Chapter XXX

The Unique Hues and Phenomenal Structure

1. Phenomenal Structure and the Color Realism Debate

The structure of phenomenal color has posed a major challenge to physicalist treatments of color.

Perceived color is thought to essentially have certain structural features, such as:

- the hues stand in similarity relations to one another (e.g., lime green is more similar to teal than it is to magenta);

- exactly four hues (red, green, blue, and yellow) admit of "unique" variants which are perceived as purely consisting of the hue in question;

- all non-unique hues are perceived as weighted binary combinations of unique hues (e.g., all purples are some mixture of red and blue);

- some binary hue combinations are permissible (e.g., red and yellow) while others are prohibited (e.g., red and green).

Eliminativists argue that no physical property of objects causally relevant to color experience corresponds to these essential features and thus colors cannot be physical properties of objects (Hardin 1988, p.66 and 2003, p.198). For a sense of how much weight is given to the objection from phenomenal structure and the key role of the unique hues in driving the objection, Hardin (1992, p.371) claims that the absence of physical counterparts for the unique hues is the "central reason" to reject color physicalism.

Some physicalists have attempted to physically ground all of the structural features just listed. For example, Byrne & Hilbert (2003a, p.7) state that a physicalist theory that fails to encompass the essential facts of phenomenal structure is not "a satisfactory theory of color at

all." Their "hue magnitude" proposal is intended to accommodate those facts and is built around the unique hues. Others have countered the objection by arguing that the absence of a physical basis for some prominent structural features, such as the unique/binary distinction, is not troublesome; e.g., Churchland (2007, p.140) dismisses such features as extra-representational structure that stems from opponent processes in the human visual system. I believe neither approach is appropriate, as I find the received thinking about unique hues to be deeply flawed in a way that undermines this whole line of argument against physicalism.[1] This chapter argues that the four canonical unique hues are not nearly as special as they are claimed to be and that they do not have the fundamental, organizing role in color experience routinely accorded to them. Once the unique hues have been de-fanged, certain correspondences between representations of phenomenal resemblance relations and of similarity relations amongst surface spectral reflectances increase in their potential significance and are worth exploring further as part of a realist approach to color. While I am not a color physicalist, this result is favorable for my objectively oriented color realism; this will be taken up further in later chapters. In addition to bearing on philosophical arguments about color, this chapter's negative verdict regarding the unique hues has consequences for empirical research on color perception and color language.

---

[1] There are some similarities between Churchland's claim about extra-representational structure and the view developed in this chapter; viz., that the unique/binary distinction is not essential to color. However, one of my main targets is the standard understanding of the unique/binary distinction that Churchland accepts and chalks up as extra-representational structure. I am also calling into question the idea that the uniqueness of the unique hues is grounded in opponent-processing in anything like the way that Churchland has in mind.

2. The Orthodoxy

According to Hering's (1920/1964) highly influential conception of the hues, red, green, blue, and yellow have a special status as <u>primary</u> hues. They are supposed to be psychologically basic elements out of which all hue sensations are constructed. They are also hypothesized to be arranged along two independent axes, red/green and blue/yellow, with an achromatic neutral point at the origin. This opponent structure is taken to explain phenomenological observations of the sort noted above, as it allows for <u>unique</u> percepts of each primary and <u>binary</u> combinations of primaries not on the same axis. It also accounts for the exclusion and similarity relations found amongst the hues; e.g., there are no reddish greens because red and green lie at opposite ends of a shared axis, lime is more similar to teal than it is to magenta because it shares greenness with teal, but lacks any shared primaries with magenta. Phenomenal purity is the standard for being a unique hue. For example, while most greens look either bluish or yellowish, unique green is perceived as having no trace of either blue or yellow in it. By contrast, orange is a binary hue, always appearing to be some mix of red and yellow.

The apparent purity of the unique hues goes hand-in-hand with their perceptual salience and the privileged status of the Hering primaries as elemental hue sensations. One way of connecting the purity of the unique hues with their role as psychological primaries is to consider just how natural it is to describe teal as a combination of blue and green while noting that it is "virtually impossible" to grasp how a particular hue might be said to appear to contain amounts of both chartreuse and teal (Abramov & Gordon 1994, p.468). As for binary hues, it is important to emphasize that they are made out to <u>look</u> to contain proportions of their component primaries and to not be perceived as unanalyzable, integral wholes formed from the primaries. Empirical findings on hue cancellation and hue scaling fit with the preceding phenomenological

3

observations and Hering's opponent colors theory; see Hurvich & Jameson (1957) and Abramov & Gordon (2005). To illustrate, subjects in hue scaling experiments can produce judgments about hue content for all hue stimuli using only the Hering primaries. Subjects' hue content judgments total to 100% using either permissible binary combinations for non-unique hues or a single Hering primary for unique hues. As was just noted, the binary hues look to be completely unsuitable for use in such a task. Moreover, given the subjective purity of, say, unique yellow, judging what proportions of chartreuse and orange (or red and green, for that matter) appear to be in it seems to be a hopeless exercise; see Palmer (1999, p.109).

While there is no a priori reason to think this must be the case, it is routinely believed (or hoped) that the psychological Hering opponent hue axes have a direct neurophysiological realization. Hering himself held such a view, although importantly different in detail than the picture that has emerged over the last one hundred years. It is risky to read neurophysiology off of phenomenology, but the apparent purity, perceptual salience, and elemental status of the unique hues make it natural to suppose that they must have some correspondingly distinctive neural representation. A familiar idea is that there are separate, independently operating red/green and blue/yellow neural "systems" or "channels", the combined outputs of which account for all hue appearance. For instance, unique green is triggered when the blue/yellow system is nulled and the red/green system indicates green, while purple is experienced when the red/green and blue/yellow systems point toward red and blue, respectively. Inspired by Hurvich & Jameson's work, Hardin (1988, pp.29-30) links phenomenology and neural processing:

> The phenomenal characters of purple and yellow thus reflect their neural representations. The phenomenally complex color purple is represented by the joint occurrence of red and blue processes, and the phenomenally simple color yellow is represented by a

noncomposite yellow process, the red and green processes in this case being in neutral balance.

Averill (2005, pp.224-226) develops an anti-physicalist view based, in part, on the claim that vision science has shown that unique hue experiences are correlated with opponent cell activity. Amongst physicalists, Byrne & Hilbert (2003a, pp.14-15) appeal to the operation of mechanisms tied to the Hering primaries and (tentatively, at least; see their 2003b, p.55) connect those mechanisms with neural opponent processing, to flesh out their "hue magnitude" proposal for dealing with the objection from phenomenal structure.

A direct neurophysiological correspondence for the subjective purity of and opponent relations amongst the unique hues would make for a tidy arrangement. Such a clear neural basis would also lend credence to the strong claims about the significance of the unique hues. However natural the Hering opponent colors framework might seem now, it was the subject of much controversy for quite some time. The resistance to Hering's theory largely stemmed from (i) its seeming biological implausibility (it appeared to require four, not three, types of chromatic receptor), (ii) the competing Young-Helmholtz trichromatic theory's appeal to those oriented along the lines of physics, (iii) Helmholtz's disciples' dominance of the field of psychophysics, and (iv) the subjective basis of Hering's main claims; see Crone (1999, pp.199-200), Hardin (1988, p.30), and Ladd-Franklin (1929/1973, pp.158-164). By the middle of the twentieth century, though, Hering's theory was thought "the most likely description of color processes in the optic nerve and cortex" (Judd 1951, p.836), despite lacking empirical support. Hurvich & Jameson's (1957) psychophysical research supplied a much-needed boost. Their hue cancellation experiments provided a quantitative grounding for claims about opponent relations amongst the Hering primaries. Further support came from neuroscientific work that found opponent-

processing cells in the primate lateral geniculate nucleus (LGN) (De Valois et al 1964). At first

glance, it appears that we have achieved the highly desirable co-incidence of phenomenology,

psychology, and neuroscience. Moreover, certain patterns in color terms across human languages

are claimed to be explained by the Hering primaries being so important to the structure of

perceived color and rooted in features of visual processing shared by all humans; see Cook et al

(2005), Hardin (2005), Kuehni (2005), and Regier et al (2005).

