

**Dimitria Electra Gatzia**

The University of Akron, Institute of Philosophy of the Czech Academy of Sciences  
(In press *Synthese Special Issue*, (Eds. Brogaard, B. and French, R.)

Penultimate Draft. Please do not use it for quotations.

## **Reliable color misrepresentation and color vision**

**Abstract:** Tracking theories of mental representation posit a privileged relation between color representations and the color properties of objects. Tracking theories of mental representation have been used to motivate color realism as they posit that the function of color vision is to represent the colors of objects. It has been argued that tracking theories have a major flaw, namely they cannot account for reliable misrepresentation. It has further been suggested that reliable color misrepresentation is a live possibility. In this chapter, I argue that the current evidence indicates that our color representations reliably misrepresent. This conclusion undermines tracking theories and the color realist theories they purport to motivate.

**Keywords:** reliable misrepresentation; tracking theories of mental representation; color realism; color vision; Bayesian decision theory; color perception; empirical ranking theory; evolution of color vision; invariance principle

### **Introduction**

The world appears colored to creatures like us. Color realists maintain not only that things in the world such as strawberries appear red to creatures like us but also that they are red. Color realists disagree about which physical properties are the colors. At least in relation to opaque objects, various alternatives have been proposed, including surface spectral reflectances (Byrne & Hilbert 2003), dispositions (Johnston 1994; Levin

1997), relations between subjects, objects, and circumstances (Cohen 2009; Chirimuuta 2015), and so forth.

Tracking theories of mental representation are often thought to motivate color realism. Alex Byrne and David Hilbert (2020), for example, argue that Objectivist Reductionism, which identifies colors with types of spectral reflectance properties, “can be motivated in a much more local (and much more convincing) fashion.” One of the local motivations the authors discuss is that “the natural world strongly suggests that a lot of animal colouration is the result of natural selection, and moreover can only be selected because other animals can detect colours.” At the same time, tracking theorists of mental states and color realists alike want to account for error in color representation since there will be cases in which perceivers misrepresent the color of objects.

Mendelovici (2012, 2016) argues that while tracking theories may be able to account (albeit not well) for occasional misrepresentations, they cannot account for, what she calls, “reliable misrepresentations”:

It is a live possibility that there are no colors. Objects appear to be colored, but upon closer examination, it could turn out that they do not have the properties our color-experiences represent them as having. If this is the case, then our color-experiences are mistaken; they misrepresent. Further, they misrepresent in the same way all the time. If our color-experiences misrepresent an object as red on one occasion, they are likely to misrepresent it as red on other occasions; they reliably misrepresent. Whether or not this is the right view of colors, it seems there could turn out to be such cases of reliable misrepresentation.

Mendelovici does not argue that color representation is an actual case of reliable misrepresentation. Rather, she argues that it is a live possibility. In this chapter, I argue that the current evidence on human color vision supports the claim that color representation is an actual case of reliable misrepresentation. This presents a real threat to tracking theories and the color realist theories they purport to motivate.

The discussion proceeds as follows. The first half of the chapter provides the framing of the problem of reliable misrepresentation. In Section 1, I provide a brief introduction of two of the most relevant tracking theories of mental representation. In Section 2, I distinguish between occasional and reliable misrepresentation. The second part of the chapter presents arguments for a negative and a positive claim. In Section 3, I argue that the current evidence indicates that the function of color vision is not to detect color properties. In Section 4, I argue that the current evidence indicates that reliable color misrepresentation can be explained without reference to light (or any other physical) properties.

### **Section 1: Tracking theories of mental representation**

Tracking theories of mental representation posit that states of mind represent aspects of the world by tracking, in some sense, external objects and properties that they are *about* (Dretske 1981, 1986, 1995; Millikan 1984, Fodor 1987, 1992). More specifically, they posit a privileged relation between mental representations (which are thought to be vehicles) and properties (which are thought to be part of the content).<sup>1</sup> Representational vehicles are thus considered to be physically realized states that are the bearers of content understood in terms of *aboutness*. Some tracking theories, for example, take the relation between a mental representation and what it represents to be a causal relation. They thus maintain that the mental representation RED gets to represent redness because *redness* causes the tokening of RED in appropriate circumstances. Tracking theories posit that such a privileged relation holds between representational vehicles and properties (or objects) in the world in circumstances in which the tokening of a representation is useful, adaptive, involves a sufficiently strong causal connection, and so forth. Following Mendelovici (2012), I will call such circumstances “content-endowing conditions.”

Assigning contents to mental representations requires empirical justification, which, in turn, requires a certain fit between the organism and the world. Two of the most prominent tracking theories of mental representation in the debate about the

---

<sup>1</sup> The term “representation”, as it is used here, refers to having an experience with a certain phenomenology. Although on tracking theories having an experience (e.g., a green cucumber) essentially involves standing in a relation R to certain properties (e.g., greenness), R can be understood as an existence-neutral relation (Pautz, 2021).

metaphysics of color take the content-endowing conditions to be either conditions of optimal-functioning (see Tye 2000; Chirimuuta 2015; Byrne & Hilbert 2003) or design (Millikan 1989; Dreske 1995; Byrne & Hilbert 2020).<sup>2</sup> Let's look at each in turn.

Optimal-functioning tracking theories of mental representation take the content-endowing conditions to be conditions of optimal functioning, namely, the conditions in which a given mental state aids its bearer survive or flourish. On this account, color vision aids in the survival or flourishing of organisms by allowing them to, among other things, spot ripe fruit. Red strawberries are edible, for example, but green strawberries are not. When color vision performs optimally, it accurately represents ripe strawberries as red and unripe strawberries as green. Color properties are thus a part of the content of accurate representations of ripe or unripe fruits.

Teleological tracking theories of mental representation take the content-endowing conditions to be design conditions, namely, the conditions in which the tokenings of a representation have given our ancestors an evolutionary advantage. The function of color vision is thus tied to natural selection. On this account, color vision was designed, through natural selection, to detect colors, thereby providing our ancestors an evolutionary advantage. Color vision aided our ancestors' survival by allowing them to, among other things, spot ripe fruit. When color vision performs as it was designed to perform, it accurately represents ripe strawberries as red and unripe strawberries as green. Color properties are thus a part of the content of accurate representations of ripe or unripe fruits.

