguish illuminant from material changes. Consequently, the function of color constancy might be to tell illuminant changes from reflectance changes, rather than maintaining equal color appearance across illuminant changes. Foster and colleagues have shown in a series of experiments that observers are good at discriminating illuminant changes from changes in object properties (e.g., [83, 133, 134]). The advantage of this method is the naturalness and ease of the discrimination task, but as other performance-based measures, it does not inform us about *how* object color appearance changes in different illuminations. Indeed, one interesting implication of this research is that operational color constancy may be good even when *appearance* constancy fails.

In a variant of the operational color constancy task, Pearce et al. [135] quantified color constancy by measuring discrimination thresholds for illuminant changes in different color directions. They found that illumination discrimination was poorest on the daylight axis toward bluish illuminations. The fact that observers are the least sensitive to bluish illuminant changes implies that color constancy is *best* for these illuminants. This is consistent with the suggestion that color constancy should be best for natural daylight variation; a common hypothesis that has lacked empirical evidence so far (but see Ref. [15]).

6.3.5 The Role of Scene Complexity

Figure 6.2 shows an array of displays with different levels of scene complexity. It is possible to quantify the effect of color context on color appearance in a simple display such as the simultaneous contrast (Fig. 6.2a). As seen in this classical illusion, context can affect color appearance quite dramatically. It is now known, however, that the complexity of the viewing context modulates the strength of context effects. Comparing the middle and bottom panels of Fig. 6.2a reveals that a complex surround may, at least in some cases, have a smaller effect on target color appearance than a simple one, even with the same average surround chromaticity [43, 75, 136, 137]. Manipulating the number and type of surfaces in a scene also affects color constancy (e.g., [138–142]). Finally, Brown and MacLeod [33] showed that the same low-contrast targets appear more colorful on uniform surrounds than on variegated surrounds (Fig. 6.2c). Taken together, these results show that findings from simple scenes cannot be straightforwardly generalized to complex scenes and ultimately to color perception in the real world.

It is important to note that scene complexity can be increased by adding more variability in the visual scene without adding more structure. The display in the bottom panel of Fig. 6.2a has more chromatic variability than the middle panel, but not considerably more spatial structure. The scene in Fig. 6.2b, on the other hand, has both more chromatic variability and structure than the displays in Fig. 6.2a. It is conceivable that variability and structure separately modulate the strength of context effects on color appearance. In a seminal demonstration, Adelson [64] showed that lightness percepts are influenced by perceived scene structure although the pattern of luminance across the scene was held constant (see also [70]).

With the advent of physically based rendering tools, several labs have moved to using more realistic displays to study color constancy. These displays confer several advantages over more traditional 2D displays. They allow for more freedom in manipulating the objects—their shape and surface material, etc.—along with illumination properties. Such scenes allow studying the role of complex scene cues to color constancy; for instance stereo disparity [143], highlights [29, 144, 145], object pose [146, 147], and material [76]. Computer graphics also enables us to study the perception of more complex illumination and reflectance properties, such as the effect of illumination geometry on the perception of glossiness [148–151].

One might argue that it would be most ecologically valid to use real objects and illuminants, because they contain cues that are challenging to reproduce in rendered scenes. Indeed, some early studies in color constancy were conducted with real (albeit comparatively simple) stimuli under real illuminants (e.g., [36, 79, 152]). Even after the advent of digital displays, some groups still employ real surfaces and illuminants with the thought that they might tap more "natural" constancy mechanisms [85, 122, 153–158]. One notable disadvantage in using real displays is the difficulty to parametrically manipulate object or illumination properties. To overcome this limitation, some laboratories have built setups that combine real objects with projectors so that the apparent object and illuminant colors can be independently and parametrically manipulated [85, 157]. It is important to note, however, that no large differences between rendered and real scenes in terms of color constancy performance have been found [122, 159, 160], and thus it is appropriate to use the experimental setup that is most practical for a given research question.

6.4 The Role of Individual Differences in Theory Development

More than 50 years ago, Cronbach [161] pointed to a curious and unfortunate theoretical schism dividing psychology into two largely separate schools of thought he referred to as "correlational psychology" and "experimental psychology." The main difference between them is their perspective on the importance of individual differences. It is probably fair to say that research on perception has been, and to some extent still is, deeply entrenched in the one-sided perspective of the "experimental psychology" described by Cronbach and has yet to fully exploit the benefits of complementing traditional experimental studies with analyses of natural variation [162–164].

This is particularly tangible in the literature on color constancy and color appearance. Many studies have been performed with a small number of observers, quite often only the authors and perhaps a couple of naive observers. This common practice is probably more strongly rooted in tradition [165] along with practical issues[3] than based on a principled scientific deliberations. One could argue that the fair inter-observer agreement evident in many published studies suggests that individual differences are small and thus insignificant. The idea that inter-observer agreement tends to be good may, however, be a self-perpetuating prejudice caused and maintained by a publication bias. Whenever large individual differences are observed, many perceptual psychologists are probably prone to think that something went wrong in the experiment and hesitate to publish the results, particularly if data suggesting a higher precision have already been published. In the early days of perception science, large inter-individual variability was considered "prima facie evidence that the attempted isolation of critical determining factors had failed and that uncontrolled disturbing processes had supervened" ([165], p. 73) and even today, this kind of attitude may be encountered ([166], p.101).

[3] Perception experiments typically involve long sessions with a large number of stimuli presented to each observer, which poses a challenge to recruiting large samples of naive observers.

In the literature on color constancy and color induction, there is often good agreement among the few observers participating in single studies, but vastly different results across studies [54]. More recent research documents surprisingly large individual differences within studies [96, 97, 167–169], which suggests that publication bias may indeed have been a real issue. As a notable exception in color constancy research, Allen et al. [167, 168] used individual differences in working memory performance to successfully account for individual differences in color constancy, specifically in how scene complexity affects color constancy performance (see also [170]).

The tendency to neglect individual differences in studies of color constancy and color induction is not entirely irrational. First, it is well known that the phenomena under study depend crucially on a host of stimulus variables [53, 54]. Thus, even small differences in the stimuli between studies may explain why they produce rather diverging results. Second, it is also clear that different methods for measuring how color appearance depends on the stimulus can lead to dramatically different results [84]. Thus, any differences observed across different studies can plausibly be attributed to the effect of known or unknown differences in the experimental variables.

