Seeing *with* Color: Psychophysics and the Function of Color Vision

Tiina Rosenqvist
Department of Philosophy, University of Pennsylvania, 249 S 36th Street, Philadelphia, PA, USA

Abstract

What is the function of color vision? In this paper, I focus on perceptual phenomena studied in psychophysics and argue that the best explanation for these phenomena is that the color visual system is a perceptual enhancement system. I first introduce two rival conceptions of the function of color vision: that color vision aims to detect or track the fine-grained colors of distal objects and scenes (*Seeing Color*) and that it aims to help organisms discriminate, detect, track and/or recognize ecologically important objects, properties, and relations more directly (*Seeing with Color*). I then discuss two kinds of systematic perceptual phenomena investigated by psychophysicists: approximate color constancy and color induction. I argue from the premise that *Seeing with Color* better accommodates and explains these phenomena to the conclusion that it is the conception that an empirically-guided philosopher of color ought to adopt.

1 Introduction

Most contemporary philosophy of color strives to be empirically-grounded. A particularly fruitful way of doing empirically-grounded philosophy of color is to begin with the question of the function of color vision since this is a question that many sciences already investigate, either directly or indirectly. In this paper, I focus on systematic perceptual phenomena studied in psychophysics, and argue that the best explanation for these phenomena is that the color visual system is a perceptual enhancement system. More specifically, I argue that the function of color vision is not to detect or track fine-grained distal colors, but to be useful in a much more general sense, *e.g.,* by helping perceivers discriminate, detect, track, or recognize objects, properties, and relations in their environments. To put it simply: we don't see color, but see *with* color.[1]

The paper proceeds as follows: I start by giving an overview of the function question in philosophy of color (§2) and differentiating between two competing conceptions of this function: *Seeing Color* and *Seeing with Color* (§3). I then introduce two kinds of systematic perceptual phenomena investigated by psychophysicists: color constancy and color induction (§4), and argue that *Seeing with Color* is the best explanation for these phenomena (§5). Finally, after

[1] I'm inspired by M. Chirimuuta's language here. Chirimuuta writes that "color vision doesn't help us see the colors of things; it helps us see things" (2015, p. 86).

considering pertinent objections and arguing that they do not succeed (§6), I conclude that *Seeing with Color* is the conception that philosophers committed to a genuinely empirically-grounded approach ought to adopt (§7).

2 The function question in philosophy of color

Philosophy of color strives to provide a coherent account of the nature, location, and status of color properties, of the correctness standards of color experiences, and of the kind of empirical knowledge that color perception primarily grounds. To arrive at such an account, many scholars use traditional *a priori* methods, such as consulting commonsense intuitions, clarifying the folk concept of color, or employing intricate thought experiments designed to reveal our deepest and truest thoughts on the issue. Unfortunately, these methods tend to deliver conflicting results. Consider the mind-dependence of color. On this question, Johnston (1992) suggests that the folk concept of color is that of a mind-*independent* primitive property, whereas Levin (2000) claims that a deeper scrutiny reveals the concept to be that of a mind-*dependent* secondary property. Experimental work by Cohen & Nichols (2010) suggests that non-philosophers' intuitions diverge here as well.

Perhaps as a result of these disagreements, many scholars now think that the traditional *a priori* methods alone cannot solve the mysteries of color. Most would accept C.L. Hardin's (1988, p. xvi) contention that philosophy of color is "intellectually irresponsible" when it fails to engage vision science, and it has become customary to cite empirical research in the physiology and psychology of color vision to defend philosophical views. In addition, it has been suggested that an anthropocentric approach to philosophy of color is equally shortsighted and should be abandoned in favor of a more comparative perspective. Many different species possess color vision and to focus on the human case might cause us to miss out on important insights (*e.g.,* Thompson 1995b).

Even though most philosophers now accept that philosophy of color should be empirically-*grounded*, there is disagreement over two core questions: (i) at what stage of inquiry should empirical science enter the picture, and (ii) which sciences are relevant. On the first question, there are two main camps. First, there are those scholars who find it sufficient to apply their *a priori*-driven theories to explain and interpret empirical data. The idea seems to be that a correct philosophical analysis of color should have coherent and consistent things to say about the fruits of empirical research, whereas an incorrect theory is expected to struggle with this task. In reality, however, the authors of very different theories argue that their views perform generally well when put to this test, especially because the theories are often refined in light of the data. I shall call this approach "empirically-*refined*." A second group of scholars maintains that we should let empirical data guide our theory-building, *i.e.,* that we should lead with the science. The rationale is this: if the traditional *a priori* methods are unreliable guides to truths about color, then why not bracket them and start with the *a posteriori* instead. Hilbert summarizes this sentiment well:

> The bread and butter of vision science is data on discrimination and matching, supplemented with physiological data. When this type of data is available and relevant it would be better for philosophers to use it rather than to display the naïve faith in our introspective powers that characterizes so much of the literature in philosophy (2005, p. 155).

Of course the sciences aren't going to serve us metaphysics or epistemology on a platter; whatever the scientists are doing, they aren't performing experiments to directly answer deep philosophical questions. But there is a simpler question that the sciences *can* help us answer—the question of the function or "aim" of color vision. The hope is that by answering this simpler question, the more complicated epistemological and metaphysical questions about color and color perception will eventually become tractable.[2] I shall call this second approach "empirically-*guided,"* and propose that only empirically-guided philosophy of color is empirically-grounded in a strong, genuine sense, because it doesn't privilege intuitions and folk notions over scientific data.

When it comes to deciding which sciences are relevant, the situation is more complex. Plenty of empirical work is potentially useful, but controversies abound. Hatfield (1992) and Thompson (1995a) appeal to visual ecology and comparative color vision in arguing for a specific answer to the function question, whereas Hilbert (1992) insists that *human* color vision should be treated as the paradigm, and that the question of what other animals possess color vision should only be answered after the function of human color vision has been adequately specified.[3] Detailed neurophilosophical arguments in favor of a specific conception can be found in Chirimuuta (2015) and Akins (2001), but critics worry that there is enough disagreement among neuroscientists to warrant suspension of judgment on what the data shows.[4] That said, there is one type of evidence that virtually everybody participating in the function debate finds relevant and accessible—*psychophysical* evidence. For this reason, I focus on psychophysics in this paper.

Before moving on to the different conceptions of the function of color vision, one last clarification is in order. I am assuming here that there is some specific task that color vision is meant to accomplish, something that it aims to do. Some readers might be suspicious of this idea; there exists prolonged debate about the nature and existence of normative functions. This is not a debate I intend

---

[2] I am not suggesting that the relevant sciences will directly answer the function question; empirical data requires interpretation, which is a task in which both scientists and philosophers can participate (see Wright, 2015 for a critical discussion; see also Chirimuuta, 2017).

[3] Hilbert argues that we need to use human color vision as a paradigm case to "[break] into the cycle" to explain what color vision amounts to (1992, p. 364). For criticism, see Thompson 1995a, pp. 7–10.

[4] This is essentially what Cohen (2015) suggests in his review of Chirimuuta (2015). It is true that, in neuroscience, there are two relevant hypotheses concerning the cortical mechanisms of color vision: (i) that chromatic information is processed in isolation of other visual attributes and (ii) that chromatic information is processed jointly with those attributes. The debate largely boils down to the question of how a cortical 'color cell' is to be defined. Conway et al. (2002) adopt a strict criterion: only cells that respond exclusively to colored stimuli are color cells. Many others, however, maintain that any cortical cell that subtracts cone inputs deserves to be called a 'color cell' (e.g., Gegenfurtner, 2003).

to enter here, however. People routinely attribute functions to biological systems, including the color visual system itself, and most philosophers and scientists participating in the project of empirically-guided philosophy of color already assume that color visual systems do have some specific goal.