## **Section 2: Occasional and Reliable Misrepresentation**

Any tracking theory of mental representation must be able to explain how a representation can misrepresent. Misrepresentation occurs when a representation does

---

<sup>2</sup> I will leave asymmetric dependency tracking theories (Fodor, 1987, 1994) aside since they are rarely used in debates about color representation. These theories distinguish between representational relations and merely informational relations on the basis of their higher-order relations to each other, meaning that informational relations depend on representational relations but not vice versa. For example, if tokens of a mental state type are reliably caused by horses, camels-in-a-distance, or cows-in-the-dark, then they carry information about horses; but if such tokens are caused by camels-in-a-distance, or cows-in-the-dark *because* they were caused by horses, but not vice versa, then they represent horses.

not represent its content veridically. Take, for example, your strawberry representation. It has a certain content: *there is something it's like* to represent a strawberry that may include *having a red color, having a heart-shape, having a bumpy surface*, and so forth. One of the difficulties that arise for tracking theories of mental representation is the *disjunction problem* (Fodor 1987; Mendelovici 2012).

Tracking theories must explain, in a principled, non-circular way, how a representation can *correctly* represent some things which cause its activation, but also *misrepresent* other things which cause its activation. The disjunction problem arises because, according to tracking theories, a representation represents *whatever causes it's activation in such and such viewing conditions*. To see this let's assume that your strawberry representation is sometimes activated by a raspberry. In such cases, your experience misrepresents the strawberry. Now if a raspberry can also cause the activation of your strawberry representation, then there seems to be no principled reason for saying that the content of your representation is *strawberry* and not *strawberry or raspberry*. But if the content of your representation is disjunctive (*strawberry or raspberry*), then your strawberry representation veridically represents *strawberry or raspberry*. But if that is the case, then tracking theories can't explain how a representation can misrepresent.

Solving the disjunction problem requires accounting for occasional misrepresentation. Tracking theories distinguish between veridical representations and misrepresentations by maintaining that the latter cases involve some nonsemantic defect. States that are nonsemantically successful occur when certain conditions are met. Optimal-tracking theory maintains that conditions in which nonsemantically successful states occur involve optimal functioning. Teleological-tracking theory maintains that conditions in which nonsemantically successful states occur involve conditions of the same type as the design conditions as those of our ancestors. States that are non-semantically defective, i.e., states that occur in conditions that do not involve optimal functioning or do not function as designed, by contrast, are said to misrepresent. Tracking theorists maintain that while, for the most part, your strawberry representations represent strawberries veridically, occasionally your color vision malfunctions resulting in misrepresentations. Since occasional misrepresentation involves some nonsemantic defect, tracking theories can account for the disjunctive problem by comparing the

causes of these representations to the causes of the same representations in nonsemantically successful conditions.

Another difficulty that arises for tracking theories of mental representation is the *reliable misrepresentation problem* (Mendelovici 2012, 2016). Mendelovici (2012: 421) frames the problem as follows:

It is a live possibility that there are no colors. Objects appear to be colored, but upon closer examination, it could turn out that they do not have the properties our color-experiences represent them as having. If this is the case, then our color-experiences are mistaken; they misrepresent. Further, they misrepresent in the same way all the time. If our color-experiences misrepresent an object as red on one occasion, they are likely to misrepresent it as red on other occasions; they reliably misrepresent. Whether or not this is the right view of colors, it seems there could turn out to be such cases of reliable misrepresentation.

As Mendelovici's hypothetical case of color indicates, the reliable misrepresentation problem arises in cases in which veridicality and reliability come apart. Mendelovici employs a distinction from statistics between *valid tests* and *reliable tests* to explain how a representation can be nonveridical and yet reliable. While valid tests detect what they are intended to detect fairly accurately, reliable tests yield more or less the same results consistently. Mendelovici argues that a similar distinction can be made between *veridical representation*, which represents that same thing it tracks, and *reliable misrepresentation*, which represents one thing but tracks another. Since the misrepresentation in this case is consistent, solving the reliable misrepresentation problem requires accounting for more than mere occasional misrepresentation. However, Mendelovici (2012, 2016) argues, tracking theories cannot account for reliable misrepresentation:

The problem is that tracking theories peg veridicality to their favored notion of nonsemantic success, a type of success distinct from veridicality. A state is nonsemantically successful when it occurs in conditions such as conditions of optimal functioning, conditions of the same type as the design conditions our ancestors found themselves in, or, for the asymmetric dependence theory, when

it is an instance of a relatively strong connection. The connections a mental representation has in content-endowing conditions determine its content, and nonsemantically successful conditions are conditions either identical to or of the same type as content-endowing conditions. As a result a representation cannot misrepresent in nonsemantically successful conditions. But that means that whenever there is misrepresentation, there must be a nonsemantic defect, a defect apart from being nonveridical (Mendelovici 2012: 434).

Cases of occasional representations, hallucinations, and illusions can be attributed to nonsemantic defects. But since reliable misrepresentations can occur in conditions of optimal functioning or conditions of the same type as design conditions, they cannot be attributed to nonsemantic defects. Following Mendelovici, let's assume that there are no colors in the world. If there are no colors in the world, then color vision misrepresents reliably, not just occasionally. For example, you reliably misrepresent ripe strawberries as red even though, by hypothesis, nothing in the world is red. Since, in this case, your reliable ripe strawberry misrepresentations cannot be attributed to nonsemantic defect, optimal-functioning tracking accounts have to deny that any actual cases of color-representation could contribute to survival and flourishing. This is, of course, implausible since there seems to make no practical difference to you whether your ripe strawberry representations are veridical or not: you can still reliably spot the ripe strawberries. Teleological-tracking theorists have to draw an equally implausible conclusion, namely that while the inner states of our ancestors veridically represented strawberries as red, the same states in us misrepresent strawberries as red.

Mendelovici (2012: 435) acknowledges that she has not offered an argument for the claim that there are actual cases of reliable misrepresentation but argues that reliable misrepresentation is still a problem for tracking theories because we cannot deny that there are any such cases on the basis of a metaphysical theory of mind:

Of course, I have not argued that there are any cases of reliable misrepresentation. So why is it a problem that tracking theories are ill-suited to allow for them? The problem is that whether or not there are such cases, it would be inappropriate to conclude that there aren't on the basis of a metaphysical theory of mental representation. By a metaphysical theory of mental

representation, I mean a theory that aims to tell us what mental representation really is, as opposed to a theory that tells us certain further facts about mental representation, such as facts about the structure of various representational spaces, which specific contents we represent, or whether any particular representation is veridical.

In what follows, I argue that the current evidence indicates that our visual system reliably misrepresents colors. And since tracking theories cannot account for reliable color misrepresentation, they cannot be used as a motivation for color realism.