Unfortunately, the situation is complicated by discordant empirical findings, such as that

the response functions of the opponent cells discovered at early stages of neural processing do

not align with the Hering primaries; see Abramov & Gordon (2005), Jameson & D'Andrade

(1997), MacLeod (2010), Malkoc, Kay, & Webster (2005), Wool et al (2015). What little

evidence there is for a higher-level "neural signature" for the unique hues either has been

disputed on methodological grounds and is hard to square with other relevant findings (see

Stoughton & Conway 2008, Mollon 2009, Conway & Stoughton 2009, Conway & Tsao 2009,

Arstila 2017, pp.16-17) or is at best neutral when it comes to their allegedly privileged status

(Forder et al 2017). [2] It should be stressed that the lack of a neurophysiological underpinning for

---

[2] To be clear, I am not questioning that Forder et al (2017) have found a strong neural marker of

the unique hues. I am only pointing out that their discovery by itself does not support the

mainstream view that the unique hues play a fundamental, organizing role in the structure of

phenomenal color. As Forder et al note (ibid., p.4), the neural signature they identify occurs as

part of the P2 event-related potential (ERP) component that reflects post-perceptual,

visuocognitive processes. They found no evidence of a neural marker of the unique hues in

earlier, visual ERP components. Forder et al are quite clear that the marker found in the P2

the unique hues does not by itself blunt the objection from phenomenal structure. <u>Prima facie</u>, its main effect would be to make things worse for the physicalist, as Byrne & Hilbert's hue magnitude proposal (the leading physicalist response to the objection) seems to be a complete nonstarter without some sort of concurrence with known features of visual processing; see Jakab & McLaughlin (2003, p.34), Wright (2010, p.29). However, the Hering theory's poor fit with neural opponent processing points toward deeper problems with the unique hue construct and its employment in philosophical debates about color. Further inspection reveals that the psychophysical and phenomenological support for the standard account of the unique hues is weak, at best, and that there is a compelling case for rejecting many of the key claims that have been made about the significance of the unique hues.

Before proceeding, I want to address the issue of phenomenology. My argument does not at all rest on this point, but I find it suggestive and it prompted my interest in this topic. The philosophical and scientific literatures contain a wealth of claims about the unique/binary distinction, such as "[there] are no purples that do not look to have some red and some blue in

---

component is neutral with respect to the thesis that the unique hues have a perceptual salience that is "hardwired" into the human visual system (<u>ibid.</u>, p.5). The authors cite several extant challenges to the hardwired perceptual salience hypothesis, including studies discussed in this chapter; note that one of the co-authors of Forder et al, Jenny Bosten, is a co-author of two of the articles I draw on. They go on to propose that, with their finding in hand, further work can be done to disentangle the various factors – e.g., social, environmental, neural – that potentially shape the significance of the unique hues. The arguments of this chapter are relevant to what direction that future research might take.

them" (Broackes 2011, p.602), "purple … is hardly unique" (Logvinenko 2012, p.110), and "[we] clearly discern in orange hues a yellowish and a reddish component" (Kuehni 2004, p.158). My own experience disagrees with such pronouncements. I can find orange and purple chips in the Munsell Book of Color (1976) that appear to me every bit as basic in hue as any unique Hering primary; I have normal color vision by the usual tests and was born and raised in the United States. I do not detect any redness or yellowness (/redness or blueness) in them, but find only certain similarities to red and yellow (/red and blue), in the same way that I find similarities between blue and green. I draw some comfort in not being completely alone on this score. Koenderink (2011, p.579) claims that he does not sense red and blue elements in "pure" purple and he maintains that cyan also has a "pure" variant. Ocelak (2014), in a paper with aims similar to those of the present chapter (although with different points of emphasis), makes remarks that suggest at least partial agreement with my phenomenological observations. It is also worth noting that there are commercially manufactured paints with names like "Pure Purple" and "Pure Orange." Wool et al (2015, p.8) observe that it is just as apt to say that there are no orangish teals as it is to say that there are no reddish greens. While it is true that these considerations merely concern phenomenological introspection and everyday language use, it should also be recognized that the empirical difficulties encountered by the Hering opponent colors framework reduce its source of support to subjective claims such as that red, green, blue, and yellow are alone in admitting of pure variants. Even those phenomenological observations are imperiled by some of the research examined herein.

3. Hue Cancellation

Hurvich & Jameson's hue cancellation studies are celebrated as providing the empirical basis the Hering framework needed to move beyond the impression that it was phenomenologically persuasive but scientifically suspect; see Hurvich & Jameson (1957) and Hurvich (1981). These studies continue to be held up as yielding quantitative findings that reveal a crucial fact about the structure of experienced color. Wandell (1995, p. 322) describes them as measuring "the psychological organization of opponent-colors." Palmer (1999, pp.110-111) presents Hurvich & Jameson's cancellation studies as offering "quantitative measurements of the opponent structure of color experiences." Kuehni (2013, p.209) characterizes Jameson & Hurvich's hue cancellation experiments as lending "strong support" to the Hering opponent colors framework. As noted earlier, Hardin (1988) relies heavily on Hurvich & Jameson's work in developing his case for color eliminativism based on phenomenal structure. Aside from Hardin, other philosophers – including many opposed to eliminativism – approvingly discuss or cite Hurvich & Jameson's cancellation studies and the backing for opponent phenomenal structure drawn from them; e.g., Byrne & Hilbert (2003, pp.14-15), Matthen (2005, p.175), Thompson (1995, pp.68-69).

Jameson & Hurvich's cancellation method turns on the idea that the Hering primary hues and their opponent relations are grounded in neural mechanisms that "correlate directly with perception" (Hurvich 1981, p.66); see also Valberg (2001, pp.1648-1649). This would allow Hurvich & Jameson to determine the response functions of the hypothesized underlying red/green and blue/yellow systems using subjective judgments about the effects of physically mixing stimuli that evoke opposing hues; viz., by nulling activity in one of the systems through such physical mixing (Hurvich & Jameson 1957, p.389). Hurvich & Jameson (1955, p.549) first had subjects determine their unique hue settings using spectral lights. Subjects were then

presented with a series of spectral lights that appeared, say, yellowish (yellowish green through unique yellow through yellowish red). They were able to control the amount of the opposing hue (unique blue, in this case) that was added to the presented stimulus, with the task being "to cancel the yellow hue without introducing any blueness" (Hurvich & Jameson 1957, p.389). The effect of this is to place the blue/yellow opponent system in equilibrium, leaving a percept that is either neutral, red, or green. Since they knew the amount of energy in both the yellowish stimulus and the unique blue light that was added to cancel it, Hurvich & Jameson were able to determine the strength of the "yellow hue response" across the range of wavelengths tested. This procedure can be adapted to also determine the strength of chromatic response throughout the spectrum for green, blue, and red. The result is a set of curves representing the red/green and blue/yellow chromatic response functions for the subject (see Hurvich 1981, p.67, fig.1) and average response functions across perceivers can be produced.

The fact that unique red is extra-spectral introduces a small wrinkle to this story. Even at 700 nm, most observers detect a yellowish aspect to the red that is perceived. An opposing unique blue (or reddish blue, as will be evident momentarily) stimulus would have to be added to cancel the yellowish component so that unique red is perceived. Consequently, we lack a red spectral stimulus that could be used to cancel greenishness. As Hurvich (1981, p.59n) explains, this is no real problem, as a 700 nm stimulus can be used to cancel greenishness:[3]

---

[3] Note also that there is no issue whatsoever for either using the unique green spectral stimulus to null the reddish component encountered at long and short wavelengths or using non-spectral unique red stimuli in other experimental settings.

The observer's task is to produce a field that looks neither red nor green. The yellow associated with the 700 nm stimulus is simply part of the 'remainder' perceived when red and green are balanced. It is, in fact, not necessary to use unique stimuli to obtain any of the chromatic response functions.

The hue cancellation method in general requires that subjects have a grasp of the hues they are being asked to cancel, in terms of what it means both for a given hue to be present or absent and for a given opponent pair to be nulled with a "remainder" perceived; Logvinenko & Beattie (2011, p.1) make a similar observation. Assuming that subjects have a grasp of those things, there is a clear rationale for using a 700 nm stimulus to measure the green chromatic response.

As influential as Hurvich & Jameson's work has been, it does not provide the strong support for the Hering opponent colors framework typically claimed for it. It certainly cannot supply the foundation for a decisive case for a position regarding the metaphysics of color. First, as noted earlier, there is no neuroscientific evidence of mechanisms that align with Hurvich & Jameson's psychophysical results. Surprisingly, psychophysical research has also failed to produce results that mark out the Hering primary hues as special in several of the ways one would expect. Some psychophysical issues will be addressed in a subsequent section. For now, I will focus on a methodological concern and a failed empirical prediction regarding the perceptual effects of nulling the hypothesized opponent hue mechanisms. The latter has been already discussed in the literature (viz., Jameson & D'Andrade 1997) but is worth revisiting in the current context. The significance of the former seems not to have been fully appreciated, at least within the philosophical literature on color; Arstila (2017) is an exception.