3 Two robots, two answers to the function question

Colors carry meaning and guide behavior; this much is uncontroversial. But controversy arises when we seek to characterize the function of color vision at its most basic. What is the primary task of color visual systems, what do the systems aim to do? Two general answers have been proposed. The first is that color visual systems aim to detect or track the stable fine-grained colors of distal objects and scenes. The second is that color visual systems aim to enhance our interactions with our environments in a more general sort of way, *e.g.,* by making it easier for us to discriminate, detect, track, and recognize objects, properties, and relations in that environment.

To see how one might arrive at the first conception, consider the following scenario:

> Ava is a conscious humanoid robot with sensory perceptions and a knack for metaphysics. Ava has color experiences, knows she has color experiences, and sets out to determine what kind of properties colors themselves are. Instead of consulting her robot intuitions or her robot common sense, she starts by collecting data about her color experiences. She soon learns that she is capable of distinguishing more than a million different colors and that her color perceptions display near-perfect constancy—that is, unless an object surface undergoes physical change, it tends to produce the same exact fine-grained color experience in her robot consciousness, regardless of lighting conditions and other contextual factors. Ava's color experiences are also useful: they allow her to recognize objects and object properties. From this Ava infers that the function of her color visual system is to detect some stable properties of objects. She also observes that there are some instances where her color experiences deviate from the norm. For example, there is sometimes a specific kind of malfunctioning in certain parts of her robot brain that gives rise to color experiences that are markedly different from her ordinary ones. She decides to label these unusual experiences "incorrect" and her normal color experiences "correct." At this point it seems clear to Ava that colors are whatever stable surface properties her color experiences correspond to when the color visual system is functioning properly. She concludes that her color visual system allows her to *see color*.

Some philosophers reason in much the same way as Ava does. They start by noting that our color perceptions display constancy, and then work their way up to the conclusion that color visual systems are in the business of detecting the stable fine-grained colors of surfaces (and perhaps lights and volumes). They do not deny that detecting those properties can enhance our perception of other things in various sorts of ways, but they maintain that this sort of usefulness does not reflect the *basic* task of color vision. Color visual systems are concerned with color only, even if their outputs can be utilized in a variety of different perceptual and cognitive tasks (see *e.g.,* Byrne & Hilbert, 2003, p. 16). Call this first conception *Seeing Color:*

> (***Seeing Color***) The function of color vision is to detect/track and represent the stable fine-grained colors of distal objects and scenes. The fundamental goal of color visual systems is to enable the perception of distal color.

If we think that color visual systems are in the business of detecting stable distal colors, then this implies that when the system is functioning well, the resulting perceptual experience will match those colors. In other words, color vision can be successful only if there is correspondence between the perceptual state and the relevant state of affairs in the world, *i.e.*, when the perception is *veridical* or *accurate*. When there is lack of correspondence, the perception is *non-veridical* or *inaccurate*. A natural next move is to go search for a property that correlates with our color experiences. This property could be a physical property (*e.g.,* Hilbert, 1992), a primitive property supervening on a physical property (*e.g.,* Allen, 2016), or perhaps even some stable relational property of physical objects, such as a disposition to produce specific fine-grained color experiences.[5]

Now consider a different scenario that illustrates how one might arrive at the second conception:

> Bhai is a conscious humanoid robot with sensory perceptions and a knack for metaphysics. He has color experiences, knows he has color experiences, and sets out to determine what kind of properties colors themselves are. Instead of consulting his robot intuitions or his robot common sense, he starts by collecting data about his color experiences. Bhai's color visual system differs from Ava's color visual system. Bhai soon learns that he is capable of distinguishing more than a million different colors and that his color perceptions display a great deal of variation—that is, even physically identical object surfaces tend to produce very different phenomenal experiences in his robot consciousness, depending on lighting conditions and other contextual factors. One particularly important factor is the spatiochromatic context in which he views the surfaces. By manipulating the context, Bhai can easily alter his perceptual experience of the color of the surface in question. Bhai's color experiences are useful to him; they enable faster and more reliable segmentation of visual scenes into separate object components. From this he infers that the function of his color visual system is to help him discern objects and spatial layouts. He also observes that there are some instances where his color experiences do not give rise to such benefits. For example, there is sometimes a specific kind of malfunctioning in certain parts of his robot brain that blurs the colors he experiences, making it more difficult, *not easier*, to segment visual scenes. Bhai decides to label these experiences "incorrect" and his normal color experiences "correct." At this point it seems clear to Bhai that colors are whatever properties are involved in the relevant kind of perceptual enhancement. He concludes that his color visual system allows him to see *with* color.

[5] We might need other considerations, including a priori ones, to arbitrate between these alternatives, but the space of plausible options has already been substantially narrowed. This is the benefit of the empirically-guided approach.

Some philosophers reason in much the same way as Bhai does. They start by noting the extent of perceptual variation in color vision and the fact that color vision nevertheless tends to be useful to the perceiving organism, *e.g.,* by helping the organism segment visual scenes. They then work their way up to the conclusion that color visual systems are in the business of helping organisms perceive things other than color. What those other things are depends on the organism. For humans, it might be things like objects (apples, prey, obstacles, etc.), properties (shape, texture, ripeness, etc.), relations (distance, position, similarity, etc.), and spatial layouts. In other words, these scholars maintain that the primary aim of color vision is not to see distal color, but to help organisms see faster and better in general. Call this second conception *Seeing with Color*:

> (***Seeing with Color***) The function of color vision is to enhance our perceptual interactions with our environments. The fundamental goal of color visual systems is to help organisms perceive things other than color (*e.g.,* objects, properties, relations, spatial layouts, etc.).

Seeing with Color is committed to the idea that the perceptual enhancement does not require tracking/detecting distal color. Whatever the color visual system is doing, it is not enabling the perception of stable color properties. If we think that color visual systems are perceptual enhancement systems (and not color detectors), then this implies that when the system is functioning well, it participates productively in the organism's perceptual and perceptual-cognitive accomplishments. In other words, color vision can be successful only if it is *useful* in the right kind of way. A natural next move is to go search for a property that helps make sense of this usefulness. For example, Chirimuuta proposes that colors are adverbial properties of perceptual interactions (2015, Ch. 6), and Thompson suggests that colors are "ecological-level" relational properties of the environment (1995b, pp. 243-5).

In the next section, I turn to the two kinds of phenomena that motivate Ava and Bhai: color constancy and color induction. Since humans don't have the same introspective rigor or the same ability to individually collect and analyze data as Ava and Bhai do, we need additional help from color scientists. The good news is that we have psychophysics—a discipline in psychology with a long history in measuring the quantitative relationships between physical stimuli and mental phenomena.

4 Psychophysics: color constancy and color induction

Psychophysics investigates the correlations between physical stimulus properties on the one hand and sensations, perceptions, and perceptually-guided behaviors on the other. Psychophysics of color is the study of how changes in the physical stimulus properties affect subjects' color experiences and judgments. A researcher might ask, for example, how the manipulation of the lighting conditions or the visual angle changes her subject's perception of the color of a target.

I will focus on two kinds of psychophysical phenomena: *color constancy* and *color induction*. 'Color constancy' refers to the perceived stability of the colors of surfaces in different kinds of lighting conditions, *e.g.* when a ripe tomato continues to looks red when taken from bright sunlight into an artificially lit room. 'Color induction' is a collective term for phenomena where changes in the chromatic context of the target induce shifts in the perceived color of that target, *e.g,* when changing the background of a red disc from yellow to green makes the disc appear redder.

Color constancy and color induction seem particularly relevant to answering the function question for two reasons: (i) they are both systematic and pervasive phenomena that characterize our ordinary color perception, and (ii) they seem to pull in opposite directions: on the face of it, constancy suggests that the function of color vision has to do with the *stability* of perceived color, whereas induction suggests that the function is consistent with the *variability* of perceived color under ordinary changes in context and illumination. As a result, even if we were to add additional perceptual phenomena to this list, that wouldn't dramatically change the explanatory task: we would still need to somehow reconcile these different tendencies.