### **Section 3: Color vision, measuring devices, and selective pressure**

Thus far, we have seen that tracking theories of mental representation do not have the resources to solve the reliable misrepresentation problem (Section 2). I think Mendelovici is right that the mere possibility of cases of reliable misrepresentation threatens tracking theories of mental representation. But, at least in the case of color, one reason the mere possibility of reliable misrepresentation may not dissuade tracking theorists to abandon ship is that they can accept that it is a possibility but insist that, in light of facts about the function of color vision, it is a contingent truth that reliable misrepresentation does not occur in the actual world.<sup>3</sup> It just so happens, tracking theorists may retort, that while it may be metaphysically possible that our color representations reliably misrepresent, given what we know about the way color vision functions in the actual world, color representations only occasionally misrepresent.

In what follows, I argue that when it comes to color vision reliability and veridically come apart opening the door to an actual case of reliable color misrepresentation. My argument focuses on tracking theories that maintain that color experience, at least sometimes, occurs in conditions of optimal functioning or conditions of the same type as design conditions. Although other nonsemantically successful conditions may be relevant here, these two are featured far more prominently in the literature on color. It is for this reason that I focus on them here, although I think similar arguments can be made for other nonsemantically successful conditions.

---

<sup>3</sup> Alternatively, tracking theorists may argue that all Mendelovici has shown is that reliable misrepresentation is logically possible but not metaphysically possible. Which of these two options (or any others) tracking theorists prefer does not affect my argument.



Discussions about the content of color representations often make reference to conditions of optimal functioning through comparisons between the function of color vision and that of measuring devices such as thermometers or speedometers, which 'track' certain properties, e.g., temperature or speed, in the world. Here's an example in which this sort of strategy is employed by color realists to argue that color vision detects colors accurately:

In order for a household thermostat to detect that the temperature is below 65°F, the thermostat dial must be set correctly. It does not follow that the property of being below 65°F is in any interesting sense dependent on, or relative to, thermostats or their settings. No one is likely to make this mistake of confusing *temperature* with *conditions necessary for the detection of temperature*. But an analogous mistake is for some reason often made in the case of color...The presence of perceivers and the occurrence of certain mental events are obviously necessary for the perception of color. Just as in the thermostat example, it does not follow that the colors themselves are in any interesting sense dependent on, or relative to, perceivers or mental events. To think it did would be to confuse conditions necessary for the perception of color with color itself (Byrne & Hilbert 2003)

A thermostat has the function of tracking a room's temperature. In optimal functioning conditions, the thermostat tracks the room's temperature correctly. However, under suboptimal conditions, it will track the room's temperature incorrectly. For example, sunblock is a feature of smart thermostats, which allows them to detect when they are in direct sunlight and discount the heat produced by it in order to track the room temperature accurately. Conditions of direct sunlight, for smart thermostats, are not suboptimal conditions since they do not cause such thermostats to misrepresent the room temperature. A thermostat that lacks such a smart feature, by contrast, will fail to detect that it is in direct sunlight and will thus fail to track the room's temperature accurately. Conditions of direct sunlight for such 'not smart' thermostats are suboptimal conditions precisely because they cause them to misrepresent the room temperature. If color vision is a tracking device that functions similarly to a smart thermostat (along with some innocuous assumptions about mental states), then it tracks the colors

accurately under optimal conditions but inaccurately under suboptimal conditions (Byrne & Hilbert 2003).

Some prefer to talk about color vision as having not a single function but a variety of functions depending on the visual task in question. For example, Mazviita Chirimuuta (2015: 77) argues that what functions color vision has depends on the contributions it makes to visual tasks, and suggests the following long list of functions associated with different visual tasks:

- segmentation of objects
- perception of form or shape
- grouping of objects
- perception of contours
- perception of texture
- object detection
- object identification
- memorization of objects
- perception of depth
- perception of the motion of complex objects
- recognition of shadows

What counts as optimal conditions in this case will, nevertheless, depend on the tracking theory of mental representation one prefers. For example, in discussing failures of color constancy (in which an object fails to appear to have the same color over time or when situated against a different background), Chirimuuta (2015: 180) argues that the misrepresentation need not involve an inaccurate color attribution so long as nonsemantically successful conditions involve optimal functioning:

In my estimation, however, the most important thing about these dramatic failures of color constancy is that in such cases you are really *seeing less well*. One of the central functions of color vision—object recognition—has gone awry. Moreover a host of other functions served by color, such as scene segmentation, differentiation of shadows from surfaces, and perception of material sameness, will all be underperforming. So we should acknowledge that some kind of

genuine misperception does occur, without analyzing it in terms of the attribution of the wrong color to an object. This is what I call *ecologically relevant misperception*. Under conditions that are hostile to our color visual system contributing to all of its usual functions (e.g., at low light levels, or if strong chromatic light leads to failures of color constancy), then we *do* misperceive in a certain sense. What we call “misperceiving the color of things” is better put as, “not seeing things as well as we are accustomed to—not seeing well enough to perform our usual visually guided tasks without difficulty.”

Presumably, given the long list of functions attributed to color vision, the list of suboptimal conditions that give rise to “ecologically relevant misperception” will be more extensive than the list associated with the view that color vision has a single function (where color vision is treated as a simple measurement device such as a thermometer). The approach is, nevertheless, the same: color vision misrepresents only under suboptimal conditions (whatever those may be); and what makes a set of conditions suboptimal is that color vision is not able to perform the desired function optimally.

Discussions about the content of color representations can also make reference to design conditions, which are often linked to claims about the ecological significance of color detection. Here’s an example:

We may take the “function” of some adaptive subsystem in an organism to be its *biological function*—roughly, the features of the system that were selected for (see, e.g., Millikan 1984: ch. 1). Thus the function of the heart is to pump blood, or to deliver oxygen to the body, or some- thing along similar lines; at any rate, it is not to make a thumping noise. How do we get from this multiplicity of functions of colour vision to the conclusion that Objective Reductionism is false? It would certainly be an embarrassment if SSR detection was not *one* of the functions of colour vision, for then there would be no obvious reason why selective pressure would have produced a system that could accurately recover (general) reflectances. Admittedly, there would presumably have been selection for accurate recovery of *differences* in reflectances (as in the example of object boundaries above), but that could have been accomplished while getting the

reflectances themselves wrong or, more simply, by not attempting to recover such information in the first place. (Byrne & Hilbert 2020)

Although the point of this passage is to provide a plausible defense of Objective Reductionism (i.e., a realist account of color, according to which colors are reducible to types of surface reflectance properties of objects) what matters for our purposes is that this defense is based on teleological-tracking theories. Byrne and Hilbert argue that if color vision was not designed to track colors, there would be no plausible explanation why selective advantage would produce such a system.