Hurvich & Jameson's hue cancellation studies did not reveal that the unique Hering primaries stand out in some way in a body of data collected for a wide range of hues. Rather,

their entire approach begins by focusing on the Hering primaries. While stimuli with non-unique hues can be (and were) used, the task instructions are given in terms of cancelling the Hering primaries perceived in the stimuli. A different set of task instructions employing alternative hue terms – say, teal, chartreuse, orange, and purple – could be used instead. Logvinenko & Beattie (2011, p.1) state:

> [The] hue cancellation procedure can, in principle, be readily applied with any (not necessarily unique) hue. As pointed out by Indow (1987 [p.254]), canceling, say, an orange hue is no more difficult than canceling yellow or red. Therefore, there is no guarantee that in a hue cancellation experiment observers cancel unique hues rather than some other hues.

Given the citation of the 1987 paper by Indow, one might think that the methodological issue I am raising here has long been recognized (and perhaps dealt with), at least by scientists and maybe by some philosophers. However, my review of the literature does not show it – and any potential trouble it might cause – to have been discussed at any length. As suggested by the continued reliance on Hurvich & Jameson's hue cancellation studies by prominent scientists and philosophers noted at the opening of this section, if it has been recognized, this point certainly has done nothing to reduce the significance attached to the results of those studies.

While it might seem more natural to use the Hering primaries instead of a set of "intermediate" hues, that naturalness is undeniably phenomenological. Consider the following passage from Abramov & Gordon (1994, p.468):

> Stemming from Hering's original work, the accepted bipolar hue axes are RG and YB ….. But are these the necessary axes? …. The spectral functions of the RG and YB mechanisms obtained from hue cancellation are approximately the same as those from

hue scaling …. However, there is no a priori justification for these precise axes; the axes might be chartreuse-violet and teal-cherry, which are approximately the hues to which the LGN cardinal axes point. Introspectively, however, we find it virtually impossible to think of canceling or scaling all hues in these terms and ultimately this is the principal justification for using RG and YB as the axes.

Broackes (1997) expresses similar sentiments. As just noted, however, subjects can cancel hues other than the Hering primaries and thus chromatic response functions could be produced for "mechanisms" other than red/green and blue/yellow. In the next section, I will discuss research in which subjects were able to perform the "virtually impossible" when it comes to hue scaling. For now, recall that Hurvich & Jameson's hue cancellation studies were thought to give Hering's theory the firm quantitative footing it sorely needed to gain respectability in the face of objections regarding its subjective nature. Given that (i) there is nothing restricting us to using red/green and blue/yellow chromatic response functions derived from hue cancellation experiments and (ii) there are ongoing difficulties with finding psychophysical and neuroscientific evidence that marks out the Hering primaries as having a privileged status, it is reasonable to conclude that the appeal of the Hering theory remains rooted in introspection. The hue cancellation results simply do not provide a quantitative basis for the Hering opponent colors framework that is independent of an appeal to phenomenology. The chartreuse/violet and cherry/teal axes mentioned by Abramov & Gordon have a much better empirical claim to a fundamental role in the structure of color, as they agree not only with LGN opponent cell profiles but also with psychophysical findings.

Jameson & D'Andrade (1997) offered a critique of the received view of the Hering primary hues, noting several empirical difficulties it encounters. In many respects, my arguments

in this chapter are a continuation of their critique. One of the issues they emphasize, which they describe as a "serious problem" with standard opponent process theory (ibid., p.305), is that the unique hues are not additive complements to one another; lights that are additive complements produce an achromatic percept when mixed in the appropriate proportions. Jameson & D'Andrade walk through a proof of a theorem which follows from basic assumptions of the received view and note its empirical failure, focusing on the implications of opponent process theory for mixtures of lights that, when viewed individually, have a unique hue appearance. For a unique hue to be perceived, one of the hue mechanisms is balanced while the other points to the hue in question (see Indow 1987, p.259). If both chromatic systems are nulled by a light stimulus, a unique white percept results (this is in the simple case of viewing light spots in dark surrounds). If a unique red stimulus is mixed with a unique green stimulus of an appropriate strength, they cancel each other, resulting in equilibrium in the red/green system. Since both stimuli being added together have balanced blue/yellow activity (as required by their unique green and unique red appearances) and their mixture nulls the red/green system, the theory predicts that the percept should be achromatic (viz., unique white). This reasoning follows Jameson & Hurvich's (1955, p.548) own logic for cancelling unique yellow with unique blue: "For a yellow spectral stimulus that is unique or pure the observer's end point [of cancelling with unique blue] is a neutral colorless sensation."

In fact, cancelling opposed unique hues tends to not lead to an achromatic percept (Kuehni & Schwarz 2008, p. 106). All mixtures of unique red and unique green that are neutral between those two hues have a yellowish appearance. The additive complements for unique red and unique green are a bluish green and magenta, respectively (see, for example, Dimmick & Hubbard 1939b, p.352). There is also evidence that unique blue and unique yellow are not

14

complementary (see Dimmick & Hubbard 1939a, p.254; Bosten & Lawrence-Owen 2014, p.A362, tab.4; Wool et al 2015, p.2), although they conform much better to the prediction of opponent colors theory (Kuehni 2013, p.46). Artists have traditionally held that "blue is the complementary of orange, yellow is the complementary of violet" (quote from Eugene Delacroix in a letter from Vincent Van Gogh to Theo Van Gogh, cited by Wool et al 2015, p.2).[4] With respect to finding a neural counterpart to the psychological structure of the Hering opponent colors framework, the failure of opposed unique hues to be additive complements makes any such effort seem unlikely to succeed (see Burns et al 1984, p.487). While results regarding perceptual responses to physical mixtures of stimuli cannot be conclusive about the structure of psychological color without strong linking propositions, the fact that what looks to be a "direct path" from unique red to unique green passes through yellow raises the possibility that color experience is not organized around the independent red/green, blue/yellow axes of the Hering theory. Recall that such linking propositions play a fundamental role in Hurvich & Jameson's hue cancellation experiments and the conclusions about the opponent structure of perceived color drawn from them. As will be discussed later, both the empirically determined complementary relations and judgments about the perceived similarity of hues fit well with the organization of the hue plane in the Munsell system, which includes importantly different structural features.

---

[4] See also Bruce MacEvoy's artist's color wheel and discussion of visual complements at https://www.handprint.com/HP/WCL/color16.html.

4. Hue scaling

Hue scaling studies provide the other major source of empirical support for the significance of the unique hues and the validity of the Hering opponent colors framework. This line of research originates with a method introduced by Jameson & Hurvich (1959). In these experiments, subjects are tasked with judging how much of each primary hue is perceptually present in stimuli. For example, Gordon & Abramov (1988, p.147) had subjects report the percentages of red, green, blue, and yellow perceived in monochromatic lights viewed against a dark background. They told their subjects that the percentages should add up to 100% and they did not forbid subjects from using any combination of primaries. Scaling functions for each primary hue at each wavelength can be constructed based on subject responses. Besides alignment between the scaling functions and the chromatic response functions derived from hue cancellation data when it comes to the locations of unique hues and "balanced" intermediaries, the scaling functions showed little overlap between opposed primaries. The "forbidden" incursions are plausibly chalked up to the "mottled" appearance of some stimuli due to irregularities in subjects' visual systems (Gordon & Abramov 1988, p.148). Hue scaling results are taken to bolster the case for the unique hues playing a fundamental, organizing role in perceived color, whatever difficulties there might be in finding a direct neural realization for them and that role.

Following the lead of hue cancellation research, hue scaling studies target the Hering primaries from the very start, as the primaries the subjects are given to scale are red, green, blue, and yellow. The reason for this was straightforwardly stated earlier by Abramov & Gordon: it seems impossible to scale all hues using primaries such as orange and purple. The natural expectation is that if subjects were given the task of scaling the amounts of, say, orange and

purple in unique red, they would not be able to account for the entire hue content of their percept; i.e., their ratings would not sum to 100%. In fact, it seems likely that the scaling function for each intermediate primary would be at zero for the unique hues. The intuitively compelling nature of this sort of thinking is evident in Broackes' (1997, p.184) commentary on Saunders & van Brakel's (1997) attack on the significance of the unique hues:

> The fears of Saunders & van Brakel will be justified if people prove to do as well with lime, purple, orange, and teal as we do with red, yellow, green, and blue. But we should not underestimate the fact that such an outcome at the moment seems almost unimaginable.