It is also well known that the results of asymmetric color matching experiments may depend on instructions ([35, 171–173]). In a similar vein, subjects sometimes find it impossible to make the targets actually appear equal in perceived color [40, 51, 85, 115, 174]. In such cases, it may be unclear to the subjects how they are supposed to proceed, and spontaneously adopt idiosyncratic criteria for complying with the impossible task. Subtle unintended demand characteristics [175] may also influence the actual settings. A further, related consideration is that the observed individual differences in color induction may be due to differences in eye movement patterns [176, 177] or the allocation of attention [178, 179] rather than genuine individual differences in color perception. Thus, individual differences observed within a single experiment may plausibly be attributed to criterion problems or subtle differences in how attention is deployed rather than to genuine individual differences in perception.

All of these considerations make it very difficult to unambiguously conclude that any observed differences in the data from different subjects reflect genuine differences in perception, but thinking in terms of biology and evolution, it appears implausible that the mechanisms underlying color constancy and color induction exhibit any less natural variability than any other parts of our biological makeup (e.g., [180]).

In 2015, interest in individual differences in color constancy and color induction was boosted by the heated discussions about “the Dress” [181–187]. When viewing this photograph of a dress (reprinted in Fig. 1D of [182]), some people say that the dress is blue-black, while others maintain that it is white-gold. It is difficult to say why precisely this phenomenon created such a stir in social media, but it appears reasonable to assume that people were particularly intrigued by the categorical differences in the colors reported by different people.

As testified by the vigorous exchanges on the Color and Vision Network (CVNet) mailing list (http://lawton.ewind.com/mailman/listinfo/cvnet), the scientific community was almost equally surprised by this phenomenon as the general public. Many interesting potentially important factors were discussed, ranging from the optics of the eye to subjective criteria, but a hypothesis that was repeatedly proposed in various guises was that the effect is due to individual differences in the strength and/or parameters of the mechanisms underlying color constancy. Importantly, though, it seems to be an entirely open question how these putative individual differences come about [181, 182]. It is probably not very far off the mark when Macknik and Martinez-Conde ([185], p.20) note that before "the discovery of The Dress, vision scientists had thought that people with normal vision experienced color illusions similarly." Some interesting experimental work directed towards elucidating the questions raised by the Dress has already been published [184, 186], and we welcome a new era in color constancy and color induction research where individual differences will no more be neglected, but rather be the main focus of interest. This would be a fortunate development, particularly because individual differences can be used as an additional tool for answering the very questions about underlying mechanisms that the field has always striven to answer with traditional experimental methods [97, 164, 188].

Ultimately, the best proof for the relevance of individual differences for perception research would be if analyzing them turns out to advance our understanding of the underlying mechanisms. While some attempts have been undertaken in this direction [97, 167, 168, 188], much remains to be done. A pressing question, therefore, is what kind of research needs to be done to turn this into a fruitful research program, what challenges it faces, and how they can be solved.

6.4.1 Individual Differences: What Needs to Be Done?

A first step would be to determine the extent and prevalence of individual differences in the susceptibility to context effects in color perception in the general population. Next, individual differences should be used to establish a general, principled, and integrative theory of the multiple visual mechanisms underlying the computation of perceived color. Here, it is important to note that meaningful individual differences are to be expected at the level of (potentially unknown) visual mechanisms, rather than at the level of directly observable effects (i.e., effects measured with psychophysical methods). There is good reason to believe that most directly observable context effects are the net result of several underlying mechanisms [28, 96, 189, 190]. In principle, it is quite possible that there does not exist any stimulus that would isolate a single mechanism, and if there are such stimuli, we can only speculate—based on preliminary and potentially misleading hypotheses—which stimuli have this property. Therefore, to be most useful and diagnostic, directly observable individual differences need to be decomposed into components attributable to specific mechanisms. Obviously, this cannot be done without explicit models, heuristic assumptions and additional empirical constraints. Thus, a one-sided focus on individual differences in themselves is unlikely to be very productive. Rather, approaches which combine the virtues of classical experimental paradigms (such as modeling of general mechanisms and how they depend on stimulus properties) with modeling of how these mechanisms may differ across individuals are called for. This not only has the advantage that a particular model can be tested against two aspects of the data, namely how the results depend on stimulus properties and how they depend on the observer, but also against how the results depend on their interaction [164]. Thus, a cleverly devised combination of the experimental approach and a correlational individual differences approach is more than the sum of its parts. If the directly observable data depend on multiple mechanisms which all may vary in their efficiency and/or influence across observers, there is no reason to expect that the effects of parametric stimulus manipulations and observer characteristics are separable. For instance, the potential pitfalls of averaging data curves across observers are well known [191, 192] and this general problem may be even more serious in asymmetric matching experiments, where reasonably simple combinations of simple mechanism may produce rather complicated-looking matching curves [96].

One of the central methodological aims of traditional psychophysical research is to isolate single mechanisms, but achieving this by purely experimental means is not likely to be simple, and may in many cases be downright impossible. Here, data from atypical individuals who lack one or more of the mechanisms in question may be particularly informative when compared to data from typical observers. This point is nicely illustrated by the important role played by data from dichromats in shaping our understanding of normal color vision [3].

Despite the intense research on color constancy and color induction over the last century, the well-developed and potentially very informative methods of behavioral genetics [193] such as twin studies [194] have hardly been employed so far, but we anticipate that they will play an important role in shaping future research in the field.

In order to use individual differences to drive theory and research on color constancy and color induction, it is important to take into account related factors that may account for the observed individual differences, such as known variations at the level of the photoreceptors, visual acuity and contrast sensitivity [195] (also see Chap. 5). It is also important to develop strategies for distinguishing between perceptual and "cognitive" or "strategic" aspects in color matching ([169], p. 761).

Using individual differences as a tool for making inferences about visual mechanisms requires using considerably larger samples of observers than has been customary. Different from the trained psychophysical observers traditionally used in studies of perception [165], these observers will, by practical necessity, have to be essentially untrained. It is therefore imperative to devise and validate methods for reducing experimental errors in psychophysical experiments associated with the use of untrained and naive observers. The methods outlined in Sect. 6.3.4 should not require much training and would thus be suitable for untrained observers.

6.5 Outstanding Questions and Suggestions for Future Research

We conclude this chapter by highlighting some outstanding questions and potential avenues for future research.

6.5.1 Being Clear About General Research Goals

To help place individual studies in a larger context it would be useful if researchers were more explicit about their research aims. There is a crucial difference in trying to understand the contents of color *experience* versus the *performance* of the visual system in different viewing conditions. Further, do the experiments test a specific model, and if yes, which? Do the experiments aim to contribute to developing neural or computational constancy models? If the goal is model development, does implementation matter? The answers to these questions bear upon the choice of experimental methods and analyses, and being clear about them when reporting experimental results helps the readers put the results in a larger context.