4.1 Approximate color constancy

We need light to see. Visible light is electromagnetic radiation that can be detected by the photoreceptors in our retinas. For humans, the visible spectrum contains wavelengths from roughly 380 to 700 nanometers. Different illuminants generally contain these wavelengths in different proportions—they have different *spectral power distributions* (SPDs).[6] For example, the light from a "warm" incandescent bulb includes relatively more long wavelength light, and a "cool white" LED light includes relatively more short wavelength light. When a light from a light source falls on an opaque object, the surface of the object absorbs and reflects that light as a function of wavelength. Different surfaces reflect light in different ways—they have different *surface spectral reflectances* (SSRs). For example, the surface of a ripe tomato reflects a lot of the longer wavelengths and absorbs most of the short and medium wavelengths.

When the light reflected from an object enters our eye, our photoreceptors convert it into an electrical signal. The light itself is the product of the spectral characteristics of the illuminant (SPD) and the spectral characteristics of the object surface (SSR). This means that the light signal is inherently ambiguous—it doesn't directly tell us about the invariant surface properties of the object. Nevertheless, psychophysics has shown that our perceptual experiences often correlate *better* with those invariant surface properties than they do with the spectral properties of the incoming light (*e.g.,* Shevell & Kingdom 2008, p. 149).

[6] Light sources can also differ in other ways. For example, direct sunlight has a much higher intensity than standard artificial lights.

In other words, our color experiences tend toward constancy. The tomato looks red to (most of) us in many different lighting conditions.

There has been a great deal of theoretical and experimental work on color constancy. Computational models have been proposed to explain the physical possibility of constancy, usually focusing on the question of how the visual system might resolve the ambiguity of the light signal.[7] On the neurophysiological side, evidence has been found of the involvement of both retinal adaptation (Smithson & Zaidi, 2004) and cortical transformations (Rüttiger et al., 1999). On the whole, however, the algorithmic and implementational details of color constancy remain poorly understood.

Psychophysics is essential when it comes to measuring the degree of color constancy. A standard measure is the constancy index: an index of 1 denotes perfect constancy and an index of 0 no constancy.[8] It is important to distinguish between two kinds of constancy judgments here. On the one hand, there is the constancy of perceptual judgments *about the way things are;* on the other hand, there is the constancy of *how things phenomenally appear*.[9] The same stimuli can elicit very different constancy judgments depending on the instructions given to the observers. Arend & Reeves (1986) found that the instruction to match two squares in different displays as if they were "cut from the same piece of paper" produced judgments with moderately high levels of constancy, whereas the instruction to match the hue and saturation of the two squares elicited judgments with much lower levels of constancy.[10] In addition, stimulus configuration, experimental apparatus, and many other components of the experimental setup affect results. All in all, indices of less than 0.7 are common in experiments (Shevell & Kingdom, 2008, p. 149).[11] This means that even though our color perceptions tend toward constancy, this constancy is approximate at best. The tomato will not look the same *shade* of red to us in different lighting conditions.

---

[7] For a helpful review, see Foster, 2011. For discussion of this approach, see Hatfield 2009, pp. 184-5, 193.

[8] The color constancy index is defined by CI = 1-b/a, where "a" is the distance between the test patch and an ideal match, and "b" is the deviation of the observer's judgment from the ideal match, when plotted into some appropriate color space (see Arend et al., 1991, p. 665; Foster, 2011, Fig. 4).

[9] See e.g., Smithson, 2005, p. 1329; Foster, 2011.

[10] As Arend & Reeves write: "Color constancy was weak for our hue matches (direct sensory representation), although two of the three observers could, if required, approximate the latter type of color constancy (the paper matches)" (1986, p. 1749). This suggests that observers are generally capable of separating the two types of judgments. It is an interesting question whether the "paper match" condition measures a genuinely visual experience (a second perceptual mode in addition to the hue and saturation mode) or a cognitive judgment instead, as Hatfield (2009) suggests. If the latter is true, then there is reason to be suspicious of the use of paper match data as evidence in philosophizing about color constancy. That said, the debate surrounding this issue is intricate and I will not rehearse it here.

[11] Foster (2011, Table 1) provides a convenient overview of results from experimental testing of constancy levels tabulated against experimental method, stimulus configuration, illuminants, judgment condition, experimental apparatus, etc. The reported constancy indices vary from 0.11 to 0.92.

4.2 Color induction: contrast and assimilation

We can easily alter the perceived color of a target by altering the chromatic context in which the target is presented. This phenomenon is known as 'color induction,' because a change in the surround of the target induces a change in the experienced hue of the target.[12] There are two kinds of color induction: *simultaneous color contrast* and *color assimilation*. Simultaneous color contrast occurs when the experienced hue of the target shifts away from that of the inducer.[13] Color assimilation occurs when the experienced hue of the target shifts toward the chromaticity of the inducer.

Simultaneous color contrast effects are ubiquitous. As Goethe already noted, the effects "will present themselves to the attentive observer on all occasions, even to an unpleasant degree" (1840/1970, p. 26). Psychophysics provides a more detailed understanding of the extent of the effect, and of the factors that influence its magnitude and direction. For example, Klauke & Wachtler (2015) report that the magnitude varies for different directions in color space. The most dramatic effects occur for induction along the perceptual blue-yellow axis, which covers most of the variation in illumination in natural scenes.[14] The authors take this to indicate that color vision is "adapted to the chromatic properties of the natural environment" (*ibid.,* p. 9). They also report that induction effects are strongest when the target and the background are somewhat similar in chromaticity.[15]

When it comes to the direction of the hue shift, early work on grayscale (achromatic) targets led Fechner (1840) to conclude that the shifts are simply complementary to the chromaticity of the inducer. More recent work by Ekroll & Faul (2012) suggests that the direction of the shift depends on both the chromaticity of the surround and the chromaticity of the target itself.[16] According

[12] Changes in the perceived saturation and brightness of the target can also be induced. 'Saturation ' refers to the vividness of perceived color. A single hue comes in different degrees of perceived vividness, ranging from completely desaturated grey to fully saturated pure color.

[13] Simultaneous color contrast differs from successive (temporal) color contrast, which is perhaps best exemplified by the phenomenon of colored afterimages.

[14] Klauke & Wachtler use stimuli presented on computer displays but note that in natural environments objects are generally illuminated by (yellow) sunlight or (blue) skylight. Because illumination within natural scenes tends to be uneven, the authors suggest that induction effects brought on by "shifting the gaze between differently illuminated areas" might help achieve color constancy (2015, 8). That said, color vision might be adapted to the chromatic properties of the natural environment in a more general sense. For example, when observing objects in the distance (against the horizon) or objects in the sky/water, the chromaticities of the surrounds often fall on the yellow-blue axis. The authors' findings might therefore also reflect the ecological significance of detecting, discriminating, and recognizing objects in such conditions.

[15] The effect increases with the difference between the target and surround up to a certain point (distance of 45° in color space) after which it decreases again (Klauke & Wachtler, 2015, pp. 3,6). Ratnasingam & Anderson (2017) report that more saturated surrounds tend to produce larger induction than muted surrounds (this is also known as "Kirschmann's fourth law").

[16] This is an issue Fechner may have missed because his targets were grey (achromatic). It should be noted that Fechner's complementarity hypothesis and the direction hypothesis make identical predictions in many familiar test cases of color contrast effect (e.g. when the target is grey or when its color is complementary to that of the surround), as Ekroll & Faul (2012, p. 109) point out.

to Ekroll & Faul's *direction hypothesis*, the direction of the effect "in three-dimensional colour space is given by the vector pointing from the target to the surround" (2012, p. 108). This means that one and the same surround can induce hue shifts in different directions in targets of different chromaticities. Subsequent experimentation has supported this idea (*e.g.,* Ratnasingam & Anderson, 2017).