In all of these cases, tracking theories of mental representation are used to motivate color realism. The assumptions made about the function of color vision pertaining to optimality or design and, the related inferences about what counts as occasional misrepresentation, are not based entirely on fiction. However, in the next two sections I argue that they are nevertheless false.

#### **Section 4: The evolution of human vision**

The previous two sections aimed to first provide an understanding of the notion of reliable misrepresentation and then show the crucial role tracking theories have played in motivating color realism. In this section, I defend a negative claim, viz. that the function of color vision is not to detect color properties. The false assumptions about the purported function of color vision, as they pertain to optimality or design, are based on the prevailing view of cone and rod photoreceptors as participating in color and achromatic vision respectively. It is, therefore, not surprisingly that the common assumption within the scientific literature, is also the one repeated within the philosophical literature, namely that cones facilitate color vision while rods facilitate achromatic vision. As we will see, however, this common assumption is false. A proper understanding of human vision shows that cones and rods are highly effective partners whose combined informational properties are greater than the properties of each component, giving rise to color, lightness, and darkness perception (Akins 2014). This reveals that what matters to a biological visual system is not the accuracy of color representation but *visibility*, which is achieved through contrast as opposed to the detection of color properties.

A common assumption within the scientific literature is that cones mediate color vision while rods mediate achromatic vision. In "Black and white and colour," Kathleen Akins (2015: 175) explains the intuitive appeal of this assumption:

It is very difficult to imagine the workings of the visual brain along any other lines except the division between the 'black and white' and the 'colour' of public images. When one first learns that the ganglion cells in the retina are of two types, 'chromatic' or 'luminance' cells, it is natural to think that here too 'black and white' and 'colour' is the essence of the divide: luminance cells encode light intensity (i.e. brightness or darkness) and chromatic cells encode, well, the *other* dimension of light, wavelength or hue. If not that, what would the nature of the division be?

According to Akins (2015: 174), it is likely that scientists borrowed the terminology 'black and white' and 'color' from photographers and illustrators and used it to refer to "to one aspect of our visual experience when we inspect black and white or colour images or when we find our way around at night....If we think of the neurophysiological distinction between luminance and chromatic systems of vision as one of 'black and white' and 'colour', this *is* an analogy." As we shall see, Akins (2015: 175) presents compelling arguments in an effort to "pry the reader...out of the analogy's firm grip."

Recent revelations about the visual system of the mantis shrimp illustrates both the firm grip of this analogy as well as how it can lead the scientific community astray. Mantis shrimps are known to have one of the most complex eyes, with up to twelve types of photoreceptors, each with a different spectral sensitivity ranging from deep ultraviolet (300 nm) to dark red (720 nm). When researchers first learned that the eye of the mantis shrimp has four different photoreceptors for ultraviolet light with spectral peak sensitivity at 315 nm, 330 nm, 340 nm, and 380 nm, they hypothesized that they must have remarkable color vision that evolved to detect the colors of the colorful tropical coral reefs (Marshall & Oberwinkler 1999). Much to their surprise, subsequent studies revealed that mantis shrimps performed very poorly in tasks involving color

discrimination, indicating that their visual system didn't evolve to detect color. The most likely hypothesis for the function of the visual system of mandi shrimps is that it evolved to respond to polarized light (i.e., a fundamental feature of light such as intensity and wavelength, which can be utilized for guiding behavior) that is reflected by their body parts and is used for intraspecific communication purposes (Heinze 2014).

Human vision has, at least, two main systems: one system is associated with chromatic vision and the other with luminance vision. The chromatic system depends upon the input of cones and is utilized during conditions of bright light such as daylight (that is why it is also known as photopic vision). The luminance system sums rod signals and is utilized during conditions of low light such as dusk (that is why it is also known as scotopic vision). As Akins (2015: 180, emphasis in the original) rightly notes, "*neither of these luminance systems—indeed no biological luminance system—encodes light intensity per se.*" Contrary to the common analogy, cone and rod photoreceptors differ *only* with respect to their spectral sensitivity, i.e., the relative sensitivity of a photoreceptor to all wavelengths, not with respect to their function:

Rods, just like cones, respond within a specific spectral window; rods are wavelength sensitive in exactly the same way as cones. The primary difference between rods and cones...is the energy required for photon absorption: rods require far less energy and are thus ideal for low light conditions. However, despite their greater sensitivity, the absolute photon catch of rods is still markedly lower than that of cones. This is why rod systems are convergent: they must pool the signals of multiple rods in order to achieve a good signal-to-noise ratio. If yet another type of rod were added uniformly throughout the retina — and one must have at least two types of receptors to discriminate wavelength — this would *halve* again the already poor spatial resolution of night vision. In the dark of night, it is thus the low photon catch of the rods that disqualifies rods for participation in colour vision.... [However,] there is nothing in the function of rods that intrinsically precludes them from chromatic processing and the question of whether (and what) rods might contribute to chromatic vision has been an active one since the 1960s (Akins, 2015: 179).

An interesting effect that arises from differences in the spectral sensitivities between cones and rods is the Purkinje shift, named after the Czech anatomist Jan Evanelista Purkyně (Purkinje & Kruta 1823/1969). This effect occurs in conditions of dark adaptation (i.e., when the system adjusts to a lower light level) during which rods are more sensitive than cones. (When the illumination reaches higher levels, e.g., during daylight or bright light, the rods saturate, meaning that they stop responding to increases in illumination.) Because rods are maximally sensitive to short wavelengths (500 nm or below) and cones are maximally sensitive to longer wavelengths (550 nm and above), during dark adaptation the peak of visual sensitivity shifts towards shorter wavelengths. As a result, blues look relatively brighter than reds (Dowling 1967; Cao et al. 2011). You can easily observe this effect by placing two objects that look red and blue under a bright light and then slowly start to dim the light. You will immediately notice that the blue object looks brighter than the red object when the light is dimmed. You will also see that the red object is now harder to see than the blue object. The Purkinje shift illustrates that the luminance and chromatic systems form an effective partnership to enhance visibility. It is nevertheless a surprising effect if one assumes that color detection is a function exclusive to the chromatic system.