6.5.2 Developing and Testing Theories

There are vast amounts of data on the effects of context on color perception, especially in simple scenes, but not many models. The existing data could be used to develop theories, which could then be tested systematically with carefully designed experiments.

The key to model testing is to derive predictions for both successes and failures in constancy. As an example, Brainard and colleagues developed a Bayesian model of color constancy based on available color matching data. Crucially, the model predicted both failures and successes in color constancy depending on the scene structure (specifically, whether the background of the target objects was manipulated together with the illumination or not); these predictions were well in line with the human data [15].

Model comparison is also a useful tool for testing theories. Olkkonen et al. [16] characterized an interaction between context and memory biases in the perceived lightness of a central target. They compared two probabilistic models that were based on existing constancy theories: ratio coding and reflectance estimation. Although both models explained the separate effects of stimulus context and memory on perceived lightness, only the reflectance model accounted for their interaction.

6.5.3 Incorporating Learning and Memory into Constancy Theories

There is accumulating behavioral and neurophysiological evidence that perception is not separate from memory and learning processes (e.g., [167, 196–200]). But only a handful of studies have investigated the relationship between memory and color constancy [157, 167, 201–204], and their results have yet to be integrated into a theory of color constancy.

Adding a memory component into a color constancy task can help adjudicate between competing models. Olkkonen and Allred [203] measured the independent and joint effects of color context and short-term memory on color appearance, and found that a 2-s memory delay decreased color constancy performance compared to simultaneous matching. Based on a comparison of ideal-observer models, a reflectance-estimation strategy accounted for this result better than a contrast-coding strategy [16].

Long-term memory and expectations about object colors can also affect color appearance as shown by Gegenfurtner and colleagues (e.g., [72, 205, 206]). In these studies, observers perceived grayscale photographs of familiar objects (e.g., a banana or a mailbox) to be slightly tinted in their typical colors, showing an influence of prior knowledge on color perception. Finally, the Dress phenomenon discussed earlier may be taken to suggest that expectation about illumination geometry can affect surface color estimates [184]. These effects need to be incorporated into color constancy theories.

6.5.4 Improving Existing Measurement Methods

How can we improve existing methods for measuring color appearance or develop new ones that avoid the problems and ambiguities of more classical methods? How can we make sense of the diverging results obtained with different methods? One problem with many classical methods and experimental tasks is that they may, though seemingly "objective," fail to be properly tailored to the actual structure of phenomenal experience. As nicely illustrated by Runeson's [207] insightful discussion of how a simple measurement device may excel at performing seemingly complicated measurements while being essentially worthless in performing seemingly simpler measurements, it is evident that the experimental task should be tailored to the actual (unknown) function and format of the visual mechanisms to yield sensible results. This makes it evident that designing good methods for measuring color appearance is not a trivial task. Some useful criteria for determining whether a particular measurement method is appropriate are (a) whether the participants experience it as easy and natural and (b) whether it yields consistent and clear results. Ultimately the appropriateness of a measurement method has to be judged in terms of how helpful it is in developing our theoretical understanding.

Finally, it would be important to understand why different measurement methods sometimes yield very different results [53, 84]. Do the measurement methods typically used in the field really work the way they are intended to? How can we cleverly combine different methods to constrain possible theories and models better?

6.5.5 Understanding the Phenomenological Structure of Color

What are the natural perceptual variables of color experience? What is the dimensionality of perceptual color space? Is it possible to understand color as an attribute detached from other attributes of perceptual experience, such as material properties, shape, and space? Is the color of the illumination simply discounted by the visual system or is it sometimes part of the perceptual experience itself [119]? Although much attention was paid to these fundamental questions in the Gestalt era of color research [40, 79], they were subsequently largely neglected for decades (with a few notable exceptions, [60]). In line with a general revival of ideas and perspectives from Gestalt psychology [208, 209] and experimental phenomenology [210], these questions have recently been pursued with renewed vigor, but much remains to be done in this area.

6.5.6 Understanding the Neural Coding of Contextual Color Perception

Is color appearance fundamentally coded by edge differences at the retina or early visual cortex, such that color constancy and strong simultaneous contrast effects can be explained by this neural difference coding while background independence (Type II constancy) requires an explanation in terms of additional, complementary mechanisms of edge integration [53, 54]? Or is the retinal code in terms of absolute values instead of contrast, such that Type II constancy is easy to explain, but color constancy and simultaneous contrast effects require another explanation? Is simultaneous contrast due to a general mechanism of difference coding or to special-purpose mechanisms that only play a role in special cases [50]? The evidence for and against difference coding as a fundamental coding principle needs to be carefully evaluated, particularly now, where one of the core findings that originally inspired the development of the difference coding perspective ([54], p. 38)—namely that the eye "ceases to see" when the retinal image is artificially stabilized [211]—is being reevaluated as a potential artifact of binocular rivalry [212].

More generally, it is important to make sure that color constancy theories are consistent with the known physiology of the visual system (for instance, ganglion cells are sensitive to luminance edges rather than absolute luminance (e.g., [213], Chap. 4), and many neurons in primary visual cortex code color contrast ([214], Chap. 7), thus potentially contributing to color constancy). To start developing a complete theory of color constancy, combining psychophysical measurements with computational modeling and existing neural data is key.