The direction hypothesis has one particularly interesting entailment for our purposes—it predicts that contrast effects occur, in susceptible individuals, whenever targets, embedded in uniform surrounds, are discriminably different from those surrounds. This would mean that there is no such thing as a "neutral" background color, even in the case of a greyscale surround (Ekroll & Faul, 2012, pp. 110-111). In other words, it would mean that the color visual system is predisposed to increase the chromatic contrast between a target and its uniformly colored background regardless of the chromaticities involved.

Whereas uniform surrounds give rise to contrast effects, variegated surrounds are more likely to induce assimilation (*e.g.* Monnier & Shevell, 2003). In color assimilation, the colors of the target and the inducer perceptually blend, and the chromatic contrast between the two is reduced. Though assimilation has received less attention than simultaneous contrast, psychophysics suggests that assimilation effects are common (*e.g.,* De Valois & De Valois, 1988) and can be observed in many different kinds of stimuli. For example, we can make red lines appear slightly more violet if we intersperse them with blue, and more striking illustrations can be created with images involving complex spatial patterns.[17]

Many factors affect the strength of the assimilation. Cerda-Company et al. (2018) report evidence that both the luminance (brightness) contrast between the target and the surround and the color of the surround play a role. The authors used symmetric patterns of 11 concentric rings as test stimuli. One of the rings was an achromatic test ring, flanked on both sides by a green, red, purple, or lime "first inducer" ring. The subjects were asked to match the color of a comparison ring in a fully greyscale stimulus to that of the test ring to measure the degree of assimilation in each condition. Interestingly, when the first inducer was green, no assimilation was ever observed, only simultaneous contrast was apparent in some luminance conditions. A plausible explanation offered by the researchers is that in our evolutionary environment it would have been important for our ancestors to be able to discriminate ripe fruit against green foliage, and assimilation of targets with green surrounds would have been detrimental to this goal (*ibid.,* 11).[18] In other words, the ecological needs of our ancestors might be coded into the mechanisms of color assimilation and simultaneous contrast.

[17] The first type of effect is known as the "Bezold effect," after von Bezold (1876). Akiyoshi Kitaoka's illustrations, which involve more complex spatial patterns, can be found here: http://www.psy.ritsumei.ac.jp/~akitaoka/color12e.html. See also Shevell & Kingdom, 2008, Fig 2.

[18] The most prominent theories of the evolution of primate trichromacy link the red-green dimension in primate color vision to the feeding strategies of our ancestors: the "frugivory hypothesis" appeals to an improved ability to discriminate ripe fruit against dappled background foliage (e.g., Mollon, 1989) and the "folivory hypothesis" appeals to an improved detection of nutritious young leaves that are often reddish in the tropics (e.g., Dominy & Lucas, 2001).

What the pervasiveness of color induction shows is that our color perceptions do not neatly correspond to the spectral characteristics of distal stimuli even when illuminants are kept constant. All we have to do is manipulate the spatiochromatic characteristics of the surrounding areas and our color perceptions change.

5 The best explanation

Recall our two robots, Ava and Bhai. Neither has color vision exactly like ours. Ava's color vision exhibits near-perfect constancy and shows no evidence of color induction; Bhai's color vision exhibits no constancy but there is an obvious influence of the spatiochromatic context on color appearance. Our human situation is messier: our color vision exhibits both approximate constancy and induction effects. This makes the function question more difficult to answer. Nevertheless, I argue that *Seeing with Color* is the best explanation for the human case, and the conception of the function of color vision that an empirically-guided philosopher ought to adopt. The argument is a straightforward inference to the best explanation, and my goal in this section is to defend the premise, to show that *Seeing with Color* explains more phenomena, unifies seemingly disparate phenomena, and generally accommodates the data better than *Seeing Color*.

5.1 Approximate color constancy: seeing color or seeing something else?

Proponents of *Seeing Color* take the phenomenon of color constancy to reveal that the goal of the human color visual system at the computational level is to solve for the surface spectral reflectances of visual objects.[19] Tye (2000, 147) claims that the idea that our color experiences represent such invariant features of surfaces is the "simplest, most straightforward explanation" for color constancy. Hilbert suggests that a version of *Seeing Color* is the only plausible explanation:

> The existence of color constancy suggests that the function of color vision is to determine aspects of the reflecting properties of distal surfaces (…) it is hard to see what other function could be subserved by a visual sub-system that displays color constancy (1992, p. 365).

It is true that *Seeing Color* would provide an elegant explanation for perfect or near-perfect constancy. This is why Ava's reasoning appears sound. If a normally functioning color visual system produced color experiences that neatly corresponded to some stable fine-grained properties of visual objects, it would be reasonable to conclude that the function of the system is to detect or track those

[19] E.g., Maloney & Wandell, 1986; Matthen, 1988; Poggio, 1990; Hilbert, 1992; Tye, 2000; and Byrne & Hilbert, 2003. Most of the philosophers who champion this view take (surface) color to be either identical to, supervenient on, or otherwise straightforwardly dependent on surface spectral reflectance.

properties. But human color constancy is not perfect.[20] If we keep this in mind, the conclusion seems unwarranted.

Other philosophers argue that approximate color constancy supports *Seeing with Color* instead. These philosophers do not deny the usefulness of the relative stability of our color perceptions. Perceptual constancies, color constancy included, can help organisms with object recognition, object categorization, object memory, and many other visual and visually-aided tasks.[21] But, importantly, for color vision to help with these tasks, full constancy of phenomenal experience isn't required (*e.g.,* Hatfield, 2003, p. 195; Hatfield, 2009, p. 194). As long as ripe Granny Smith apples present with a light to mid-tone green appearance, I'm usually able to recognize them. If the function of color vision is to help me detect, track, discriminate and/or recognize objects (Granny Smith apples), properties (ripeness) and relations (distance from me), approximate constancy is enough. On the other hand, if the function of color vision is to detect or track surface reflectances, the deviations from perfect constancy read as color visual system failures.

Proponents of *Seeing Color* might respond that perceptual systems in general are prone to mistakes. Perhaps the color visual system doesn't perform its function perfectly, but as long it performs the function well enough to be useful, everything is in order. But this response erodes the empirical case for *Seeing Color.* Color constancy features as a premise in the argument to the conclusion that color vision aims at detecting or tracking the stable fine-grained colors of distal objects. Once the notion is compromised, the argument loses its force.[22] The same goes for Hilbert's (2005, p. 150) attempt to explain away the deviations from perfect constancy by suggesting that the visual representation of the scene retains, in one way or another, the "illuminant estimate." There's nothing wrong with this idea *per se,*[23] but when it comes to the empirical case for *Seeing Color*, the rug has been pulled out. By making space for the representation of the illuminant, Hilbert implicitly acknowledges that the system doesn't straightforwardly aim at tracking fine-grained surface color. If our chromatic representation of a scene serves to inform us about both lighting conditions and about the material properties of objects, then why think that it's the goal of the color visual system to just determine the stable colors of objects?