Akins (2014) argues that the two effects that mirror the two most important principles of vision are *spectral filtering* and *luminance contrast*. Both of these effects are behind the Carnovsky *RGB exhibit*.<sup>4</sup> Spectral filtering is “a ‘trick’ that every natural system of vision ‘learns’ to employ over the course of evolution” (Akins, 2014: 181). The spectral peak sensitivity for each cone type is approximately 420 nm (blue), 534 nm (green), and 564 nm (red) while the spectral peak sensitivity for rods is approximately 498 nm (between blue and green) (Bowmaker & Dartnall 1980). The RGB exhibit uses a very restrictive filtered light source to illuminate the mural (i.e., a narrow bandwidth of light about 60 nm), which essentially reduces the spectral range of a trichromat to that of a rod achromat.<sup>5</sup> Akins (2014: 183-184) describes this transformation as follows:

---

<sup>4</sup> The Carnovsky RGB - *Color est e pluribus unus* art was created by artists Francesco Rugi and Silia Quintanilla. It's exhibition was on display at the Direktorenhaus in Berlin.

<sup>5</sup> Spectral filtering was also used by Edwin Land (1977) in his experiments on color constancy.

...the RGB exhibit uses narrow bandwidth filters to re-create the monochromat's world, a world in which perceptual 'lightness' is a function of *both* intensity and the predominant wavelength of the reflected image. With only one photopigment, rhodopsin, the rod achromat's visual world varies along a single visual dimension. So too do the perceptions of the 'functional monochromat' who views the Carnovsky world of illustrated figures under coloured light. Still, there is a crucial difference between a trichromat who views a Carnovksy exhibit under filtered light and a monochromat who views the natural world under sunlight. There is no escaping the fact that, for the trichromat, the RGB exhibit appears in shades of red (or green or blue.) The trichromat sees the light and the wall *as coloured*, as having a particular hue, even if the light and every surface are monochrome, i.e. even though they have the *same* hue. This is not information that the rod monochromat could possibly have, that the illuminant has a particular predominant wavelength as does the light reflected from every surface. We must assume therefore that the monochromat's experience is not 'coloured' red *or* blue *or* green and that, in all likelihood, it differs from our experience in this crucial way. This brings us to the second reason [i.e., luminance contrast] why the RGB exhibit works so well.

Luminance contrast refers to the relation between the intensity of light of a brighter area and that of an adjacent darker area, as opposed to the absolute luminance values of each area (see, e.g., Singh 2000). Put it more simply, luminance contrast involves intensity of light *differences* between adjacent surfaces. In the RBG exhibit, the luminance contrast can be enhanced or diminished by combining each filtering light source with the mural's ink pigments. As a result, what color a figure appears to have for a trichromat will depend on which monochromatic light source is used to illuminate the mural. Akins (2015: 185) writes:

...for the trichromat, under a red illuminant, every thing that is visible appears in shades of red from bright red to red-black. But what is *visible* against a bright red wall? A magenta figure (e.g. the fox) will reflect a large percentage of red light. A red fox does not contrast with a red wall. The same holds true for all of the magenta figures. Paradoxically, under the red illuminant, figures rendered in



the *blue* ink will be the most visible. A blue figure reflects very little red light under any lighting conditions, hence it will now reflect very little light *at all*. The blue alligator thus appears as a *black* figure against a red wall. Finally, the yellow figures will now be entirely invisible. We are not told the spectral power distributions (SPD) of the coloured lights used in the exhibit. But suppose that the red light source contained some 'yellow' light and that the yellow pigment reflects a bit of red light in addition to yellow light. This lack of visual contrast would render the yellow figures invisible.

These two effects, spectral filtering and luminance contrast, "mirror two of the most important principles of vision" (Akins 2014: 185).

Firstly, as mentioned above, contrary to the common analogy, all photopigments, including rods, act like wavelength filters responding to light as a function of both wavelength and intensity. The reason rods can't discriminate between two objects that differ only in wavelength is not that the luminance system is for achromatic or 'black and white' (as opposed to color) vision but because our visual system has only *one* type of rods.

This follows from the *principle of invariance*: a single photoreceptor type (be it rods or cones) cannot compare signals. Imagine, for example, a tap that allows you to control the flow of water by flipping or rotating a lever. Such a tap allows you to increase the volume of water that flows through it, but it does not allow you to change its temperature. To change the water temperature, you need a tap that either has two levers each connected to a cold and a hot water line or a single lever connected to both a cold and a hot water line. Connecting the tap to a cold and a hot water line allows you to control both variables, namely the flow and the temperature of the water. The same principle of invariance applies to any single type of photoreceptor: you can increase or decrease its rate of firing but you can't make it compare signals. As Akins notes (2015: 185), without signal comparisons between two different types of photoreceptors, intensity cannot be distinguished from wavelength:

Two different pigments may produce profoundly different levels of excitation in response to one and the same reflected figure. In the evolution of any visual system, the type of photopigments/filters in place will have had a direct effect on visibility within the environment and hence on the species ability to *see* its predators, find sustenance, determine the fitness of mates and so on. (In fact it is hard to imagine many physiological facts that would play as important a role as photopigment sensitivity in the general fitness of a species.)

Secondly, what matters from the perspective of evolution is not color detection but visibility: “the primary concern of evolution in vision—i.e. what natural selection hinges upon—is *what the organism can see*, the *visibility* of relevant objects, not which objects reflect the greatest or least amount of light” (Akins 2014: 187). In other words, visibility does not require accurate representations of colors. What matters, from the point of view of our visual system, is the ability to parse objects from their backgrounds, which in turn requires the ability to register *luminance contrast* between figure and ground. As those with poor eyesight, like myself, know, wearing glasses doesn’t just improve visual acuity but also makes hues appear much brighter, which makes the world look that much more beautiful.

By exploiting spectral sensitivity and luminance contrast effects, the RGB exhibit illustrates the important role the collaboration between cones and rods play with respect to visibility. It also shows that the analogy between ‘black and white’ and ‘color’ is based on a mistaken analogy pertaining to the functions of the chromatic and luminance systems. The collaboration between cones and rods illustrate that the function of the visual system is to make objects visible to creatures like us. Visibility does not depend on color detection but on contrast.

If the function of the visual system is not to detect colors, then tracking theories cannot account for reliable color misrepresentation in terms of either optimality or design. To see this, suppose that there is a strawberry and a blueberry on the table in front of you. The strawberry systematically appears red and the blueberry systematically appears blue under varying circumstances not because the visual system tracks redness and blueness respectively in optimal conditions or conditions associated with natural selection, but by employing the mechanisms available to it (which mirror spectral

filtering and luminance contrast effects, and are thus distinct from color detection) to make them visible. During daylight the strawberry looks brighter than the blueberry; but, as the Purkinje shift illustrates, under conditions of dark adaptation, where the peak of visual sensitivity shifts towards shorter wavelengths, the strawberry looks less bright and thus less visible than the blueberry (Dowling, 1967; Cao et al, 2011). Any attempts to treat dark adaptation as a non-optimal condition of viewing or attribute it to flawed design would ignore the crucial role the collaboration between cones and rods plays in enabling our visual system to maximize visibility.