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References

1. Osorio D, Vorobyev M. A review of the evolution of animal colour vision and visual communication signals. Vision Res. 2008;48(20):2042–51.
2. Judd DB. Fundamental studies of color vision from 1860 to 1960. Proc Natl Acad Sci U S A. 1966;55(6):1313–30.
3. König A, Dieterici C. Die Grundempfindungen und ihre Intensitätsvertheilung im Spectrum. Juli: Sitzungsberichte der Akademie der Wissenschaften in Berlin; 1886. p. 805–29.
4. Schnapf JL, Kraft TW, Baylor DA. Spectral sensitivity of human cone photoreceptors. Nature. 1987;325(6103):439–41.
5. Jacobs GH, Williams GA, Cahill H, Nathans J. Emergence of novel color vision in mice engineered to express a human cone photopigment. Science. 2007;315(5819):1723–5.
6. Mancuso K, Hauswirth WW, Li Q, Connor TB, Kuchenbecker JA, Mauck MC, et al. Gene therapy for red-green colour blindness in adult primates. Nature. 2009;461(7265):784–7.
7. Brainard DH, Radonjić A. Color constancy. N Vis Neurosci. 2014;1:545–56.
8. Foster DH. Color constancy. Vision Res. 2011;51(7):674–700.
9. Shevell SK, Kingdom FAA. Color in complex scenes. Annu Rev Psychol. 2008;59:143–66.
10. Smithson HE. Sensory, computational and cognitive components of human colour constancy. Philos Trans R Soc Lond B Biol Sci. 2005;360(1458):1329–46.
11. Palmer SE. Vision science: photons to phenomenology. Cambridge, MA: Bradford Books, MIT Press; 1999.
12. von Helmholz H. Handbuch der Physiologischen Optik. Leipzig: Leopold Voss; 1867.
13. Adelson EH, Pentland AP. The perception of shading and reflectance. In: Knill DC, Richards W, editors. Perception as Bayesian inference, vol. 1. New York: Cambridge University Press; 1996. p. 409–23.
14. Barrow HG, Tenenbaum JM. Recovering intrinsic scene characteristics from images. Computer Vision Systems; 1978. p. 3–26.
15. Brainard DH, Longère P, Delahunt PB, Freeman WT, Kraft JM, Xiao B. Bayesian model of human color constancy. J Vis. 2006;6(11):1267–81.
16. Olkkonen M, Saarela TP, Allred SR. Perception-memory interactions reveal the computational strategy of reflectance perception. J Vis. 2016;16:38.
17. Gilchrist AL, Kossyfidis C, Bonato F, Agostini T, Cataliotti J, Xiaojun L, et al. An anchoring theory of lightness perception. Psychol Rev. 1999;106:795–834.
18. Maloney LT. Illuminant estimation as cue combination. J Vis. 2002;2(6):493–504.
19. Zaidi Q. Identification of illuminant and object colors: heuristic-based algorithms. J Opt Soc Am A. 1998;15(7):1767–76.
20. Buchsbaum G. A spatial processor model for object color perception. J Franklin Inst. 1980;310:1–26.
21. Hurlbert AC, Poggio TA. Synthesizing a color algorithm from examples. Science. 1988 ;239(4839):482–5.
22. Land EH. Recent advances in retinex theory and some implications for cortical computations: color vision and the natural image. Proc Natl Acad Sci U S A. 1983;80(16):5163–9.
23. Land EH, McCann JJ. Lightness and retinex theory. J Opt Soc Am. 1971;61(1):1–11.

24. D'Zmura M, Lennie P. Mechanisms of color constancy. J Opt Soc Am A Opt Image Sci. 1986;3(10):1662–72.
25. Maloney LT, Wandell BA. Color constancy: a method for recovering surface spectral reflectance. J Opt Soc Am A. 1986;3(1):29–33.
26. Lee HC. Method for computing the scene-illuminant chromaticity from specular highlights. J Opt Soc Am A. 1986;3(10):1694–9.
27. Funt BV, Drew M, Ho J. Color constancy from mutual reflection. Int J Comput Vis. 1991;6:5–24.
28. Kraft JM, Brainard DH. Mechanisms of color constancy under nearly natural viewing. Proc Natl Acad Sci U S A. 1999;96(1):307–12.
29. Boyaci H, Doerschner K, Maloney LT. Cues to an equivalent lighting model. J Vis. 2006;6(6):106–18.
30. Kitazaki M, Kobiki H, Maloney LT. Effect of pictorial depth cues, binocular disparity cues and motion parallax depth cues on lightness perception in three-dimensional virtual scenes. PLoS One. 2008;3(9):e3177.
31. Snyder JL, Doerschner K, Maloney LT. Illumination estimation in three-dimensional scenes with and without specular cues. J Vis. 2005;5(10):863–77.
32. Radonjić A, Cottaris NP, Brainard DH. Color constancy supports cross-illumination color selection. J Vis. 2015;15:1–19.
33. Brown RO, MacLeod DI. Color appearance depends on the variance of surround colors. Curr Biol. 1997;7(11):844–9.
34. Arend LE, Reeves A. Simultaneous color constancy. J Opt Soc Am A. 1986;3(10):1743–51.
35. Arend LE, Reeves A, Schirillo J, Goldstein R. Simultaneous color constancy: paper with diverse Munsell values. J Opt Soc Am A. 1991;8(4):661–72.
36. Helson BYH. Fundamental problems in color vision. I. The principle governing changes in hue, saturation and lightness of non-selective samples in chromatic illumination. J Exp Psychol. 1938;23:439–76.
37. Blakeslee B, McCourt ME. A multiscale spatial filtering account of the White effect, simultaneous brightness contrast and grating induction. Vision Res. 1999;39(26):4361–77.
38. Rudd ME. A cortical edge-integration model of object-based lightness computation that explains effects of spatial context and individual differences. Front Hum Neurosci. 2014;8:1–14.
39. Hering E. Grundzüge der Lehre vom Lichtsinn. Berlin: Springer; 1920.
40. Gelb A. Die "Farbenkonstanz" der Sehdinge. In: Bethe A, von Bergman G, Embden G, Ellinger A, editors. Handbuch der normalen und pathologischen Physiologie. Berlin: Springer; 1929. p. 594–687.
41. Kingdom FAA. Simultaneous contrast: the legacies of Hering and Helmholtz. Perception. 1997;26(6):673–7.
42. Lotto RB, Purves D. An empirical explanation of color contrast. Proc Natl Acad Sci U S A. 2000;97(23):12834–9.
43. Hurlbert AC, Wolf K. Color contrast: a contributory mechanism to color constancy. Prog Brain Res. 2004;144:147–60.
44. Jameson D, Hurvich LM. Essay concerning color constancy. Annu Rev Psychol. 1989;40:1–22.
45. Wallach H. Brightness constancy and the nature of achromatic colors. J Exp Psychol. 1948;38(3):310–24.
46. Walraven J. Discounting the background: the missing link in the explanation of chromatic induction. Vision Res. 1976;16(3):289–95.
47. Whittle P. Contrast colours. In: Mausfeld M, Heyer D, editors. Color perception: mind and the physical world. Oxford: Oxford University Press; 2003. p. 115–38.
48. Anderson BL. The perceptual representation of transparency, lightness, and gloss. In: Wagemans J, editor. Oxford handbook of perceptual organization. Oxford: Oxford University Press; 2015.
49. Rizzi A, McCann J. Simultaneous contrast and intraocular glare: opposing image dependent mechanisms in appearance. In Association Internationale de la Couleur (AIC). Interim Meeting in Stockholm June 15–18; 2008.
50. Ekroll V, Faul F. Transparency perception: the key to understanding simultaneous color contrast. J Opt Soc Am A Opt Image Sci Vis. 2013;30(3):342–52.