If the color visual system isn't trying to solve for surface reflectances, then what explains the constancy? Chirimuuta (2015, p. 56) suggests that color constancy has more to do with maintaining stable relations between the perceived

[20] The advocates of the comparative approach would add that there might also be important interspecies differences in the degree of constancy. It might even be that the color vision of some animals displays no constancy at all. Hilbert, in his blatant anthropocentrism, would argue that such animals lack color vision altogether (see 1992, pp. 363–4).
[21] For empirical evidence, see Bramão et al., 2011.
[22] Chirimuuta makes a similar case against Michael Tye and other color "realists" when she argues that painting deviations from perfect constancy as inefficiencies of the reflectance recovery process "no longer supports the idea that in virtue of having properly working constancy mechanisms we are thereby gaining perceptual access to the fine grained, physical color of things" (2015, p. 56).
[23] For a discussion, see Mausfeld, 2003.

colors of objects across lighting conditions than it does with tracking SSRs. Operationally, this kind of *relational* color constancy has been defined as the ability "to correctly attribute changes in the color appearance of a scene either to changes in the spectral composition of the illuminant or to changes in the reflecting properties of that scene, *i.e.* its materials" (Foster 2011, p. 680; see also Foster & Nascimento, 1994). Research has shown that humans are able to make these discriminations reliably and with little effort, and it has been proposed that the physical substrate of relational color constancy could be found in the retinal cone excitation ratios that tend to stay invariant under illuminant changes (*e.g.,* Foster, 2011, p. 681). The extent to which relational color constancy mechanisms could explain the perceived stability of the colors of surfaces across lighting conditions (*i.e.,* color constancy in the usual sense) is unclear, however (Smithson, 2005, p. 1335). It seems likely that other mechanisms are also involved (see *e.g.* Kraft & Brainard, 1999).

More specifically, it seems likely that the human color visual system relies on some way of "discounting the illuminant" to ensure that bananas continue to look yellow, strawberries red, and Granny Smith apples green. But this need not mean that the system aims to detect or track stable fine-grained colors of distal objects and scenes. It need not even mean that the system attempts to infer or compute an estimation of the spectral properties of the illuminant. For example, Dixon & Shapiro (2017) suggest that employing a simple high-pass filter (a type of an image-processing algorithm) to neutralize some of the effects of changes in lighting conditions might do the job. The idea here is that there is relevant information available in the proximal stimulus itself. Visual images carry information at different spatial scales and most of the variation in chromatic information is contained at low spatial frequencies. By discounting the low spatial frequency color information, the resulting representation would already exhibit approximate constancy. This possibility is consistent with *Seeing with Color*. For example, Thompson argues that color constancy should be understood "as an adaptation for integrating a physically heterogenous collection of distal stimuli into a small set of visually salient equivalence classes, ones that can be employed in a variety of perceptual situations" (1995a, p. 23). The high-pass filter could be understood as a feature of (some) color visual systems that allows for such integration. The same could be said about other discounting methods too, as long as they result in approximate constancy.

Contrary to what the proponents of *Seeing Color* quoted earlier suggest, *Seeing with Color* is consistent with most of the experimental and theoretical work on color constancy. It is the proponent of *Seeing Color* who is faced with the demanding task of having to show that the color visual system specifically aims at tracking or detecting stable fine-grained colors. This is a strong claim, and difficult to defend in light of the empirical data. Unsurprisingly, some proponents of *Seeing Color* have gradually softened their position on what the data shows. Whereas Hilbert (1992) suggests that *Seeing Color* might be the only plausible explanation for color constancy, Hilbert (2005) only suggests that the data does not show that *Seeing Color* is wrong:

> …there is no reason to be found in the consideration of the facts of color constancy and the associated pattern of stability and change to reject standard computational and representational theories of vision (2005, p. 156).

But if there is a better explanation for those facts and patterns, then we do have a reason to reject standard theories of vision (including *Seeing Color*). I've argued here that *Seeing with Color* is the better explanation for the constancy data. In the next section I argue that *Seeing with Color* is the better explanation for the color induction data as well.

5.2 Color induction: failure or accomplishment?

The pervasiveness of color induction shows that our color perceptions do not neatly correspond to the spectral characteristics of distal stimuli even when illuminants are kept constant. As Lotto & Purves (2000) note, the existence of color induction has been "particularly difficult to rationalize." This is especially true in the context of *Seeing Color*, because rationalizing color induction here requires reconciling it with the idea that the function of color vision is to detect stable fine-grained colors. Color induction effects are deviations from the constancy of color appearance and therefore mark another way in which the color visual system fails under this view.

Proponents of *Seeing Color* sometimes suggest that induction effects are mere illusions and as such deserve no special attention (*e.g.,* Tye, 2000). Byrne & Hilbert (2003), in their detailed discussion of the compatibility of color science with the metaphysical view that colors are surface spectral reflectances, never seriously discuss induction effects; they only mention, in passing, that simultaneous contrast is a type of color illusion (2003, p. 4). But if neighboring surfaces (and lights) almost always induce shifts in the perceived chromaticity of the target, and if such shifts are illusory, then the color visual system seems to be doing a rather poor job, and doing a poor job in a strangely systematic manner. If nothing else, this again erodes the empirical case for *Seeing Color,* because it was the stability of color perceptions that was supposed to lead us to the conclusion that the aim of color vision is to enable the perception of stable fine-grained colors. There doesn't appear to exist any genuinely *empirical* reason for the differential treatment of constancy and induction, no *a posteriori* reason to assume that one is a clue to the function of color vision and the other isn't. If so, then the differential treatment can only be motivated with antecedent commitments, perhaps concerning the nature of color or the nature of perception.[24]

[24] Sometimes this is made explicit. For example, Hilbert (1992) begins with the thesis that the function of the visual system, on a general level, is to "extract information about the properties of distal objects from the structured light in the environment" (1992, p. 360). Then, honing in on color vision, he goes on to claim that "the relevant function that provides the criterion for possession of color vision is a function defined in terms of the visual acquisition of information about some distal property" (ibid., p. 362). But there are obvious issues here. First, the claim about the function of color vision need not

On the other hand, it's easy to see how both color contrast and color assimilation could help us see better in general, allow us to see *with* color. First, simultaneous contrast makes objects and patterns stand out against their backgrounds. In the visually complex environment of the forest canopy, added contrast could have helped our primate ancestors quickly segment visual scenes and detect and discriminate fruits, leaves, flowers, and other edible plant parts. Second, color assimilation plausibly helps us see objects as integrated wholes even when the surfaces of those objects aren't perfectly homogeneous. And, indeed, assimilation often occurs within clearly defined (object) boundaries.[25]

But can we find, in the psychophysical literature, specific examples of induction being tied to seeing better? One example might be the so-called "watercolor illusion" in which the color of a thin line flanking a darker chromatic boundary spreads to cover the enclosed white area (Pinna et al., 2001). Here the assimilative color spreading seems to enhance our perception of the spatial structure of the image; it is *how* we see that structure. In addition, the results of the experiment by Cerda-Company et al. (2018) cited earlier suggest that both assimilation and contrast are driven by bottom-up processes. Recall that the green inducers tended to trigger contrast instead of assimilation. If the researchers are right that this connects to our ancestors' need to locate food, then the study provides clear support for *Seeing with Color*. If our ancestors' ecological needs have been coded into our color visual system in a way that directly shifts color appearance away from constancy, then why think that the system aims at detecting stable colors?[26] A much more likely story is that the system aims to make ecologically significant objects conspicuous.

In summary, there is good reason to think that simultaneous contrast helps us perceive objects as separate from their backgrounds and assimilation helps us perceive objects as integrated wholes. Vision scientists too sometimes draw a connection between color induction and philosophy of color:

> One major philosophical view is that color is an objective physical property (…). However, those who study visual perception know that surrounding colors have a great influence on color perception (…), a fact that implies that color is not simply objective (Shapley et al., 2014, p. 569).

---

follow from the claim about the function of vision. Vision as a whole might be in the business of extracting information about the distal world, but not all the visual qualities we experience need to correspond to such extracted information; some might be how the extracted properties are experienced. Second, the claim about the overall function of the visual system can be—and has been—challenged. For example, Hatfield (2009) argues that the function is to guide action via perceiver-relative phenomenal structures. See also Purves et al., 2015.