Jameson (2010, pp.190-194) argued that empirical findings that seem to support the privileged status of the Hering primaries could very well be an artifact of the task instructions that are used. She contends that it is plausible that a small change to those instructions would lead subjects to find hues such as "balanced orange" and "balanced teal" to be just as salient as the unique Hering primaries. One possible response to this suggestion is that even if the balanced intermediate hues were to turn out to be highly salient, the Hering primaries have a role in structuring color experience that could not plausibly be usurped by the intermediate hues. Following Abramov & Gordon, the seeming impossibility of finding a certain amount of orange to be contained in unique red, and the ease of finding redness in balanced orange, makes it evident that the Hering primaries form cardinal axes for perceptual color space. As was the case with hue cancellation, however, it turns out that subjects in hue scaling experiments can do what has been frequently said to be impossible and neglected from experimental study on such grounds. This shared methodological flaw vitiates what had been considered the strongest body of empirical support for the Hering framework.

Bosten & Boehm (2014) conducted a hue scaling experiment in which half their subjects used the standard four Hering primaries and the other half used a set of intermediate primaries (lime, teal, purple, orange). Both groups were presented the same stimuli, which comprised thirty-six equally spaced locations on a circle in chromaticity space centered on an achromatic point. For both groups, each subject was instructed to rate "how much of [the primaries] your subjective experience of that color contains" (ibid., p.A387). Subjects used a scale from 0 to 9 for each primary and, crucially, were told that their ratings did not have to sum to any particular number and that they were free to assign a rating of 0 to all four primaries if they thought that was appropriate. The obvious prediction for the results was described above: subjects using the Hering primaries should produce ratings that result in functions in line with those of standard hue scaling experiments, while subjects using intermediate primaries should produce functions that peak at the associated hue (e.g., balanced orange) and quickly taper off on both sides to zero at the unique hues (ibid., p.A386, fig.1).

Contrary to intuitive expectations, the functions derived for the intermediate hues strongly resemble those of the unique hues, simply translated along the x-axis (which represents hue angle). Mimicking the behavior of the scaling functions for the Hering primaries, the curves for the intermediate primaries peak at the associated hues and cross-overs between neighboring primaries occur around the unique hues (ibid., p.A387, fig.3). For example, the orange function peaks at the location of the orange primary, the other three intermediate primaries are near zero at that point, and the orange and lime functions meet (at ratings in the middle of the scale) very close to the point at which the yellow function peaks in the condition that used the standard primaries.

Bosten & Boehm's results not only meet Broackes' challenge and block the use of hue scaling studies to prop up the special status of the Hering primaries, they also call into question phenomenological claims about red, green, blue, and yellow admitting of pure variants and being alone in that regard. On one reading of what their intermediate condition subjects were doing, subjects were just as successful at finding the intermediate hues "in" the Hering primaries as the other way around. In that case, the unique hues do not have the subjective purity routinely claimed for them. In support of this interpretation, recall that Bosten & Boehm explicitly instructed subjects in both conditions that they were to base their ratings on the amount of the intermediate primaries their "subjective experience … contains" and told them that they were free to assign zero ratings for all four intermediate primaries if they felt that was appropriate. Thus there is a prima facie case for taking the intermediate condition results as showing that the subjects saw, for example, unique yellow as containing balanced amounts of orange and lime. On the other hand, I have concerns about the plausibility of the mutual containment this would require; e.g., orange contains yellowness while yellow contains orangeness. My sense that (at least some of) the intermediate hues admit of pure variants also leads me to doubt this explanation, as I do not find redness or yellowness in balanced orange and I also do not detect any other hues in unique green or unique red.

Of course, subjects might adopt an understanding of their task different than that intended by the experimenters, no matter how clearly instructions are given. This is certainly a risk if subjects are asked to do something they are actually incapable of, but wish to be cooperative with the experimenter. Thus the other leading account of subject performance is that they could not find the intermediate primaries in the unique hues and simply relied on perceived similarity in making their ratings in the intermediate condition. In considering the hypothesis that subjects

in the intermediate condition based their ratings on perceived similarity rather than "containment," Bosten & Boehm (ibid., p.391) observe that "if this could explain [the intermediate condition results], it could also explain the form of all other results from hue scaling where unique hues are given as primaries"; a similar idea is lurking in Jameson & D'Andrade's (1997) alternative perspective on the unique hues (see also Wright 2011, p.634). This is an important point that cannot be easily dismissed, given the strong similarities between the intermediate and standard condition results.

Bosten & Boehm's second experiment provides some support for the hypothesis that subjects rely on similarity judgments when scaling both unique and binary hues. They found that by varying the color terms included in instructions for making unique hue settings for red and blue, subjects' unique selections would shift. For example, for unique blue, subjects were to find a "pure color" that satisfied one of three conditions they might be assigned to: (i) "neither greenish nor reddish," (ii) "neither tealish nor reddish," or (iii) "neither greenish nor purplish" (Bosten & Boehm 2014, p.A389). To be clear, subjects were assigned to only one of those conditions and did not see the instructions for the other unique blue conditions. Subjects in the conditions involving intermediate hue terms ((ii) and (iii)) had mean hue settings that were shifted away from the mean hue settings made in the condition that mentioned only Hering primary hues (i). These shifts (for both unique blue and unique red) were in the direction opposite the intermediate term used in the instructions received; e.g., settings for (ii) were shifted toward purple while those for (iii) were shifted toward teal (ibid., p.A390, fig.5e). A plausible interpretation of this finding is that subjects used the color terms in the instructions received as anchor points for an in-between selection (presumably based on similarity) and did not rely on a

20

consistent standard of purity. A similar use of anchor points could be present in hue scaling with both standard and intermediate primaries.

5. Do the Unique Hues Have an Objective Basis?

It is typically thought that the unique hues undermine color physicalism because they have no plausible objective basis. But, if such an objective basis could be found for them – e.g., if surface reflectances corresponding to the unique hues were shown to be distinctive in some way – that would lend support to the Hering opponent colors framework. Such a discovery would certainly provide a way of getting around the difficulties for the Hering opponent colors framework raised by the lack of evidence for a neural realization and might also suggest strategies for dealing with the other issues that this chapter has focused on.

Philipona & O'Regan (2006, p.332) offer an account of certain color phenomena grounded entirely in what they term the "accessible information" in the light, which "[is] the restricted information about the spectral composition of that light which is accessible through an organism's photopigment set." They explicitly focus on the cone quantum catch, omitting altogether neural coding or processing (ibid., p.332). Philipona & O'Regan make a striking observation: unlike most colors, focal examples of the four Hering primaries are "singularities." That is, these surfaces have one or two coordinates that are approximately zero in the particular bases Philipona & O'Regan employ in their mathematical analysis. This outcome is completely unexpected since, as noted just above, it has been widely believed that there is no remotely objective basis for the special nature of the unique hues. Philipona & O'Regan contend that their finding accounts for data from psychophysical studies (viz., hue cancellation) and the World Color Survey (WCS). That all this could be achieved without invoking any sort of processes or

representations beyond the retina would be a major achievement and would point toward a potentially revolutionary way of studying vision in general, much along the lines of Gibson's (1979) ecological psychology.

Philipona & O'Regan's project has three parts: they (i) mathematically analyze the reflectance and illumination data, (ii) measure the results with a particular index of singularity, and (iii) compare these measurements with some empirical data (e.g., from the WCS). Here I will limit myself to briefly characterizing (i) and (ii), and closely examining (iii); for critical evaluation of (i) and (ii), see Johnson & Wright (2008).

Philipona & O'Regan begin by representing the accessible information from illuminants, which may have been reflected off a surface, as 3×3 matrices. The rows of these matrices correspond to the information that is accessible to the L, M, and S photoreceptors, and the columns correspond to the three (hypothesized) components of natural light. Philipona & O'Regan show that if the matrix associated with the unreflected light is invertible,[5] then the amount of accessible information in a reflected illuminant that is available to a given type of photoreceptor is a linear function of the amount of accessible information in the unreflected illuminant available to the photoreceptors. To examine the underlying structure of the data they are working with, Philipona & O'Regan perform an eigenanalysis on the 3×3 matrix of coefficients of these linear combinations, using the resulting eigenvectors as a new basis for representing the 3×1 vectors of information accessible to the three photoreceptors. In this new

---

[5] A matrix $\mathbf{A}$ is invertible just in case there exists a matrix $\mathbf{A^{-1}}$ that yields the unit matrix when it is multiplied with $\mathbf{A}$; i.e., $\mathbf{AA^{-1} = A^{-1}A = 1}$.

basis, Philipona & O'Regan report that best exemplars of the four Hering primaries are of less than full dimensionality.