51. Ekroll V, Faul F, Niederée R. The peculiar nature of simultaneous colour contrast in uniform surrounds. Vision Res. 2004;44(15):1765–86.
52. Arend LE, Buehler JN, Lockhead GR. Difference information in brightness perception. Percept Psychophys. 1971;9(3):367–70.
53. Whittle P. Contrast brightness and ordinary seeing. In: Gilchrist AL, editor. Lightness, brightness, and transparency. Hillsdale, NJ: Erlbaum; 1994. p. 111–58.
54. Whittle P. The psychophysics of contrast brightness. In: Gilchrist AL, editor. Lightness, brightness, and transparency. Hillsdale, NJ: Erlbaum; 1994. p. 35–110.
55. Whittle P, Challands PD. The effect of background luminance on the brightness of flashes. Vision Res. 1969;9(9):1095–110.
56. Gilchrist AL. Introduction: absolute versus relative theories of lightness perception. In: Gilchrist AL, editor. Lightness, brightness, and transparency. Hillsdale, NJ: Erlbaum; 1994. p. 1–34.
57. Gilchrist AL. Lightness contrast and failures of constancy: a common explanation. Percept Psychophys. 1988;43(5):415–24.
58. Koffka K. Principles of gestalt psychology. Trench: Kegan Paul; 1936.
59. Allred SR, Olkkonen M. The effect of background and illumination on color identification of real, 3D objects. Front Psychol. 2013;4:1–14.
60. Evans RM. The perception of color. New York: Wiley; 1974.
61. Schmid AC, Anderson BL. Do surface reflectance properties and 3-D mesostructure influence the perception of lightness? J Vis. 2014;14:1–24.
62. Mausfeld R. The perception of material qualities and the internal semantics of the perceptual system. In: Albertazzi L, van Tonder GJ, Vishwanath D, editors. Perception beyond inference. The information content of visual processes. Cambridge, MA: MIT Press; 2010. p. 159–200.
63. Vishwanath D. Coplanar reflectance change and the ontology of surface perception. In: Albertazzi L, editor. Visual thought: the depictive space of perception, advances in consciousness research. Amsterdam: John Benjamins Publishing Company; 2006. p. 35–70.
64. Adelson EH. Perceptual organization and the judgment of brightness. Science. 1993;262(5142):2042–4.
65. Adelson EH. On seeing stuff: the perception of materials by humans and machines. Proc SPIE. 2001;4299:1–12.
66. Anderson BL. A theory of illusory lightness and transparency in monocular and binocular images: the role of contour junctions. Perception. 1997;26(4):419–53.
67. Anderson BL, Winawer J. Image segmentation and lightness perception. Nature. 2005;434:79–83.
68. Brainard DH, Maloney LT. Perception of color and material properties in complex scenes. J Vis. 2004;4(9):ii–v.
69. Fleming RW, Nishida S, Gegenfurtner KR. Perception of material properties. Vis Res. 2015;115:157–302.
70. Gilchrist AL. Perceived lightness depends on perceived spatial arrangement. Science. 1977 ;195(4274):185–7.
71. Mausfeld R. 'Colour' as part of the format of different perceptual primitives: the dual coding of colour. In: Mausfeld R, Heyer D, editors. Colour perception: mind and the physical world. Oxford: Oxford University Press; 2003. p. 381–429.
72. Olkkonen M, Hansen T, Gegenfurtner KR. Color appearance of familiar objects: effects of object shape, texture, and illumination changes. J Vis. 2008;8(5):13.1–16.
73. Smithson HE. Perceptual organization of colour. In: Wagemans J, editor. Oxford handbook of perceptual organization. Oxford: Oxford University Press; 2015.
74. Werner A. The influence of depth segmentation on colour constancy. Perception. 2006 ;35(9):1171–84.
75. Wollschläger D, Anderson BL. The role of layered scene representations in color appearance. Curr Biol. 2009;19(5):430–5.
76. Xiao B, Hurst B, MacIntyre L, Brainard DH. The color constancy of three-dimensional objects. J Vis. 2012;12(4):6.
77. Blakeslee B, McCourt ME. Comments and responses to "Theoretical approaches to lightness and perception". Perception. 2015;44(4):359–67.