We have thus far established that the visual system uses principles that mirror spectral filtering and luminance contrast effects to enhance visibility, not through the detection of color but through contrast. It follows that the visual system reliability (not just occasionally) misrepresents the colors of objects. Tracking theorists may counter by acknowledging that the visual system is not tracking color properties while denying that this shows that the visual system reliably misrepresents. So long as the visual system registers color contrast accurately, they may argue, the visual system correctly represents the objects (even if it does not represent colors). As it turns out, they may claim, what matters for veridical color representation is not the accurate registration of color properties, but the registration of accurate color contrast. This line of reasoning, however, is problematic as Akins explains (Akins 2014: 187, emphasis added):

It does not matter whether, for this particular visual system, the object has positive or negative contrast with its background—or *whether the luminance contrast arises as a function of genuine intensity differences between the object and its background or because, while the figure and ground reflect the same intensity of light, the spectral sensitivity of the cones ‘creates’ luminance contrast given their difference in [their wavelength sensitivity].*

The function of the visual system is not to accurately recover genuine intensity or contrast. Contrast is ‘created’ by the visual system to enhance visibility.

One may object that all I have shown so far is that the visual system is not tracking color properties. But if the visual system is tracking some other property, e.g. changes in a scene’s spectral reflectance profile, tracking theorists may be able to hold on to the claim

that the visual system accurately represents the colors of objects by *indirectly* representing some other property of objects. In the next section, I provide an empirical explanation for reliable misrepresentation, which suggests that the visual system is not indirectly representing colors by representing some other properties of objects.

## **Section 5: Color misrepresentation**

So far we have seen that detecting colors is not a function of our visual system (or any biological system for that matter).<sup>6</sup> One of the main reasons the visual system has to rely on principles that mirror spectral filtering and luminance contrast effects is that the properties of light (e.g., illumination, luminance, reflectance, or any other property we may try to identify with color) that reach the retina from any source are conflated in the retinal image. This problem is known as the *inverse problem*. (The label ‘the disambiguation problem’ is also used in philosophy to highlight the fact that retinal stimulations are ambiguous.) For example, the same external stimulus can be seen as convex or concave depending on whether the visual system interprets it as being lit either from above or from below respectively (Stone 2011). Similarly, two spectrally identical targets can be seen as having different hues such as blue, yellow, or gray under different backgrounds depending on the contrast the visual system ‘creates’.

A wealth of psychophysical studies indicate that the inverse problem is not limited to luminance and color but extends to the contents of most of our mental representations of the world, including size, distance, depth and so forth (Stevens 1975; Rock 1984; Robinson 1998; Purves & Lotto 2003/2011; Yang & Purves 2004; Wojtach et al. 2008, 2009; Sung et al. 2009; Purves et al. 2014). Contrary to tracking theories, the current evidence suggests that such “differences between perception and reality cannot be dismissed as minor errors or approximations that are “close enough” to succeed, since the discrepancies are ubiquitous and often profound” (Purves et al. 2015: 156).

How does the visual system decide to treat a stimulus as, say, red or blue in relation to the circumstances of viewing? One of the most dominant empirical approaches to color vision uses Bayesian decision theory to formalize Helmholtz’s unconscious inferences

---

<sup>6</sup> An implication of this conclusion is that, contrary to color realists, tracking theories of mental representation cannot provide motivation for color realism.

which are thought to be used by the visual system to construct color representations (Maloney & Mamassian 2009; Brainard 2008; Maloney et al. 2002; Mamassian et al., 2002; Rao 2002). The guiding hypothesis of a Bayesian approach is that color representations can be understood as approximations to well-defined information processing tasks. Bayesian algorithms are then used to model color perception. For example, Marr's theory of vision provides a computational approach to Bayesian modeling, which aims to specify the likelihood function, i.e., the process by which scene parameters determine image data (Brainard 2008).

To see this let us suppose that we want to calculate the brightness of a stimulus. Bayesian modeling (as per Bayes' rule) requires that we first determine the probability distributions of surface reflectance and illumination values (known as the priors). These can be estimated by measurements in the environment. We then need to derive the probability of a specific luminance being generated by various surface reflectance and illumination intensities (this is known as the likelihood function). Multiplying these values (priors and likelihood function) gives us the (conditional) probability of a certain state of the environment given our observables (this product is known as the posterior probability). We then normalize these factors by dividing them by the luminance probability. The final step is to select particular reflectance and illumination values from a set according to an assumed gain-loss function. This step is necessary because the posterior distribution indicates only the relative probabilities of a set of possible sources. Brightness, on Bayesian modeling, is considered to be an estimate of surface reflectance. The outcome of these calculations will thus be a brightness representation that is expected to accord with the surface reflectance at the most likely combination of surface reflectance and illumination intensity values.

A major problem with the Bayesian approach is that biological visual systems cannot acquire the information that Bayesian modeling demands; that is why the visual system has to rely on principles that mirror spectral filtering and luminance contrast. The inherent ambiguity of external stimuli makes it impossible for a human ideal observer (where an ideal observer is a hypothetical device Bayesian modeling relies on) to predict what color (or any other light property) an object will appear to have because "Bayesian priors and likelihoods of reflectance, illumination or other physical variables

are not available to biological visual systems” (Purves et al. 2015: 4). As a result any modeling “based on recovering or estimating real-world parameters, statistically or otherwise, will fail as a canonical explanation of visual perception” (Purves et al. 2015: 4).

Our visual system must employ “a strategy that does not rely on real world properties as such” (Purves et al. 2015: 5). Since the visual system cannot recover or estimate color properties, it reliably misrepresents them. But how does our visual system manage to misrepresent *reliably* without (directly or indirectly) tracking any other properties of objects? For example, strawberries are consistently misrepresented as red, blueberries are consistently misrepresented as blue, and so forth. How does that happen if our visual system cannot rely on the detection or estimation of color (or any other) properties?