[25] Some researchers have suggested that there is a tight connection between color induction and perceptual grouping. Xian & Shevell (2004) note that "several perceptual properties, such as depth, form, and brightness, which affect chromatic induction, also play a role in perceptual grouping." King (2001) suggests that assimilation is tied to the perception of one "whole" and simultaneous contrast to the perception of two separate "wholes."

[26] For my purposes here, it is important to show that color induction sometimes aids perceptual grouping and results from bottom-up processing, though this is consistent with the idea that there could also be top-down influences on assimilation (see e.g., Fuchs, 1923).

Of course the existence of color induction does not directly speak against the objectivity of color; color induction effects could be mere illusions, as both Tye and Byrne & Hilbert suggest. But if induction effects are taken seriously as a clue to the function of color vision, the connection is clear.

5.3 Summary: the third robot

Let us now consider one final robot scenario:

> Coda is a conscious humanoid robot with sensory perceptions and a knack for metaphysics. Coda has color experiences, knows she has color experiences, and sets out to determine what kind of properties colors themselves are. Instead of consulting her robot intuitions or her robot common sense, she starts by collecting data about her color experiences. She soon learns that she is capable of distinguishing more than a million different colors and that her color perceptions display *approximate* constancy, *e.g.,* a ripe tomato will continue to look red in most lighting conditions, even though there is a great deal of variation in its fine-grained color appearance. Coda also learns that other contextual factors affect her color perception. One particularly important contextual factor is the chromatic context in which she views objects, *e.g.,* a ripe tomato looks redder against a uniform green background that it does against a grey background. Coda observes that her color experiences are useful to her in a variety of different ways; they enable faster and more reliable segmentation of visual scenes as well as faster and more reliable recognition of objects (*e.g.,* tomatoes), properties (*e.g,* ripeness) and relations (*e.g.,* similarity). From this she infers that the function of her color visual system is to help her see faster and better in general. She also notes that there are instances where her color experiences do not connect to such benefits. For example, there is sometimes a specific kind of malfunctioning in certain parts of her robot brain that causes her to hallucinate free-floating volumes of color. Coda decides to label these experiences "incorrect" and her normal useful color experiences "correct." At this point it seems clear to Coda that colors are whatever properties are involved in the relevant kind of perceptual enhancement. She concludes that her color visual system allows her to see *with* color.

Psychophysics tells us that our human color visual system is similar to Coda's in certain key respects. First, it gives rise to perceptions that display *approximate* constancy. This is consistent with the phenomenology of color experience: at the level of coarse-grained colors, our experiences of the colors of objects remain relatively stable in different lighting conditions, but at the level of fine-grained colors there is considerable variation. Second, psychophysics tells us that our color experiences are systematically influenced by the spatiochromatic contexts in which we view our targets. Changing the context alters the perceptual experience: embedding targets in homogeneously colored backgrounds tends to give rise to simultaneous contrast, whereas more variegated contexts often lead to assimilation. Finally, our color experiences appear to be useful to us in various ways, as vision scientists well know:

> …the converging behavioral, neurophysiological and neuropsychological evidence demonstrate that color plays a critical role in both low-level and high-level vision. At the lower level, color segments the complex visual input into coherent regions,

> thereby helping to differentiate objects from the background. At the higher level of recognition, objects and scenes imbued with characteristic colors are recognized more readily when seen in their natural colors than when not (Tanaka et al., 2001, p. 215).

I have endeavored to show that *Seeing Color* is not a satisfactory explanation for either approximate color constancy or color induction. To simplify somewhat, it appears that the proponents of *Seeing Color* have mistaken our color visual system for a system like Ava's. I have likewise endeavored to show that *Seeing with Color* can accommodate both approximate color constancy and color induction within a single, unified framework. It can also explain why these phenomena occur: approximate constancy is useful for recognition and induction effects are useful for segmentation. In summary, *Seeing with Color* explains more phenomena, unifies seemingly disparate phenomena, and provides a more elegant answer to the function question.

6 Objections and replies

I now consider three objections.

6.1 Contributory mechanism to constancy

I've suggested that empirically-guided philosophers of color need to address color induction. Proponents of *Seeing Color* might respond that color induction merely reflects mechanisms by which our color visual system computes constancy. If this were true, then assimilation and contrast would not present a challenge for the view.

At first glance, the response seems sophisticated. We do not have a clear understanding of the mechanisms of constancy, and neuroscientists have proposed that the very same neural populations in the primary visual cortex might be involved in both constancy and contrast transformations (*e.g.,* Shapley et al., 2014; Conway, 2009). The idea also makes intuitive sense. Consider a ripe Red Delicious apple against a neutral background and a greenish illumination covering both. The light reflected from the apple in these conditions might be close to achromatic, but if the (now) greenish surround induced a shift in the perceived color of the apple, the apple would appear reddish. This is how the contrast mechanism might help discount the illuminant. Scientists, too, have suggested that color contrast might be a contributory mechanism to constancy. Recall Klauke & Wachtler's (2015) finding that the most dramatic color contrast effects occur for induction along the axis from blue to yellow. Since this is the axis that covers most daylight illuminants, and since our color vision likely evolved for seeing in daylight, it could be argued that these biases in the contrast mechanisms reflect the role contrast mechanisms play in constancy computations (*ibid.*, pp. 8-9). That said, Foster, in his review of constancy research, advocates caution and reminds us that "[t]he precise relationship between color constancy and chromatic induction remains to be determined" (2011, p. 696).

From a philosophical point of view, this account of the relationship between contrast and constancy seems somewhat *ad hoc.* Even if we grant that contrast mechanisms contribute to constancy, this need not mean that such contribution explains why the mechanisms exist. It is an old idea that antagonistic evidence cannot prove a hypothesis wrong, and that any hypothesis can be saved by tweaking its auxiliary assumptions (Hempel, 1966). In this case the tweak is the assumption that color contrast exists *just* to serve constancy. But for all we know, the contrast mechanism was selected for some other purpose, *e.g.,* improved scene segmentation. An independent empirical rationale for thinking that contrast is nothing but a contributory mechanism to constancy is missing. In addition, there is experimental evidence suggesting that the connection between constancy and induction isn't as tight as this response requires. As Foster explains, if color contrast (or color induction more generally) is nothing but a contributory mechanism to constancy, then we'd only expect to see surround effects if the surround and the target are taken to be under the same illumination (2011, p. 683). Increasing the relative motion or depth between the target and its background makes the shared illumination assumption less likely, and should therefore lead to decreases in the magnitude of induction. But as experimental data suggests, it doesn't, at least not always (see *e.g.,* Hurlbert & Wolf, 2004).[27] Perhaps a better explanation for both color induction and color constancy is that our visual system has evolved certain reflex-like associations resulting in perceptions that allowed our ancestors to successfully interact with their environments (see Purves et al., 2015). This would explain why green surrounds are less likely to induce assimilation, why color contrast effects are strongest for natural illuminants, and why color vision is productively involved in so many different kinds of tasks.

Hempel (1966, p. 28) warns us that tweaks to an original hypothesis might turn out be burdensome. The assumption that color induction mechanisms are nothing but contributory mechanisms to constancy is burdensome not only because it's *ad hoc*, but also because it entails that the independent usefulness of induction is merely accidental. For example, if the color visual system doesn't aim to make objects pop out against their backgrounds by increasing the contrast between them, then it's nothing but a happy accident when this happens.

6.2 Neglected alternatives

Some might worry that I've only shown that *Seeing with Color* is a better explanation than *Seeing Color*, without showing that it is the conception that an empirically-guided philosopher ought to adopt. Perhaps there is a neglected third alternative that explains the psychophysical data even better.

[27] The researchers themselves take this to indicate that the contrast mechanisms operate at low levels of visual processing, before the image segmentation mechanisms based on computing relative motion or depth (Hurlbert &Wolf 2004, p. 154).