Of particular interest for the purposes of this this chapter is Philipona & O'Regan's comparison of a graph of singularity measures to a plot of data from the WCS (p.335, Fig.3; see also Fig.2 of Regier et al 2005). The plot of WCS data they are comparing is for a focal choice task, where for each of their language's basic color terms,[6] WCS participants were to select from the stimulus array a particular Munsell chip as the best exemplar of that term. Given received thinking about the unique hues and their hypothesized relevance to color naming phenomena, these best exemplar choices are plausibly interpreted as proxies for unique hue selections; see Kuehni (2005).

About the relationship between WCS focal choice data and singularity index scores for the WCS stimuli, Philipona & O'Regan write:

> The chips most often given a name by widely separated human cultures … and which we call 'red', 'yellow', 'green', and 'blue' in English, can be seen to be within one chip of those having maximally singular reflecting properties …. It could thus be argued that the reason the colors 'red', 'yellow', 'green', and 'blue' are so often singled out among all other colors as being worth giving a name, is that surfaces of these colors have the particularity that they alter incoming light in a simpler way than other surfaces. (ibid., pp.335 – 336)

---

[6] A language's basic color terms form the smallest set of simple terms that could be used to name any color. For more on how basic color terms were determined, see Cook et al (2005).

However, of the 110 unwritten languages surveyed in the WCS, only 38 had basic color terms for all four Hering primaries and some of those languages had more than one basic term corresponding to the same Hering primary; see Kuehni (2005).[7] Several WCS languages that lacked a basic term for one of the Hering primaries had basic terms for colors considered non-fundamental from the standpoint of the Hering primaries. Furthermore, while plenty of languages have separate terms for green and blue, many instead have a basic color term that covers both; i.e., "grue" terms. In sum: 65% of WCS languages find at least one of the Hering primaries to not be "worth giving a name" and many languages have basic color terms that do not have a simple correspondence with them. Thus clarification is needed of just what color naming phenomenon, and consequently what color perception phenomenon, Philipona & O'Regan take themselves to be accounting for when they highlight the special status of certain surfaces according to their singularity index.

Inspection of the full WCS focal choice data presented in Cook et al (2005) and Regier et al (2005) raises further questions about just what Philipona & O'Regan can claim to have accomplished. Approximately 2640 total speakers took part in the WCS. The peaks of the focal choice distribution, along with the number of participants who selected a particular Munsell chip as a best exemplar of one of his or her language's basic color terms are: A0 (2048), J0 (1988), G1 (668), C9 (752), F17 (351), F29 (253). A0 and J0 are at the extreme ends of the range of achromatic Munsell chips used in the WCS and correspond to best exemplars of English "white"

---

[7] Jameson (2010) emphasizes Kuehni's findings in arguing against the idea that pan-human features of color experience are the largest factor in explaining cross-cultural color naming patterns.

and "black", respectively. The remaining chips (G1, C9, F17, and F29) align well with averaged focal points for English "red", "yellow", "green" and "blue" respectively; see Cook et al (2005), Sturges & Whitfield (1995). As Philipona & O'Regan (p.335) mention, the WCS focal choice peaks line up nicely with the chips having the highest singularity scores: G2, C9, F16, and H31. (Note, however, that H31 is two chips and four coordinate changes away from F29, not just one, as Philipona & O'Regan claim.)

The numbers associated with the chromatic chips reveal substantially less consistency than is found for the achromatic ones. If a chip gets a very high singularity score, fewer than 30% of the participants will pick it as a best exemplar. Using the focal choice data for F17 and F29 to evaluate chips F16 and H31 that Philipona & O'Regan have identified as special, fewer than 15% of participants select as best exemplars chips with singularity values in the middle of the scale.

Philipona & O'Regan do not quantitatively analyze the similarities and differences between their singularity index values and the WCS focal choice data. The main argumentative force on behalf of their claims seems to come from visual inspection of the graphs they provide. Hence, it is not obvious what significance should be attached to the patterns just noted, to the (unknown) extent they exist. For example, simply looking at reflectance coefficients and singularity values does not give any insight into why a high score on a measure of chromatic singularity should lead to only ca. 10-29% of participants picking a chip as a best exemplar. Moreover, there are marked differences in the graphs (ibid., p.335, fig.3) comparing the WCS focal choice data with their singularity index. For example, the spread, skew, and kurtosis about the corresponding peaks look rather distinct. A cluster in the focal choice plot in the blue region (ca. hue line 30) has two peaks while its singularity index counterpart has only one. Without a

25

more detailed analysis of the geometry of these two plots, it is virtually impossible to draw any conclusions whatsoever about their apparent similarities.

Philipona & O'Regan's strategy also does not suit their aim to explain the existence of "four special surface colors" by taking into account only "constraints satisfied by natural illuminants and surfaces" (ibid., p.331). For that purpose, it would be appropriate for Philipona & O'Regan to plot the Munsell chips from the WCS stimulus set according to a metric defined by the bases and reflectance coordinates they derive through their eigendecomposition. Ideally, chips with high singularity values would appear at the edges of such a plot and chips would cluster in the space in a way that suggests four distinct categories. That is, Philipona & O'Regan should be able to (in some sense) reconstruct the WCS stimulus array from their objective account of reflectance and thus also derive any similarities between singularity values and focal choice results. However, Philipona & O'Regan cannot do this, since, their eigendecomposition is done chip-by-chip, rather than across the entire set of chips. Their approach results in each chip being represented in its own basis, rather than all the chips having their coordinates represented in a common basis. They are then left to use singularity values alone, plotted on the original stimulus array, to make their case. That approach, however, relies heavily on the conceptual organization of the Munsell chip set used in the WCS to establish the four special color categories; the chips are arranged in 40 equal hue steps at eight levels of lightness.

Essentially, rather than using the results of their mathematical analysis to produce a representation of reflectance properties that puts the chips into a structure that coincides with the structure of the Munsell array and the focal choice data plotted on it, Philipona & O'Regan begin by organizing the chips in just the way they are set out in the Munsell array and then plot their singularity scores on top of that. Nothing about the details of their mathematical analysis or

26

singularity index dictates that two chips that are adjacent in the Munsell array should also be adjacent in the graph they produce. To illustrate, the reflectance coordinates Philipona & O'Regan (ibid., p.335) report for focal green and focal blue are nearly identical, while the peak singularity scores for green and blue coincide with values that are in the middle of the ranges for yellow and red. Since they are building in so much perceptual structure, even if they were to succeed in showing that the Hering primaries are special in some way, it is hard to take seriously their claim to have shown that that distinctiveness is grounded in objective features alone. A similar point applies to their plots of singularity scores for surfaces represented in the CIE xy chromaticity diagram (ibid., p.336, fig.4).

Some remarks are in order regarding the specific predictions they make for perceivers' unique hue locations and the range of variability of subject responses; this data is represented in their table 1 (ibid., p.337). For unique yellow, their predictions are in good agreement with psychophysical findings. The other three unique hues are a mixed bag and include some significant discrepancies. Their unique green prediction of 540 nm fits with one of the peaks of the distribution for subject settings revealed in experiments, but nothing in their data suggests a counterpart for the shorter wavelength mode (ca. ≤ 520 nm). Moreover, while the top end of their predicted range is in line with the top end of psychophysical results, the short wavelength end of their range is 12-22 nm higher than that of the studies they cite; in fact, their prediction of 510 nm for the floor of the range coincides with the reported mean setting in some studies. Their unique blue prediction of 465 nm is a good bit shorter than the range of experimentally determined means they cite, which run from 472-480 nm. There are also disagreements between the floor and ceiling of their predicted range, and those reported in psychophysical studies. As for unique red, their prediction of 625 nm is quite troubling. Unique red is typically found to be

27

extraspectral; note that only one of the six studies they cite reports a spectral location for unique red, the others either labelling it as extraspectral or not even bothering to investigate it. A stimulus of 625 nm is typically found to have a quite noticeable yellowish aspect and that location is within the empirically determined spectral range for orange. An example drawn from hue scaling bears this out: Abramov & Gordon (2005, p.2145, fig.1a) report a yellow hue content of ca. 25% at 625 nm. Philipona & O'Regan (2006, p.337) do not address these matters in any sort of detail and simply note that their predictions are "in agreement" with empirical findings, leaving the reader to wonder at just what to make of the hits and misses revealed in their table 1.

To be clear, I do not take this discussion to amount to an outright refutation of Philipona & O'Regan. And I do not have a deflationary (or debunking) explanation of the correspondences that survive the critiques I have offered. However, the problems raised herein (which are not addressed in their reply to Johnson & Wright 2008; see Philipona & O'Regan 2008) make it very hard to see just what of consequence about the unique hues Philipona & O'Regan can claim to have discovered. Thus it would be very risky to follow them in their proposed radically new way of studying perception in general and their highly contentious thesis regarding the unique hues in particular.