The empirical ranking theory provides an empirically supported explanation for reliable color misrepresentation. Through trial and error, our visual system learned to rely on the recurring scale-invariant patterns (which do not change if scales of length, energy, or other variables, are multiplied by a common factor, and thus represent a universality) to rank color (or any other such) experiences (Purves et al. 2015). The visual system learned to rank the frequency of occurrences of stimulus patterns to the frequency of occurrence of useful color experiences on the basis of survival and reproductive success. The visual system thus relied on a biological feedback loop, which progressively organizes “both ordinal (e.g., lighter-darker, larger-smaller) and non-ordinal (e.g., color, direction) visual qualities over useful ranges according to the relative frequency of pattern occurrences and feedback from behavior” (Purves et al. 2015: 5; see also Purves & Lotto, 2003/2011). This explains why the same stimulus, say, a yellow square may look yellow under one background but green under another.

The current psychophysical evidence indicate that our visual system utilizes the relative frequency of the occurrence of a given stimulus parameter (that is, any stimulus that can vary) in relation to all other instances of that parameter experienced in the past to promote useful behaviors (Purves et al., 2011; Wojtach, et al. 2008; Long et al., 2006; Yang & Purves, 2004; Sung et al., 2009). Specifically, studies show that the color representations do not correspond to light stimuli, including wavelength, intensity, or

surface spectral reflectance. Rather, they correspond to the relative frequency of the occurrence of these stimulus parameters in relation to a full range of intensity and wavelength values experienced in the past in that same context (Yang & Purves, 2004). Purves and his colleagues explain:

In general terms, understanding this strategy is straightforward. Imagine a population of primitive organisms whose behavior is dictated by rudimentary collections of photoreceptors and associated neural connections. As stipulated by neo-Darwinian theory, the organization of both the receptors and their connections in the population is subject to small random variations in structure and function that are acted on by natural selection. Based on interactions with the environment, variations of pre-neural and neural configurations that promote survival tend to be passed down to future generations. As a result, the ranks of visual qualities an agent perceives over some evolved range (darkest-lightest, largest-smallest, fastest-slowest, etc.) reflect biological utility rather than the physically measurable properties of objects and conditions in the world. In short, the role of perceptual states is not to reveal the physical world, but to promote useful behaviors. In this scheme, the world is simply the arena in which the utility of perceptions and other behavioral responses pertinent to survival and reproduction is tested, with feedback from the environment acting as the driving force that gradually instantiates the needed circuitry (Purves et al., 2015)

For any biological visual system, reliability comes apart from veridicality. Biological visual systems prize reliability over veridicality because they lack the ability to veridically estimate color (or any other) properties. The reliability comes from the ability of biological visual systems to “progressively organize both ordinal (e.g., lighter-darker, larger-smaller) and non-ordinal (e.g., color, direction) visual qualities over useful ranges according to the relative frequency of pattern occurrences and feedback from behavior” (Purves et al. 2015: 5; see also Purves et a. 2014). This indicates that reliability has as much biological utility as veridicality.

We are now in a position to answer the question posed earlier: How does our visual system manage to misrepresent *reliably* without (directly or indirectly) tracking any properties of objects? Color misrepresentations are reliable because they correspond to

the relative frequency of the occurrence of, say, a strawberry or a blueberry in a given context, in relation to all other instances of strawberries or blueberries experienced throughout our evolutionary history. This ensures that misrepresentations of color are reliable. Reliable misrepresentations thus have the same benefits (e.g., they promote useful behaviors) as veridical representations would have had if the visual system were able to track color properties. So long as our visual system reliably misrepresents objects as having stable colors, we can successfully navigate our environments. Contrary to Byrne and Hilbert (2020), then, it would certainly not “be an embarrassment if SSR detection was not *one* of the functions of colour vision.” Of course if we mistakenly assume that the visual system’s function is to accurately recover light properties, as tracking theories encourage us to do, then indeed we would not find any “obvious reason why selective pressure would have produced a system that could accurately recover” SSRs. What the evidence, however, indicates is two-fold. First, color vision cannot be correctly understood without a prior understanding of the crucial role the collaboration between cones and rods as well as context play in vision in solving the inverse problem. Second, biological visual systems face unique limitations. Since biological visual systems do not have the ability to estimate physical stimuli, they have to learn, through trial and error, to rely on the frequency of stimulus parameters in relation to all other instances of these parameters experienced in the past. It is thus easy to see why the visual system prizes reliability over veridicality.

## **Conclusion**

I have argued that the current evidence indicates that our color representations reliably misrepresent, which seriously undermines tracking theories of mental representation. One of the consequences of my argument is that tracking-theories of color representation fail to motivate color realism not only because they are unable to handle reliable misrepresentations but also because they tell the wrong story about the relation between color representations and their contents.

## **Acknowledgments**

Many thanks to the Trattenbach Lecture Series audience at the Institute of Philosophy, Czech Academy of Arts and Science, for helpful comments. I am especially grateful to



Tomaš Marvan and Juraj Hvorecky for reading drafts of this paper and offering invaluable feedback.

## References

- Akins, K. (2014) Black and White and Colour. In Richard Brown (ed.) *Consciousness Inside and Out: Phenomenology, Neuroscience and the Nature of Experience*. Dordrecht: Springer (pp.173-223).
- Bowmaker, J. K., Dartnall, J. A. (1980) Visual pigments of rods and cones in a human retina. *J. Physiol.* 298: 501-511.
- Byrne, A., D. Hilbert. (2003) Colour realism and colour science. *Behavioral and Brain Sciences*, 26: 3-64.
- Byrne, A. and Hilbert D. R. (2020) Objectivist Reductionism. In D. Brown and F. Macpherson (Eds.) *The Routledge Handbook of Philosophy of Colour*. London: Routledge.
- Brainard, D. H. (2004) Color constancy. In Leo M. Chalupa and John S. Werner *The Visual Neuroscience (Volume 2)*. Cambridge, MA: MIT Press.
- Brainard, D. H. (2009). Bayesian approaches to color vision. In Gazzaniga, M. S. (Ed.) *The Cognitive Neurosciences*, Fourth Edition. Cambridge (MA): MIT Press, pp. 395-408.
- Brown, D. (2006) On the dual referent approach to colour theory. *Philosophical Quarterly*, 56: 96-113.
- Cao, D., Pokorny, J., Grassi, M. A. (2011) Isolated mesopic rod and cone electroretinograms realized with a four-primary method. *Documenta Ophthalmologica Advances in Ophthalmology* 123(1): 29–41.
- Chirimuuta, M. (2015) *Outside Colour: Perceptual Science and the Puzzle of Colour in Philosophy*. MIT Press.
- Cohen, J. (2009) *The Red and the Real*. New York: Oxford University Press.
- Dowling, J. (1967) The site of visual adaptation. *Science*, 155 : 273-279.
- Dretske, E. (1981) *Knowledge and the flow of information*. Cambridge, MA: MIT Press.
- Dretske, E. (1986) *Misrepresentation*. Oxford: Blackwell.
- Dretske, E. (1995) *Naturalizing the mind*. Cambridge, MA: MIT Press.
- Fodor, J. (1987) Meaning and the World Order. In *Psychosemantics* (pp. 97-133). Cambridge Mass.: MIT Press. A Bradford Book.
- Fodor, J. A. (1992) *A theory of Content and other essays*. Cambridge, MA: MIT Press.
- Heinze, S. (2014) Polarization Vision. In Dieter Jaeger and Ranu Jung (Eds) *Encyclopedia of Computational Neuroscience*. Springer, New York, NY. [https://doi.org/10.1007/978-1-4614-7320-6\\_334-5](https://doi.org/10.1007/978-1-4614-7320-6_334-5).
- Howe, C. Q., and Purves, D. (2005). *Perceiving Geometry: Geometrical Illusions Explained by Natural Scene Statistics*. New York: Springer Press.