I don't deny that there are many possible answers to the function question. One might argue, for example, that the function of human color vision is to bring aesthetic pleasure. But this conception wouldn't explain *any* of the data considered, at least not in a straightforward manner. It seems fairly safe to assume that the primary function of a *visual* subsystem has something to do with seeing. In this case, it presumably has to do with either seeing color or seeing something else. These options are two conceptions I've considered here. *Seeing Color* is the view that the function of color vision is help us to see color, *Seeing with Color* is the view that the function of color vision is to help us see something else.

But perhaps the neglected third alternative is not some completely unrelated conception, but a hybrid of *Seeing Color* and *Seeing with Color;* perhaps the function of color vision is both to see color and to see with color. The problem with this alternative is that, unless the second conception is rendered dependent on the first (in which case the hybrid isn't a genuine hybrid, but just a version of *Seeing Color*), the two options are mutually exclusive. Notice, for example, that they often deliver conflicting verdicts on the question of success vs. failure. If the color appearance of a target changes with a change in the illuminant or with a change in the chromatic context, *Seeing Color* entails that something has gone wrong whereas *Seeing with Color* need not entail that, and often doesn't.

Finally, *Seeing Color* could be modified to state that the function of color vision is to detect or track *coarse-grained* colors only, as Tye (2006, p. 176) proposes. This would mean that instead of being equipped with determinate hue detectors, we'd have color *type* detectors. The modified view can accommodate approximate color constancy, but it has nothing more to say about the independent usefulness of color induction than the traditional version of *Seeing Color*.[28] In addition, the view might lead some scholars to conclude that objects only possess coarse-grained colors—a conclusion which Tye himself does not welcome.[29]

6.3 Common sense

I've suggested that *a priori* reasoning often plays a role in motivating *Seeing Color,* even when its proponents see themselves as doing empirically-guided philosophy. It wouldn't therefore be surprising if some of these scholars took *Seeing with Color* to be in violation of common sense and considered this a serious blow against the view. These philosophers might again take the lead from Tye who suggests that we are *prima facie* justified in believing something like *Seeing Color* and that the existence of perceptual variation is not a defeater to the view (see 2012, p. 229). But note that it would be very difficult for any empirical observation to act as a defeater to a view that we take ourselves to be *prima facie* justified in believing (recall Hempel on auxiliary assumptions). This shows that objections appealing to common sense just aren't compatible with a genuinely

[28] Tye's modification is motivated by a desire to specify the colors of objects in the face of widespread interpersonal variation in color perception. Tye assumes that interpersonal variation doesn't extend to the perception of coarse-grained hues. Cohen et al. (2006) argue that he is wrong.
[29] Some other scholars, e.g., Gert (2018), advocate this view.

empirically-guided approach. Philosophers need to choose between an empirically-*refined* and an empirically-*guided* approach.

7 Conclusion

Psychophysics tells us that there are two kinds of pervasive, systematic color perceptual phenomena that characterize our ordinary color perception: approximate color constancy and color induction. I've argued that the best explanation for these phenomena is that the aim of color vision is to help us see better in general, rather than to detect or track stable (fine-grained) colors of distal objects and scenes. This conclusion coheres well with conclusions based on data from neuroscience (Akins, 2001; Chirimuuta, 2015) and visual ecology (Thompson 1995a, 1995b).

8 References

Akins, K. (2001). More Than Mere Coloring: A Dialog Between Philosophy and Neuroscience on the Nature of Spectral Vision. In S. Fitzpatrick & J.T. Breur (Eds.), *Carving our Destiny* (pp. 77-116). Joseph Henry Press.

Allen, K. (2016). *A Naïve Realist Theory of Colour*. Oxford University Press.

Arend, L. & Reeves, A. (1986). Simultaneous color constancy. *Journal of the Optical Society of America A, 3*(10), 1743–1751. https://doi.org/10.1364/JOSAA.3.001743

Arend, L.E., Reeves, A., Schirillo, J. & Goldstein, R. (1991). Simultaneous color constancy: Paper with diverse Munsell values. *Journal of the Optical Society of America A, 8*, 661–672. https://doi.org/10.1364/JOSAA.8.000661

Bezold, W., Koehler, S.R., & Pickering, E.C. (1876). *The theory of color in its relation to art and art-industry*. Rev. and enl. L. Prang and Company.

Bramão, I., Reis, A., Petersson, K.M., & Faísca, L. (2011). The role of color information on object recognition: A review and meta-analysis. *Acta Psychologica, 138*, 244–253. https://doi.org/10.1016/j.actpsy.2011.06.010

Byrne, A. & Hilbert, D. (2003). Color realism and color science. *Behavioral and Brain Sciences 26*, 3–21. https://doi.org/10.1017/S0140525X03000013

Cerda-Company, X., Otazu, X., Sallent, N., & Parraga, C.A. (2018). The effect of luminance differences on color assimilation. *Journal of Vision, 18*(11), 1–23. https://doi.org/10.1167/18.11.10

Chirimuuta, M. (2015). *Outside Color: Perceptual Science and the Puzzle of Color in Philosophy*. MIT Press.

Chirimuuta, M. (2017). Perceptual Pragmatism and the Naturalized Ontology of Color. *Topics in Cognitive Science, 9*, 151–171. https://doi.org/10.1111/tops.12222

Cohen, J., Hardin, C.L., & McLaughlin, B. (2006). True Colours. *Analysis, 66*(4), 335–340. https://doi.org/10.1093/analys/66.4.335

Cohen, J. & Nichols, S. (2010). Colours, colour relationalism and the deliverances of introspection. *Analysis, 70*(2), 218–228. https://doi.org/10.1093/analys/anp161

Cohen, J. (2015). Review of M. Chirimuuta, Outside Color: Perceptual Science and the Puzzle of Color in Philosophy. *Notre Dame Philosophical Reviews.* Retrieved December 6, 2022, from https://ndpr.nd.edu/reviews/outside-color-perceptual-science-and-the-puzzle-of-color-in-philosophy/

Conway, B.R., Hubel, D.H., & Livingstone, M.S. (2002). Color contrast in macaque V1. *Cerebral Cortex, 12*, 915–925. https://doi.org/10.1093/cercor/12.9.915

Conway, B.R. (2009). Color Vision, Cones, and Color-Coding in the Cortex. *Neuroscientist, 15*(3), 274–290. https://doi.org/10.1177/10738584083313

Conway, B.R., Eskew, R.T., Martin, P.R., & Stockman, A (2018). A tour of contemporary color vision research. *Vision Research, 151,* 2--6. https://doi.org/10.1016/j.visres.2018.06.009

De Valois, R.L. & De Valois, K.K. (1988). *Spatial Vision*. Oxford University Press.

Dixon, E.L. & Shapiro, A.G. (2017). Spatial filtering, color constancy, and the color-changing dress. *Journal of Vision, 17*(3), 1–20. https://doi.org/10.1167/17.3.7

Dominy, N.J. & Lucas, P.W. (2001). Ecological importance of trichromatic vision to primates. *Nature, 410,* 363–366. https://doi.org/10.1038/35066567

Ekroll, V. & Faul, F. (2012). New laws of simultaneous contrast? *Seeing and Perceiving 25*(2), 107–141. 10.1163/187847612X626363

Fechner, G.T. (1840). Ueber die subjectiven Nach-bilder und Nebenbilder. *Annalen der Physik, 126*(6), 193–221. https://doi.org/10.1002/andp.18401260703

Foster, D.H. & Nascimento, S.M. (1994). Relational colour constancy from invariant cone-excitation ratios. *Proceedings of the Royal Society of London B, 257*, 115–121. https://doi.org/10.1098/rspb.1994.0103

Foster, D.H. (2011). Color Constancy. *Vision Research, 51,* 674–700. https://doi.org/10.1016/j.visres.2010.09.006

Fuchs, W. (1923). Experimentelle Untersuchungen über die Anderung von Farben unter dem Einfluss von Gestalten (Angleichungserscheinungen) (Experimental investigations on the alteration of color under the influence of Gestalten). *Zeitschrift für Psychologie, 92,* 249–325.