6. Further Empirical Problems

Returning to the concerns raised in sections three and four, the issues with hue cancellation and hue scaling are sufficient to deal a significant blow to received thinking about the unique hues and the structure of phenomenal color more generally. Other research on the unique hues reveals additional reasons to doubt that they stand out from the intermediate hues in any perceptually

28

meaningful way. This section surveys some relevant studies. I will not explore research on cross-cultural naming patterns and other color language phenomena beyond what was addressed in the preceding section. The reason for this is that (i) the findings I discuss here strike me as more deeply connected to claims about the unique hues that have played a pivotal role in debates about the nature of color and color perception and (ii) issues of color language have received sufficient critical attention elsewhere; see Jameson & D'Andrade (1997), Jameson (2010), Ocelak (2014), and Arstila (2017).

If the unique hues are fundamental to the organization of color space, unique hue settings should be correlated with one another and binary hue settings should be predictable on the basis of the settings for the combined primaries. Without such relations obtaining amongst the hues, it is far from clear that there is any reason to think that the Hering primaries could impose structure on phenomenal color; viz., serving as cardinal axes in color space and determining all hue appearances. Moreover, given their alleged perceptual purity and salience, the unique hues should be easier for subjects to find than (and stand out from) intermediate hues. This is particularly reasonable to expect if those perceptual features of unique hues are (as is routinely claimed) due to them enjoying a distinctive neural representation; I will offer here another reminder about this being a foundational assumption of Hurvich & Jameson's hue cancellation studies.

This last point is called into question by the shifts in unique hue settings Bosten & Boehm's subjects showed as the instructions to find a "pure color" varied from including only unique hue terms to including an intermediate hue term. If the purity of the unique hues makes them easier to locate, such manipulations to task instructions should have little or no effect on subjects' unique hue selections. Further reason for doubt comes from Bosten & Lawrence-Owen

(2014). They gave subjects a hue selection task with instructions to find, for example, "a red that is neither too orange nor too purple" or "a purple that is neither too red nor too blue" (Bosten & Lawrence-Owen 2014, p.A358). Subjects made multiple settings for the four unique hues and four intermediate hues. Bosten & Lawrence-Owen calculated the variance of subjects' settings for each hue. They also determined how much variability should be expected for each hue, given its location in chromaticity space; discrimination is not uniform across chromaticity space. For each hue, the observed variance was compared to the predicted variance. Nothing in the pattern of results distinguished unique hues from intermediate ones. As a case in point, green and orange settings are less variable (to a similar extent) than expected, while purple and red are more variable than expected; see Bosten & Lawrence-Owen (2014, p.A359, fig.2e and p.A361, fig.4c). Bosten & Lawrence-Owen's findings cast doubt upon the idea that the unique hues are represented in a way that allows subjects to make more consistent judgments about them than the intermediate hues. Bosten & Lawrence-Owen (2014, p.A363) attribute this to there being no advantage for the unique hues when it comes to the accuracy with which the visual system represents them. Several other candidate explanations are worth taking seriously. Subjects might have struggled to consistently apply a criterion of purity, due either to the nature of their percepts (e.g., no stimuli actually have a pure appearance) or something about the criterion itself. Another possibility is that the intermediate hues appeared just as pure as the unique hues, thus denying the latter a "purity advantage." Of course, if the subjects relied on a similarity judgment of the sort discussed earlier for all their settings, there very well could be no difference in the variability of those judgments between unique and intermediate hues. Whatever the explanation, this is not the outcome one would expect, if the unique hues were as salient and special as routinely claimed.

Subject performance in the visual search task of Wool et al (2015) also does not show a salience advantage for the unique hues. Each subject first selected four unique hues, for each of which the experimenters also determined complementary hues; in keeping with the discussion at the end of section 3, none of the unique hue selections formed complementary pairs. Each unique hue and its non-unique complement were used to create a textured background (composed of an equal number of randomly arranged blocks of both hues) on which one, two, or three targets were presented. For each trial, one of the two hues comprising the background was randomly selected and assigned to all targets. Subjects had to indicate the number of targets presented in a trial as quickly and accurately as possible. A similar study with light and dark stimuli (Komban et al 2011) found that dark stimuli were more salient than light stimuli, enjoying shorter response times (RTs). Wool et al (ibid., p.4) did not find a similar salience effect for the unique hues, as their subjects' RTs for unique hues were not significantly shorter than their RTs for the non-unique complementary hues; these subjects did replicate the findings of Komban et al in a search task with light and dark stimuli. The unique hues do not "pop out" from their non-unique complementary hues.

The situation is no better when it comes to correlations amongst unique and intermediate hue settings. Webster et al (2000) investigated, inter alia, whether a subject's unique hue settings constrain one another. They failed to find significant correlations for any pairs of different unique hue settings, nor did they find correlations between unique hue settings and a subject's chromatic (cone) sensitivities. Malkoc et al (2005, p.2155) write of these results that "[for] example, a subject whose unique yellow is more reddish than average is not more likely to choose a unique blue that is more reddish (or more greenish) than average." With respect to intermediate hues and their neighboring primaries, there was little correlation amongst unique

31

and binary hue settings; orange's correlation with yellow and red was the lone (and slight) exception (ibid., pp.2157-2158). Binary hue settings also show little or no predictability from the midpoint between settings for neighboring unique hues and the same holds for unique hue settings and their flanking binary hues (ibid., pp.2158-2159). The unique hues just do not behave as though they are arranged in pairs forming orthogonal axes and the binary hues show no sign of being under the control of mechanisms defined by such unique hue axes. These results also bear on the interpretation of what hue scaling subjects are actually doing discussed in connection with Bosten & Boehm (2014). If subjects are relying on similarity when scaling hue content, the lack of correlation between hue settings and midpoints (between either unique or intermediate hues) suggests that such judgments involve more than a simple evenly-weighted comparison to clearly grasped anchor points.

Also worth noting is that the range of variation in settings between Malkoc et al's observers did not distinguish unique and intermediate hues; e.g., yellow and blue-green had the narrowest ranges of variation across subjects, while blue, green, and orange showed considerably higher levels of variation (ibid., pp.2156-2158). Not only do individual subjects fail to more reliably identify the unique hues than the intermediate hues (Bosten & Lawrence-Owen 2014), but across subjects there is not a greater tendency to converge on the same selections for the unique hues than for the intermediate hues. Consequently, were it the case that the unique hues play a critical role in structuring color experience, that role is not biologically significant enough for evolution to have specially "tuned" our responses to them, either for each observer individually or across the population.

Summarizing their findings regarding the independence of the hues from one another, Malkoc et al (2005, p.2155) write that "the unique hues do not emerge as special and do not

alone fully anchor the structure of color appearance for an individual." In the light of their findings and the rest of the research examined so far, I would go further and say that it is difficult to see why the unique hues should be accorded any privileged status (in theorizing about perception) or thought to play a fundamental role in determining all color appearances. The empirical problems that have emerged for the standard account of the unique hues are significant and undermine its psychophysical, neural, and phenomenological plausibility. Thus it is appropriate to consider theories of color that are not grounded in the unique hue construct (Jameson & D'Andrade 1997, p.309; Wool et al 2015, p.9)

7. The Munsell system and spectral reflectances

If the hues are not organized around red/green, blue/yellow axes, what sort of structure might they have? The Munsell color system has several advantages over the Hering opponent colors framework that make it a much more plausible candidate for being (in limited but important respects) a useful approximation of human color space. Informative accounts of the Munsell system and its physical embodiment in sets of painted chips are provided by Indow (1988), Kuehni (2013, pp.96-100), Romney (2008, pp.658-659), and Wyszecki & Stiles (1982, pp.507-509).

In the Munsell system, hues are arranged in a circle and are represented by radii that extend from the achromatic origin. The system arbitrarily divides hue into one hundred steps, comprised of ten steps in each of ten equally spaced sectors named by the system's five principal hues (the Hering primaries plus purple) and five intermediate pairings of them. While each hue sector has ten steps, the Munsell hue circle is typically displayed using 2.5 step intervals, as in figure 1. The Munsell system was designed with the aim that equal steps along each of its three

dimensions (hue, value, chroma) correspond to equal perceptual differences. This goal is

(roughly) achieved within each dimension, but it is widely recognized that there are differences

in the perceptual significance of steps between dimensions. Indow (1988, 1999) found that

multidimensional scaling of color similarity judgments across a variety of studies produced a

structure quite similar to that of the Munsell system, while noting that the perceptual difference

of one value (lightness) step is a bit more than double that of one chroma (chromatic purity) step.