78. Gilchrist A. Theoretical approaches to lightness and perception. Perception. 2015;44(4):339–58.
79. Katz D. Die Erscheinungsweisen der Farben und ihre Beeinflussung durch die individuelle Erfahrung. Leipzig: Barth; 1911.
80. MacLeod D. New dimensions in color perception. Trends Cogn Sci. 2003;7(3):97–9.
81. Tokunaga R, Logvinenko AD. Material and lighting hues of object colour. Ophthalmic Physiol Opt. 2010;30(5):611–7.
82. Vladusich T. Gamut relativity: a new computational approach to brightness and lightness perception. J Vis. 2013;13(1):14.
83. Foster DH. Does colour constancy exist? Trends Cogn Sci. 2003;7(10):439–43.
84. Bosten JM, Mollon JD. Kirschmann's fourth law. Vision Res. 2012;53(1):40–6.
85. Brainard DH, Brunt WA, Speigle JM. Color constancy in the nearly natural image. I. Asymmetric matches. J Opt Soc Am A. 1997;14:2091–110.
86. Brainard DH, Maloney LT. Surface color perception and equivalent illumination models. J Vis. 2011;11(5):1–18.
87. Ekroll V, Faul F. New laws of simultaneous contrast? Seeing Perceiving. 2012;25(2):107–41.
88. Mausfeld R, Niederée R. An inquiry into relational concepts of colour, based on incremental principles of colour coding for minimal relational stimuli. Perception. 1993;22(1975):427–62.
89. Koenderink JJ. Color for the sciences. Cambridge: MIT Press; 2010.
90. Hillis JM, Brainard DH. Do common mechanisms of adaptation mediate color discrimination and appearance? Uniform backgrounds. J Opt Soc Am A. 2005;22(10):2090–106.
91. Hering E. Eine Methode zur Beobachtung contrastes. Pflügers Arch. 1890;47(1):236–42.
92. Bramwell DI, Hurlbert AC. Measurements of colour constancy by using a forced-choice matching technique. Perception. 1996;25(2):229–41.
93. Brainard DH. Color constancy in the nearly natural image II. Achromatic loci. J Opt Soc Am A. 1998;17:307–25.
94. Helson BYH. Adaptation-level as a basis for a quantitative theory of frames of reference. Psychol Rev. 1948;55(6):297–313.
95. Speigle JM, Brainard DH. Predicting color from gray: the relationship between achromatic adjustment and asymmetric matching. J Opt Soc Am A. 1999;16:2370–6.
96. Ekroll V, Faul F. A simple model describes large individual differences in simultaneous colour contrast. Vision Res. 2009;49(18):2261–72.
97. Ekroll V, Faul F, Wendt G. The strengths of simultaneous colour contrast and the gamut expansion effect correlate across observers: evidence for a common mechanism. Vision Res. 2011;51(3):311–22.
98. Miyahara E, Smith VC, Pokorny J. The consequences of opponent rectification: the effect of surround size and luminance on color appearance. Vision Res. 2001;41(7):859–71.
99. Smith VC, Pokorny J. Color contrast under controlled chromatic adaptation reveals opponent rectification. Vision Res. 1996;36(19):3087–105.
100. Takasaki H. Lightness change of grays induced by change in reflectance of gray background. J Opt Soc Am. 1966;56(4):504–9.
101. Takasaki H. Chromatic changes induced by changes in chromaticity of background of constant lightness. J Opt Soc Am. 1967;57(1):93–6.
102. Arend LE. How much does illuminant color affect unattributed colors? J Opt Soc Am A Opt Image Sci Vis. 1993;10(10):2134–47.
103. Hurvich LM, Jameson D. An opponent-process theory of color vision. Psychol Rev. 1957;64(6 Pt 1):384–404.
104. Schultz S, Doerschner K, Maloney LT. Color constancy and hue scaling. J Vis. 2006 ;6(10):1102–16.
105. Giesel M, Hansen T, Gegenfurtner KR. The discrimination of chromatic textures. J Vis. 2009;9:1–28.
106. Krauskopf J, Gegenfurtner KR. Color discrimination and adaptation. Vision Res. 1992 ;32(11):2165+2175.
107. Miyahara E, Smith VC, Pokorny J. How surrounds affect chromaticity discrimination. J Opt Soc Am A Opt Image Sci. 1993;10(4):545–53.
108. Whittle P. Brightness, discriminability and the "crispening effect". Vision Res. 1992;32(8): 1493–507.

109. Kingdom FAA, Prins N. Psychophysics: a practical introduction. London: Academic; 2010.
110. Maloney LT, Yang JN. Maximum likelihood difference scaling. J Vis. 2003;3(8):573–85.
111. Abrams AB, Hillis JM, Brainard DH. The relation between color discrimination and color constancy: when is optimal adaptation task dependent? Neural Comput. 2007;19(10):2610–37.
112. Heinemann EG. The relation of apparent brightness to the threshold for differences in luminance. J Exp Psychol. 1961;61:389–99.
113. Niederée R. More than three dimensions: what continuity considerations can tell us about perceived color. In: Cohen J, Matthen M, editors. Color ontology and color science. Cambridge: MIT Press; 2010. p. 91–122.
114. Ekroll V, Faul F. Basic characteristics of simultaneous color contrast revisited. Psychol Sci. 2012;23(10):1246–55.
115. Burgh P, Grindley GC. Size of test patch and simultaneous contrast. Q J Exp Psychol. 1962;14(2):89–93.
116. Logvinenko AD, Maloney LT. The proximity structure of achromatic surface colors and the impossibility of asymmetric lightness matching. Percept Psychophys. 2006;68(1):76–83.
117. Robilotto R, Zaidi Q. Limits of lightness identification for real objects under natural viewing conditions. J Vis. 2004;4:779–97.
118. Robilotto R, Zaidi Q. Lightness identification of patterned three-dimensional, real objects. J Vis. 2006;6(1):18–36.
119. Zaidi Q, Bostic M. Color strategies for object identification. Vision Res. 2008;48(26):2673–81.
120. Radonjić A, Cottaris NP, Brainard DH. Color constancy in a naturalistic goal-directed task. J Vis. 2015;15(13):3.1–3.21.
121. Hansen T, Walter S, Gegenfurtner KR. Effects of spatial and temporal context on color categories and color constancy. J Vis. 2007;7(4):2.1–2.15.
122. Olkkonen M, Witzel C, Hansen T, Gegenfurtner KR. Categorical color constancy for real surfaces. J Vis. 2010;10(9):9.1–9.22.
123. Smithson H, Zaidi Q. Colour constancy in context: roles for local adaptation and levels of reference. J Vis. 2004;4(9):693–710.
124. Speigle JM, Brainard DH. Is color constancy task independent. In: The fourth color imaging conference: color science, systems and applications; 1996. p. 167–72.
125. Troost JM, de Weert CM. Naming versus matching in color constancy. Percept Psychophys. 1991;50(6):591–602.
126. Olkkonen M, Hansen T, Gegenfurtner KR. Categorical color constancy for simulated surfaces. J Vis. 2009;9(12):6.1–6.18.
127. Jacobs GH, Gaylord HA. Effects of chromatic adaptation on color naming. Vision Res. 1967;7(7):645–53.
128. Uchikawa K, Yokoi K, Yamauchi Y. Categorical color constancy is more tolerant than apparent color constancy. J Vis. 2004;4(8):327.
129. Norman LJ, Akins K, Heywood CA, Kentridge RW. Color constancy for an unseen surface. Curr Biol. 2014;24(23):2822–6.
130. Reeves AJ, Amano K, Foster DH. Color constancy: phenomenal or projective? Percept Psychophys. 2008;70(2):219–28.
131. Blackwell KT, Buchsbaum G. Quantitative studies of color constancy. J Opt Soc Am A Opt Image Sci. 1988;5(10):1772–80.
132. Gerhard HE, Maloney LT. Detection of light transformations and concomitant changes in surface albedo. J Vis. 2010;10(9):1–14.
133. Craven BJ, Foster DH. An operational approach to colour constancy. Vision Res. 1992;32(7):1359–66.
134. Foster DH, Nascimento SM, Amano K, Arend LE, Linnell KJ, Nieves JL, et al. Parallel detection of violations of color constancy. Proc Natl Acad Sci U S A. 2001;98(14):8151–6.
135. Pearce B, Crichton S, Mackiewicz M, Finlayson GD, Hurlbert A. Chromatic illumination discrimination ability reveals that human colour constancy is optimised for blue daylight illuminations. PLoS One. 2014;9(2):e87989.