Gegenfurtner, K.R. (2003). Cortical mechanisms of Colour Vision. *Nature Reviews Neuroscience,* 4, 563–572. https://doi.org/10.1038/nrn1138

Gert, J. (2018). *Primitive Colors: A Case Study in Neo-Pragmatist Metaphysics and Philosophy of Perception*. Oxford University Press.

Goethe, J.W. (1970). *Theory of Colours.* MIT Press. (Reproduced from *Goethe's Theory of Colours* (1840), tr. Charles Lock Eastlake. John Murray).

Hardin, C.L. (1988). *Color for Philosophers: Unweaving the Rainbo*w. Hackett Publishing.

Hatfield, G. (1992). Color Perception and Neural Encoding: Does Metameric Matching Entail A Loss of Information. *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association, 1*, 492–504. https://doi.org/10.1086/psaprocbienmeetp.1992.1.192778

Hatfield, G. (2003). Objectivity and Subjectivity Revisited: Color as a Psychobiological Property. In R. Mausfeld & D. Heyer (Eds.), *Colour Perception: Mind and the Physical World* (pp. 187–202). Oxford University Press.

Hatfield, G. (2009). On Perceptual Constancy. In G. Hatfield, *Perception and Cognition: Essays in the Philosophy of Psychology* (pp. 178–211). Clarendon Press.

Hempel, C. (1966). *Philosophy of Natural Science.* Prentice-Hall.

Hilbert, D. (1992). What is color vision? *Philosophical Studies, 68*(3), 351-370. https://doi.org/10.1007/BF00694851

Hilbert, D. (2005). Color Constancy and the Complexity of Color. *Philosophical Topics, 33*(1), 141-158. https://doi.org/10.1007/BF00694851

Hurlbert, A. & Wolf, K. (2004). Color contrast: a contributory mechanism to color constancy. *Progress in Brain Research, 144,* 145–160. https://doi.org/10.1016/S0079-6123(03)14410-X

Johnston, M. (1992). How to Speak of the Colors. *Philosophical Studies, 68,* 221–263.

Klauke, S. & Wachtler, T. (2015). “Tilt” in color space: Hue changes induced by chromatic surrounds. *Journal of Vision, 15*(13): 17. https://doi.org/10.1167/15.13.17

King, D.L. (2001). Grouping and Assimilation in Perception, Memory, and Conditioning. *Review of General Psychology, 5*(1), 23–43. https://doi-org.proxy.library.upenn.edu/10.1037/1089-2680.5.1.23

Kraft, J.M. & Brainard, D.H. (1999). Mechanisms of color constancy under nearly natural viewing. *PNAS, 96,* 307–312. https://doi.org/10.1073/pnas.96.1.307

Levin, J. (2000). Dispositional Theories of Color and the Claims of Common Sense. *Philosophical Studies, 100,* 151–174. https://doi.org/10.1023/A:1018660204635

Lotto, R.B. & Purves, D. (2000). An empirical explanation of color contrast. *PNAS, 97*(23), 12834–12839. https://doi.org/10.1073/pnas.210369597

Maloney, L.T. & Wandell, B.A. (1986). Color constancy: a method for recovering surface spectral reflectance. *Journal of the Optical Society of America A, 3*(1), 29–33. https://doi.org/10.1364/JOSAA.3.000029

Matthen, M. (1988). Biological Functions and Perceptual Content. *Journal of Philosophy, 85,* 5–27. https://doi.org/10.2307/2026898

Mausfeld, R. (2003). The dual coding of colour: ‘Surface colour’ and ‘illumination colour’ as constituents of the representational format of perceptual primitives. In R. Mausfeld & D. Heyer (Eds.), *Colour Perception: Mind and the Physical World* (pp. 381–434). Oxford University Press.

Mollon, J.D. (1989). ‘Tho ’she kneel’d in that place where they grew’ The uses and origins of primate colour vision. *Journal of Experimental Biology, 146,* 21–38. https://doi.org/10.1242/jeb.146.1.21

Monnier, P. & Shevell, S.K. (2003). Large shifts in color appearance from patterned chromatic backgrounds. *Nature Neuroscience, 6*(8), 801–802. https://doi.org/10.1038/nn1099

Pinna, B., Brelstaff, G., & Spillmann, L. (2001). Surface color from boundaries: a new ‘watercolor ’ illusion. *Vision Research, 41,* 2669–2676. https://doi.org/10.1016/S0042-6989(01)00105-5

Poggio, T. (1990). Vision: The ‘other ’face of AI. In K.A. Mohyeldin Said, W.H. Newton-Smith, R.Viale & K.V. Wilkes (Eds.), *Modeling the mind* (pp. 139–154). Clarendon Press.

Purves, D., Morgenstern, Y., & Wojtach, W.T. (2015). Perception and Reality: Why a Wholly Empirical Paradigm is Needed to Understand Vision. *Frontiers in Systems Neuroscience, 9, 156.* https://doi.org/10.3389/fnsys.2015.00156

Ratnasingan, S. & Anderson, B.L. (2017). What predicts the strength of simultaneous color contrast? *Journal of Vision, 17*(2), 1–17. https://doi.org/10.1167/17.2.13

Rüttiger, L., Braun, D.I., Gegenfurtner, K.R., Peterson, D., Schönle, P., & Sharpe, L.T. (1999). Selective color constancy deficits after circumscribed unilateral brain lesions. *Journal of Neuroscience, 19,* 3094–3106. https://doi.org/10.1523/JNEUROSCI.19-08-03094.1999

Shapley, R., Hawken, M., & Johnson, E. (2014). Color in the Primary Visual Cortex. In J.S. Werner, & L.M Chalupa (Eds.), *The New Visual Neurosciences* (pp. 569–582). MIT Press.

Shevell, S.K. & Kingdom, F.A.A. (2008). Color in Complex Scenes. *Annual Review of Psychology, 59,* 143–166. https://doi.org/10.1146/annurev.psych.59.103006.093619

Smithson, H.E. & Zaidi, Q. (2004). Colour constancy in context: roles for local adaptation and levels of reference. *Journal of Vision, 4,* 693–710. https://doi.org/10.1167/4.9.3

Smithson, H.E. (2005). Sensory, computational and cognitive components of human colour constancy. *Philosophical Transactions of the Royal Society B, 360,* 1329–1346. https://doi.org/10.1098/rstb.2005.1633

Tanaka, J., Weiskopf, D., & Williams, P. (2001). The role of color in high-level vision. *TRENDS in Cognitive Sciences, 5*(5), 211–215. https://doi.org/10.1016/S1364-6613(00)01626-0

Thompson, E. (1995a). Colour Vision, Evolution, and Perceptual Content. *Synthese, 104*(1), 1–32. https://doi.org/10.1007/BF01063672

Thompson, E. (1995b). *Colour Vision: A Study in Cognitive Science and the Philosophy of Perception*. Routledge.

Tye, M. (2000). *Consciousness, Color and Content*. MIT Press.

Tye, M. (2006). The puzzle about true blue. *Analysis 66*(3), 173–78. https://doi.org/10.1093/analys/66.3.173

Tye, M. (2012). Cohen on Color Relationalism. *Analytic Philosophy, 53*(3), 297–305. https://doi.org/10.1111/j.2153-960X.2012.00569.x

Wright, W. (2010). Perception, Color, and Realism. *Erkenntnis, 73,* 19–40. https://doi.org/10.1007/s10670-010-9223-5

Xian, S.X. & Shevell, S.T. (2004). Changes in color appearance caused by perceptual grouping. *Visual Neuroscience, 21,* 383–388. https://doi.org/10.1017/S0952523804213062