Indow (1988, p.461) also pointed out that judgments of similarity break down as distance in the

Munsell space increases. Thus the considerable distance between red and green explains why

perceivers have the sense that they are "entirely different" from one another and why there are no

reddish greens (nor orangish teals); see Jameson & D'Andrade (1997, pp.310-311). Such

judgments, however, cannot serve as a reliable guide to the specific location of those hues in

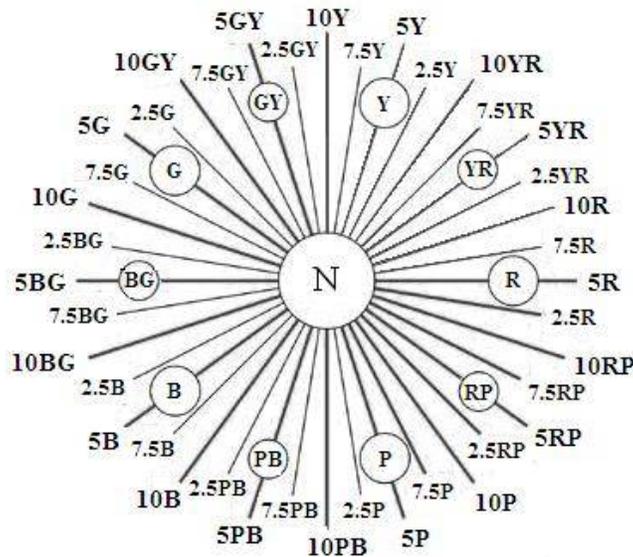color space; viz., whether they lie opposite one another.

Figure 1: The Munsell hue circle. R: Red; YR: Yellow-Red; Y: Yellow; GY: Green-Yellow; G: Green; BG: Blue-Green; B: Blue; PB: Purple-Blue; P: Purple; RP: Red-Purple; N: Neutral.

Significant for present purposes is that the Hering opponent axes are not found in the Munsell hue plane. Consistent with the complementary hue relations noted in section 3, red is opposed by blue green, green by magenta (reddish purple), blue by orange (yellow red), and yellow by violet (purplish blue); opposed Munsell hues in general fit well with empirically determined complementary relations. Also of consequence is that the cherry/teal and chartreuse/violet axes of LGN opponent cell activity are in good agreement with the 5R/5BG and 10Y/10PB axes suggested by the orientation of the Munsell hue circle in figure 1. There is no a priori reason to favor any rotation of the Munsell hue circle as providing cardinal axes and it may turn out that there are no such privileged axes at all. However, as pointed out by Jameson & D'Andrade (1987, pp.304,309), the true opponent relations amongst colors are best understood in terms of complementary relations (cancellation to an achromatic percept), which are plausibly grounded in "equal but opposite" responses within LGN opponent cells. Thus if there are canonical hue axes, cherry/teal and chartreuse/violet have a much stronger claim to being them than do red/green and blue/yellow, pace Abramov & Gordon (1994).

Should the Munsell hue system provide an adequate representation of perceptual color space, this would be a boon to color physicalists and objectively-inclined realists more generally. This would open the way for arguing that, contrary to what eliminativists have claimed, there is a good match (to some interesting degree, relative to certain concerns) between perceived color and the surface reflectance properties of objects. Consider first that, as even eliminativists admit, the relationship between perceived color and the physical causes of color is largely systematic.

For example, slight variations in spectral reflectances of surfaces or spectral power distributions of lights tend to be met by slight variations in perceived color (Isaac 2014, p.494). Additionally, there are patterns that tend to hold up very well across sets of natural and artificial reflectances. To illustrate, typical green stimuli have bell-shaped reflectance spectra centered near the middle of the visible spectrum, while yellows commonly have staircase-shaped spectra that begin to rise from low-reflectance to high-reflectance somewhere in the vicinity of 500 nm; see Maloney (2003, p.243) and Wright (2011, p.636, fig.1). Given that color similarity relations are well represented within the Munsell system, establishing a clear link between the structure of the physical causes of color experience and the Munsell system would go a long way toward making a positive case for color realism.

At this juncture it is helpful to take into account studies that have used dimensionality reduction techniques (e.g., principal component analysis) on collections of natural and artificial surface reflectances. Such techniques are used to represent data sets of high dimension in (relatively) few dimensions; e.g., by transforming the original dimensions in order to maximize the amount of remaining variance that can be projected on each new dimension. A consistent pattern across such research is that empirical reflectances can be approximated to a high degree of precision (ca. 99%) in as few as three dimensions. While there are important issues to be addressed regarding the criteria for determining the number of dimensions required for a perceptually adequate approximation of empirical reflectances (see Nascimento et al 2005 and Oxtoby & Foster 2005), it is noteworthy that Romney (2008) produced a plot of Munsell chips in a three-dimensional "reflectance space" that has a qualitative resemblance to the conceptual Munsell space. He also showed that approximated surface reflectances can be mapped into the Munsell conceptual space by means of a linear transformation. In other words, Romney has

supplied a means of relating a representation of the structure underlying surface reflectance properties to the structure of the Munsell conceptual system, with the latter agreeing with judgments of perceived similarity, complementary relations amongst the hues, and the axes of LGN opponent cells.

As for the broader implications of this result, the first three basis functions (dimensions) Romney derived are in line with those reported in studies of surface reflectances of natural objects; e.g., compare Romney (2008, p.662, fig.3) and Chiao et al (2000, p.221, fig.3), see also Craven & Foster (1992, p.1361) for a more general remark on the consonance between basis functions derived for Munsell chips and for natural surfaces. Thus the relation between reflectance space and Munsell space is not merely an artifact of having analyzed the painted Munsell chips. Color realists should be greatly encouraged by this development, although much more work needs to be done to develop an objectively-oriented account of color from findings such as Romney's. Chapter XXX will take up this labor.

References

Abramov, L. & J. Gordon. 1988. Scaling procedures for specifying color appearance. Color Research and Application, 13, 146-152.

_____. 1994. Color appearance: on seeing red – or yellow, or green, or blue. Annual Review of Psychology, 45,451-485.

_____. 2005. Seeing unique hues. Journal of the Optical Society of the Optical Society of America A, 22, 2143-2153.

Arstila, V. 2017. What makes unique hues unique? Synthese. On-line first publication.

Averill, E. 2005. Toward a projectivist account of color. Journal of Philosophy, 102, 217-234.

Bosten, J. & A. Boehm. 2014. Empirical evidence for unique hues? Journal of the Optical

    Society of America A, 31, A385-A393.

Bosten, J. & A. Lawrence-Owen. 2014. No difference in variability of unique hue selections and

    binary hue selections. Journal of the Optical Society of America A, 31, A357-A364.

Broackes, J. 1997. Could we take lime, purple, orange, and teal as unique hues? Behavioral and

    Brain Sciences, 20, 183-184.

_____. 2011. Where do the unique hues come from? Review of Philosophy and Psychology, 2,

    601-608.

Burns, S., A. Elsner, J. Pokorny, & V. Smith. 1984. The Abney effect: Chromaticity coordinates

    of unique and other constant hues. Vision Research, 24, 479-489.

Byrne, A., & Hilbert, D. 2003a. Color realism and color science. Behavioral and Brain Sciences,

    26, 3–21.

_____. 2003b. Color realism redux. Behavioral and Brain Sciences, 26, 52-63.

Chiao, C, T. Cronin, & D. Osorio. 2000. Color signals in natural scenes: characteristics of

    reflectance spectra and effects of natural illuminants. Journal of the Optical Society of

    America A, 17, 218-224.

Churchland, P. M. 2007. On the reality (and diversity) of objective colors: How color-qualia

    space is a map of reflectance-profile space. Philosophy of Science, 74, 119–149.

Conway, B. & C. Stoughton. 2009. Response: Towards a neural representation for unique hues.

    Current Biology, 19, R442-R443.

Conway, B. & D. Taso. 2009. Color-tuned neurons are spatially clustered according to color

    preference within alert macaque posterior inferior temporal cortex. Proceedings of the

    National Academy of Sciences, 42, 18034-18039.

Cook, R., Kay, P., Regier, T. 2005. The World Color Survey Database: History and Use. In H. Cohen & C. Lefebvre (eds.) <u>Handbook of Categorisation in the Cognitive Sciences</u>. London: Elsevier.

Craven, B. & D. Foster. 1992. An operational approach to colour constancy. <u>Vision Research, 32,</u> 1359-1366.

Crone, R. 1999. <u>A History of Color: The Evolution of Theories of Light and Color</u>. Dordrecht: Kluwer Academic Publishers.

De Valois, R., I. Abramov, & G. Jacobs. 1964. Analysis of response patterns of LGN cells. <u>Journal of the Optical Society of America, 56,</u> 966-977.