136. Ekroll V, Faul F. Perceptual organization in colour perception: inverting the gamut expansion effect. i-Perception. 2013;4(5):328–32.
137. Shevell SK, Wei J. Chromatic induction: border contrast or adaptation to surrounding light? Vision Res. 1998;38(11):1561–6.
138. Bäuml KH. Color appearance: effects of illuminant changes under different surface collections. J Opt Soc Am A Opt Image Sci Vis. 1994;11(2):531–42.
139. Jenness JW, Shevell SK. Color appearance with sparse chromatic context. Vision Res. 1995;35(6):797–805.
140. Linnell KJ, Foster DH. Scene articulation: dependence of illuminant estimates on number of surfaces. Perception. 2002;31(2):151–9.
141. Zaidi Q, Spehar B, DeBonet J. Color constancy in variegated scenes: role of low-level mechanisms in discounting illumination changes. J Opt Soc Am A. 1997;14(10):2608–21.
142. Zemach IK, Rudd ME. Effects of surround articulation on lightness depend on the spatial arrangement of the articulated region. J Opt Soc Am A Opt Image Sci Vis. 2007;24(7):1830–41.
143. Yang JN, Shevell SK. Stereo disparity improves color constancy. Vision Res. 2002;42(16):1979–89.
144. Yang JN, Maloney LT. Illuminant cues in surface color perception: tests of three candidate cues. Vision Res. 2001;41:2581–600.
145. Yang JN, Shevell SK. Surface color perception under two illuminants: the second illuminant reduces color constancy. J Vis. 2003;3(5):369–79.
146. Boyaci H, Maloney LT, Hersh S. The effect of perceived surface orientation on perceived surface albedo in binocularly viewed scenes. J Vis. 2003;3(8):541–53.
147. Doerschner K, Boyaci H, Maloney LT. Human observers compensate for secondary illumination originating in nearby chromatic surfaces. J Vis. 2004;4(9):92–105.
148. Doerschner K, Boyaci H, Maloney LT. Estimating the glossiness transfer function induced by illumination change and testing its transitivity. J Vis. 2010;10(4):8.1–9.
149. Fleming RW, Dror RO, Adelson EH. Real-world illumination and the perception of surface reflectance properties. J Vis. 2003;3(5):347–68.
150. Olkkonen M, Brainard DH. Perceived glossiness and lightness under real-world illumination. J Vis. 2010;10(9):5.1–5.19.
151. Olkkonen M, Brainard DH. Joint effects of illumination geometry and object shape in the perception of surface reflectance. i-Perception. 2011;2(9):1014–34.
152. Judd DB. Hue saturation and lightness of surface colors with chromatic illumination. J Opt Soc Am. 1940;30(1):2–32.
153. Allred SR, Olkkonen M. The effect of memory and context changes on color matches to real objects. Atten Percept Psychophys. 2015;77(5):1608–24.
154. de Almeida VMN, Nascimento SMC. Perception of illuminant colour changes across real scenes. Perception. 2009;38(8):1109–17.
155. Granzier JJM, Vergne R, Gegenfurtner KR. The effects of surface gloss and roughness on color constancy for real 3-D objects. J Vis. 2014;14:1–20.
156. Hedrich M, Ruppertsberg AI. Color constancy improves for real 3D objects. J Vis. 2009;9:1–16.
157. Ling Y, Hurlbert A. Role of color memory in successive color constancy. J Opt Soc Am A. 2008;25(6):1215–26.
158. Radonjić A, Gilchrist AL. Depth effect on lightness revisited: the role of articulation, proximity and fields of illumination. i-Perception. 2013;4:437–55.
159. Agostini T, Bruno N. Lightness contrast in CRT and paper-and-illuminant displays. Percept Psychophys. 1996;58(2):250–8.
160. Brainard DH, Ishigami K. Factors influencing the appearance of CRT colors. In: Proceedings of the IS&T/SID 1995 Imaging Conference, Scottsdale, AZ. IS&T, Springfield, VA; 1995. p. 62–6.
161. Cronbach LJ. The two disciplines of scientific psychology. Am Psychol. 1957;12:671–84.
162. De-Wit L, Wagemans J. Individual differences in local and global perceptual organization. In: Wagemans J, editor. Oxford handbook of perceptual organization. Oxford: Oxford University Press; 2015.
163. Kanai R, Rees G. The structural basis of inter-individual differences in human behaviour and cognition. Nat Rev Neurosci. 2011;12(4):231–42.