- Howe, C. Q., Lotto, B. R., Purves, D. (2006) Comparison of Bayesian and empirical ranking approach to visual perception. *Journal of Theoretical Biology* 241: 866-875.
- Howe, C. Q., and Purves, D. (2002) Range image statistics can explain the anomalous perception of length, *Proceedings of the National Academy of Sciences of the United States of America* 99(20): 13184–13188.
- Johnston, M. (1992) How to Speak of the Colors. *Philosophical Studies* 68(3): 221-263.
- Land, E H. (1977) The Retinex Theory of Color Vision, *Scientific American*, 237(6): 108-128.
- Levin, J. (2000) Dispositional theories of color and the claims of common sense. *Philosophical Studies* 100 (2):151-174.
- Long et al., 2006 Long, F., Yang, Z., and Purves, D. (2006). Spectral statistics in natural scenes predict hue, saturation and brightness. *Proc. Natl. Acad. Sci. U S A* 103: 6013–6018. doi: 10.1073/pnas.0600890103
- Lotto, B. R. and Purves, D. (2000) The empirical explanation of color contrast. *Proceedings of the National Academy of Sciences, USA* 97(23): 12834-12839.
- Marshall, J., Oberwinkler, J. (1999) The colourful world of the mantis shrimp. *Nature* , 401(6756): 873-874.
- Mendelovici, A. (2013) Reliable misrepresentation and tracking theories of mental representation. *Philosophical Studies* 165 (2): 421-443.
- Mendelovici, A. (2016) Why tracking theories should allow for clean cases of reliable misrepresentation. *Disputatio* 8(42): 57-92.
- Millikan, R. G. (1984) *Language, thought and other biological categories*. Cambridge, MA: MIT Press.
- Maloney, L., and Mamassian, P. (2009) Bayesian Decision Theory as a Model of Human Visual Perception: Testing Bayesian Transfer, *Visual Neuroscience* 2009: 147-155.
- Maloney, L., and Mamassian, P. (2009) Bayesian Decision Theory as a Model of Human Visual Perception: Testing Bayesian Transfer, *Visual Neuroscience* 2009: 147-155.
- Mamassian, P., Landy, M., and Maloney, L. (2002) Bayesian Modeling of Visual Perception, in *Probabilistic Models of the Brain*, eds. R. Rao, B. Olshausen, and M. Lewicki. Cambridge, MA: MIT Press.
- Pautz, A. (2021) *Perception*. New York: Routledge.
- Purkinje, J. E., Kruta, V. (1823/1969) *Physiologist: A short account of his contributions to the progress of physiology, with a bibliography of his work*. (Trans. Vladislav Kruta, pp. 75–131). Prague: Academia, Publishing House of the Czechoslovak Academy of Sciences.
- Purves, D., Morgenstern, Y. and Wojtach, W. T. (2015) Perception and Reality: Why a Wholly Empirical Paradigm is Needed to Understand Vision. *Front. Syst. Neurosci.* 9:156. doi: 10.3389/fnsys.2015.00156
- Purves, D., Monson, B. B., Sundararajan, J., and Wojtach, W. T. (2014). How biological vision succeeds in the physical world. *Proc. Natl. Acad. Sci. U S A* 111: 4750–4755. doi: 10.1073/pnas.1311309111

- Purves, D., and Lotto, R. B. (2003/2011). *Why We See What We Do Redux: A Wholly Empirical Theory of Vision*. Sunderland, MA: Sinauer Associates.
- Purves D., Wojtach W. T., Lotto R. B. (2011) Understanding vision in wholly empirical terms. *Proc Natl Acad Sci*. doi:10.1073/pnas.1012178108.
- Rao, R. P.N., Olshausen, B. A., Lewicki, M. S. (Eds.) 2002. *Probabilistic Models of the Brain: Perception and Neural Function*. The MIT Press, Cambridge, MA.
- Robinson, 1998; Robinson, J. O. (1998). *The Psychology of Visual Illusions*. New York: Dover
- Rock, 1984; Rock, I. (1984). *Perception*. New York: MacMillan.
- Stone, J. 2011. Footprints Sticking Out of the Sand, Part 2: Children's Bayesian Priors for Shape and Lighting Direction. *Perception* 40: 175-190.
- Singh, R-N. P. (2000) An intelligent approach to positive target identification, In Naresh K. Sinha and Maden M. Gupta, *Academic Press Series in Engineering, Soft Computing and Intelligent Systems Theory and Applications* (pp. 549-570). New York: Academic Press.
- Stevens, 1975; Stevens, S. S. (1975). *Psychophysics*. New York: John Wiley.
- Sung et al., 2009; Sung, K., Wojtach, W. T., and Purves, D. (2009). An empirical explanation of aperture effects. *Proc. Natl. Acad. Sci. U S A* 106: 298–303. doi: 10.1073/pnas.0811702106
- Tye, M. (2000) *Consciousness, Color, and Content*. Cambridge (MA): MIT Press.
- Wojtach, W. T., Sung, K., and Purves, D. (2009). An empirical explanation of the speed-distance effect. *PLoS One* 4:e6771. doi: 10.1371/journal.pone.0006771
- Wojtach, W. T., Sung, K., Truong, S., and Purves, D. (2008). An empirical explanation of the flash-lag effect. *Proc. Natl. Acad. Sci. USA* 105: 16338–16343. doi: 10.1073/pnas.0808916105
- Yang, Z., and Purves, D. (2004). The statistical structure of natural light patterns determines perceived light intensity. *Proc. Natl. Acad. Sci. U S A* 101: 8745–8750. doi: 10.1073/pnas.0402192101