Derrington, A., J. Krauskopf, & P. Lennie.1984. Chromatic mechanisms in lateral geniculate nucleus of macaque. <u>Journal of Physiology, 357,</u> 241-265.

Dimmick, F. & M. Hubbard. 1939a. The spectral location of psychologically unique yellow, green, and blue. <u>American Journal of Psychology, 52,</u> 242-254.

_____. 1939b. The spectral components of psychologically unique red. <u>American Journal of Psychology, 52,</u> 348-353.

Forder, L., J. Bosten, X. He, & A. Franklin. 2017. A neural signature of the unique hues. <u>Scientific Reports, 7,</u> 1-8.

Gibson, J.J. 1979. <u>The Ecological Approach to Visual Perception</u>. Boston: Houghton Mifflin.

Hardin, C.L. 1988. <u>Color for Philosophers: Unweaving the Rainbow.</u> Indianapolis: Hackett.

_____. 1992. The virtues of illusion. <u>Philosophical Studies, 68,</u> 371-382.

_____. 2003. A spectral reflectance doth not a color make. <u>Journal of Philosophy, 100,</u> 191-202.

_____. 2005. Explaining basic color categories. <u>Cross-Cultural Research: The Journal of Comparative Social Science, 39,</u> 72-87.

Hering, E. 1920/1964. <u>Outlines of a theory of the light sense</u>. Cambridge (MA): Harvard University Press.

Hurvich, L. 1981. <u>Color Vision</u>. Sunderland (MA): Sinauer Associates.

Hurvich, L. & D. Jameson. 1957. An opponent-process theory of color vision. <u>Psychological Review, 64,</u> 384-404.

Indow, Y. 1987. Psychologically unique hues in aperture and surface colors. <u>Die Farbe, 34,</u> 253-260.

_____. 1988. Multidimensional studies of Munsell color solid. <u>Psychological Review, 95,</u> 456-470.

_____. 1999. Predictions based on Munsell notation. I. Pereceptual color differences. <u>Color Research and Application, 24,</u> 10-18.

Isaac, I. 2014. Structural realism for secondary qualities. Erkenntnis, 79, 481-510.

Jakab, Z. & B. McLaughlin. 2003. Why not color physicalism without color absolutism? <u>Behavioral and Brain Sciences, 26,</u> 34-35.

Jameson, D. & L. Hurvich. 1955. Some quantitative aspects of an opponent-colors theory. I. Chromatic responses and spectral saturation. <u>Journal of the Optical Society of America, 45,</u> 546-552.

_____. 1959. Perceived color and its dependence on focal, surrounding, and preceding stimulus variables. <u>Journal of the Optical Society of America, 49,</u> 890-898.

Jameson, K. 2010. Where in the World Color Survey is the support for the Hering Primaries as the basis for Color Categorization? In J. Cohen & M. Matthen (eds.) <u>Color Ontology and Color Science</u>. Cambridge (MA): MIT Press.

Jameson, K. & R. D'Andrade. 1997. It's not really red, green, yellow, blue: an inquiry into

    perceptual color space. In C. Hardin & L. Maffi (eds.) <u>Color Categories in Thought and</u>

    <u>Language</u>. Cambridge: Cambridge University Press.

Johnson, K. & W. Wright. 2008. Reply to Philipona and O'Regan. <u>Visual Neuroscience, 25,</u> 221-

    224.

Judd, D. 1951. Basic correlates of the visual stimulus. In S. Stevens (ed.) <u>Handbook of</u>

    <u>Experimental Psychology</u>. New York: John Wiley & Sons.

Koenderink, J. 2010. <u>Color for the Sciences</u>. Cambridge (MA): MIT Press.

Komban, S., J.-M. Alonso, & Q. Zaidi. 2011. Darks are processed faster than lights. <u>Journal of</u>

    <u>Neuroscience, 31,</u> 8654-8658.

Kuehni, R. 2003. <u>Color Space and Its Divisions</u>. Hoboken (NJ): John Wiley & Sons.

_____. 2004. Variability in unique hue selection: A surprising phenomenon. <u>Color Research and</u>

    <u>Application, 29,</u> 158-162.

_____. 2005. Focal color variability and unique hue stimulus variability." <u>Journal of Cognition</u>

    <u>and Culture, 5,</u> 409-426.

_____. 2013. <u>Color: An Introduction to Practice and Principles</u>. Hoboken (NJ): John Wiley &

    Sons.

Kuehni, R. & A. Schwarz. 2008. <u>Color Ordered: A Survey of Color Order Systems from</u>

    <u>Antiquity to the Present</u>. Oxford: Oxford University Press.

Ladd-Franklin, C. 1929/1973. <u>Colour and Colour Theories</u>. New York: Arno Press.

Logvinenko, A. 2012. A theory of unique hues and colour categories in the human colour vision.

    <u>Color Research and Application, 37,</u> 109-116.

Logvinenko, A. & L. Beattie. 2011. Partial hue-matching. <u>Journal of Vision, 11,</u> 1-16.

41

MacLeod, D. 2010. Into the neural maze. In J. Cohen & M. Matthen (eds.) <u>Color Ontology and Color Science</u>, Cambridge (MA): MIT Press.

Malkoc, G., Kay, P., Webster, M. 2005 Variations in normal color vision. IV. Binary hues and hue scaling. <u>Journal of the Optical Society of America A, 22,</u> 2154-2168.

Maloney, L. 2003. Surface color perception in constrained environments. In R. Mausfeld & D. Heyer (eds.) <u>Colour Perception: Mind and the Physical World</u>. London: Oxford University Press.

Matthen, M. 2005. <u>Seeing, Doing, and Knowing</u>. Oxford: Oxford University Press.

Mollon, J. 2009. A neural basis for unique hues? <u>Current Biology, 19,</u> R441-R442.

Munsell Color Company. 1976. <u>Munsell Book of Color: Matte Finish Collection</u>. Baltimore: Munsell.

Nascimento, S. D. Foster, & K. Amano. 2005. Psychophysical estimates of the number of spectral reflectance basis functions needed to reproduce natural scenes. <u>Journal of the Optical Society of America A, 22,</u> 1017-1022.

Ocelak, R. 2014. The myth of unique hues. <u>Topoi, 34,</u> 513-522.

Oxtoby, E. & D. Foster. 2005. Perceptual limits on low-dimensional models of Munsell reflectance spectra. <u>Perception, 34,</u> 961-966.

Palmer, S. 1999. <u>Vision Science: Photons to Phenomenology</u>. Cambridge (MA): MIT Press.

Philipona, D. & J.K. O'Regan. 2006. Color naming, unique hues, and hue cancellation predicted from singularities in reflection properties. <u>Visual Neuroscience, 23,</u> 331-339.

_____. 2008. Reply to Johnson and Wright. <u>Visual Neuroscience, 25,</u> 225-226.

Regier, T., P. Kay, & R. Cook. 2005. Focal colors are universal after all. <u>Proceedings of the National Academy of Science, 102,</u> 8386–8391.

Romney, A.K. 2008. Relating reflectance spectra space to Munsell color appearance space. Journal of the Optical Society of America A, 25, 658-666.

Saunders, B. & J. van Brakel. 1997. Are there nontrivial constraints on colour categorization? Behavioral and Brain Sciences, 20, 167-179.

Stoughton, C. & B. Conway. 2008. Neural basis for unique hues. Current Biology, 18, R698-R699.

Sturges, J. & T. Whitfield. 1995. Locating basic colours in the Munsell space. Color Research and Application, 20, 364-376.

Thompson, E. 1995. Colour Vision. New York: Routledge.

Valberg, A. 2001. Unique hues: an old problem for a new generation. Vision Research, 41, 1645-1657.

Wandell, B. 1995. Foundations of Vision. Sunderland (MA): Sinauer Associates.

Webster, M. E. Miyahara, G. Malkoc, & V. Raker. 2000. Variations in normal color vision. II. Unique hues. Journal of the Optical Society of America A, 17, 1545-1555.

Wool, L., S. Komban, J. Kremkow, M. Jansen, X. Li, J.-M. Alonso, & Q. Zaidi. 2015. Salience of unique hues and implications for color theory. Journal of Vision, 15, 1-11.

Wright, W. 2010. Perception, color, and realism. Erkenntnis, 73, 19-40.

_____. 2011. More on the origin of the hues: a reply to Broackes. Review of Philosophy and Psychology, 2, 629-641.

_____. forthcoming. Eliminativism. In D. Brown & F. Macpherson (eds.) The Routledge Handbook of Philosophy of Colour. London: Routledge.

Wyszecki, G. & W.S. Stiles. 1982. Color Science: Concepts and Methods, Quantitative Data and Formulae. New York: John Wiley & Sons.