164. Wilmer JB. How to use individual differences to isolate functional organization, biology, and utility of visual functions; with illustrative proposals for stereopsis. Spat Vis. 2008;21(6):561–79.
165. Danziger K. Constructing the subject: historical origins of psychological research. Cambridge: Cambridge University Press; 1994.
166. Navarro DJ, Griffiths TL, Steyvers M, Lee MD. Modeling individual differences using Dirichlet processes. J Math Psychol. 2006;50(2):101–22.
167. Allen EC, Beilock SL, Shevell SK. Working memory is related to perceptual processing: a case from color perception. J Exp Psychol Learn Mem Cogn. 2011;37(4):1014–21.
168. Allen EC, Beilock SL, Shevell SK. Individual differences in simultaneous color constancy are related to working memory. J Opt Soc Am A. 2012;29(2):A52–9.
169. Ripamonti C, Bloj M, Greenwald S, Maloney SI, Brainard DH. Measurements of the effect of surface slant on perceived lightness. J Vis. 2004;4(9):7.
170. Kraft JM, Maloney SI, Brainard DH. Surface-illuminant ambiguity and color constancy: effects of scene complexity and depth cues. Perception. 2002;31(2):247–63.
171. Arend LE, Goldstein R. Simultaneous constancy, lightness, and brightness. J Opt Soc Am A. 1987;4(12):2281–5.
172. Arend LE, Spehar B. Lightness, brightness, and brightness contrast: 2. Reflectance variation. Percept Psychophys. 1993;54(4):457–68.
173. Bäuml KH. Simultaneous color constancy: how surface color perception varies with the illuminant. Vision Res. 1999;39(8):1531–50.
174. Burzlaff W. Methodologische Beträge zum Problem der Farbenkonstanz. Z Psychol. 1931;119:177–235.
175. Orne MT. Demand characteristics and the concept of quasi-controls 1. In: Rosenthal R, Rosnow RL, Kazdin AE, editors. Artifacts in {behavioral} {research}. Oxford: Oxford University Press; 2009. p. 1–33.
176. Cornelissen FW, Brenner E. Simultaneous colour constancy revisited: an analysis of viewing strategies. Vision Res. 1995;35(17):2431–48.
177. Granzier JJM, Toscani M, Gegenfurtner KR. Role of eye movements in chromatic induction. J Opt Soc Am A Opt Image Sci Vis. 2012;29(2):A353–65.
178. Festinger L, Coren S, Rivers G. The effect of attention on brightness contrast and assimilation. Am J Psychol. 1970;83(2):189–207.
179. Tse PU, Reavis EA, Kohler PJ, Caplovitz GP, Wheatley T. How attention can alter appearances. In: Albertazzi L, editor. Handbook of experimental phenomenology: visual perception of shape, space and appearance. New York: Wiley; 2013. p. 291–315.
180. Hess RF, Wang G, Cooperstock JR. Stereo vision : the haves and have-nots. i-Perception. 2015;6(3):1–5.
181. Brainard DHH, Hurlbert ACC. Colour vision: understanding #TheDress. Curr Biol. 2015 ;25(13):R551–4.
182. Gegenfurtner KR, Bloj M, Toscani M. The many colours of 'the dress'. Curr Biol. 2015 ;25:R1–2.
183. Gilchrist A. Perception and the social psychology of 'The Dress'. Perception. 2015 ;44(3):229–31.
184. Lafer-Sousa R, Hermann KL, Conway BR. Striking individual differences in color perception uncovered by 'the dress' photograph. Curr Biol. 2015;25(13):R545–6.
185. Macknik SL, Martinez-Conde S. Unraveling "the dress". Sci Am Mind. 2015;26(4):19–21.
186. Winkler AD, Spillmann L, Werner JS, Webster MA. Asymmetries in blue-yellow color perception and in the color of 'the dress'. Curr Biol. 2015;25(D):2–3.
187. Why do different observers see extremely different colours in the same photo?; http://lpp.psycho.univ-paris5.fr/feel/?page_id=929. Retrieved on September 16th, 2016.
188. Bosten JM, Mollon JD. Is there a general trait of susceptibility to simultaneous contrast? Vision Res. 2010;50(17):1656–64.
189. Adelson EH. Lightness perception and lightness illusions, chapter 24. In: Gazzaniga M, editor. The new cognitive neurosciences, vol. 3. 2nd ed. Cambridge, MA: MIT Press; 2000. p. 339–51.

190. Kingdom FAA. Levels of brightness perception. In: Harris L, Jenkin M, editors. Levels of perception. New York: Springer; 2003. p. 23–46.
191. Estes WK. The problem of inference from curves based on group data. Psychol Bull. 1956;53(2):134–40.
192. Gallistel CR, Fairhurst S, Balsam P. The learning curve: implications of a quantitative analysis. Proc Natl Acad Sci U S A. 2004;101(36):13124–31.
193. Neale M, Cardon L. Methodology for genetic studies of twins and families, vol. 67. Dordrecht, The Netherlands: Kluwer; 1992.
194. Miller SM, Hansell NK, Ngo TT, Liu GB, Pettigrew JD, Martin NG, et al. Genetic contribution to individual variation in binocular rivalry rate. Proc Natl Acad Sci U S A. 2010;107(6):2664–8.
195. Peterzell DH, Teller DY. Individual differences in contrast sensitivity functions: the lowest spatial frequency channels. Vision Res. 1996;36(19):3077–85.
196. O'Herron P, von der Heydt R. Short-term memory for figure-ground organization in the visual cortex. Neuron. 2009;61(5):801–9.
197. Scocchia L, Cicchini GM, Triesch J. What's "up"? Working memory contents can bias orientation processing. Vision Res. 2013;78:46–55.
198. Serences JT, Ester EF, Vogel EK, Awh E. Stimulus-specific delay activity in human primary visual cortex. Psychol Sci. 2009;20(2):207–14.
199. Silvanto J, Soto D. Causal evidence for subliminal percept-to-memory interference in early visual cortex. Neuroimage. 2012;59(1):840–5.
200. Sreenivasan KK, Gratton C, Vytlacil J, D'Esposito M. Evidence for working memory storage operations in perceptual cortex. Cogn Affect Behav Neurosci. 2014;14(1):117–28.
201. de Fez MD, Capilla P, Luque MJ, Pérez-Carpinell J, del Pozo JC. Asymmetric colour matching: memory matching versus simultaneous matching. Color Res Appl. 2001;26(6):458–68.
202. Jin EW, Shevell SK. Color memory and color constancy. J Opt Soc Am A. 1996;13(10):1981–91.
203. Olkkonen M, Allred SR. Short-term memory affects color perception in context. PLoS One. 2014;9(1):e8648.
204. Uchikawa K, Kuriki I, Tone Y. Measurement of color constancy by color memory matching. Opt Rev. 1998;5(I):59–63.
205. Hansen T, Olkkonen M, Walter S, Gegenfurtner KR. Memory modulates color appearance. Nat Neurosci. 2006;9(11):1367–8.
206. Witzel C, Valkova H, Hansen T, Gegenfurtner KR. Object knowledge modulates colour appearance. i-Perception. 2011;2:13–49.
207. Runeson S. On the possibility of "smart" perceptual mechanisms. Scand J Psychol. 1977;18(3):172–9.
208. Wagemans J, Elder JH, Kubovy M, Palmer SE, Peterson MA, Singh M, et al. A century of Gestalt psychology in visual perception: I. Perceptual grouping and figure–ground organization. Psychol Bull. 2012;138(6):1172–217.
209. Wagemans J, Feldman J, Gepshtein S, Kimchi R, Pomerantz JR, van der Helm PA, et al. A century of Gestalt psychology in visual perception: II. Conceptual and theoretical foundations. Psychol Bull. 2012;138(6):1218–52.
210. Koenderink JJ. Experimental phenomenology. In: Wagemans J, editor. Oxford handbook of perceptual organization. Oxford: Oxford University Press; 2015.
211. Yarbus AL. Eye movements and vision. New York: Plenum Press; 1967.
212. Rozhkova GI, Nikolaev PP. Visual percepts in the cases of binocular and monocular viewing stabilized test objects, Ganzfeld stimuli, and prolonged afterimages. Perception. 2015. doi:10.1177/0301006615594957.
213. Shapley RM, Enroth-Cugell C. Visual adaptation and retinal gain controls. Prog Retin Res. 1984;3:263–345.
214. Johnson EN, Hawken MJ, Shapley R. The spatial transformation of color in the primary visual cortex of the macaque monkey. Nat Neurosci. 2001;4(4):409–16.