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What makes unique hues unique?

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Abstract

There exist two widely used notions concerning the structure of phenomenal color space. The first is the notion of unique/binary hue structure, which maintains that there are four unique hues from which all other hues are composed. The second notion is the similarity structure of hues, which describes the interrelations between the hues and hence does not divide hues into two types as the first notion does. Philosophers have considered the existence of the unique/binary hue structure to be empirically and phenomenally well-grounded, and the structure has been considered to be primary because this can account for the similarity structure. Consequently, the unique/binary hue structure has played a central role in color philosophy. This calls for the assessment of the justification for its existence carried out in this paper. It is concluded that, despite the prevalent view among philosophers, none of their reasons for endorsing the existence of the unique/binary hue structure are justified. Since the notion of the unique/binary hue structure appears intuitively plausible for many, however, a sketch explaining this intuition is outlined at the end.

Keywords: Color space, Unique/binary hues, psychophysics, color cognition

1. Introduction

Philosophers and scientists have used two significantly different notions of structure in the discussion concerning *the structure of phenomenal color space*.[1] According to the first notion, colors can be ordered by means of the similarity and dissimilarity relations. By doing so, a notion of three-dimensional color space where colors are characterized by their hue, saturation, and brightness emerges. Turquoise, for example, is more similar to green and blue than to red or yellow. Focusing only on hues, I call this the *similarity structure of hues*. When hues are arranged according to their similarity relations, they form a closed circle in which red is followed by yellow, green, and blue (in this order) and again by red. The second notion of structure is based on the distinction between *unique hues* and *binary hues*. Unique hues are "simple" in the sense that they are not composed from other hues. There are four unique hues: red, green, yellow, and blue. All other hues are binary hues; they are composed of unique hues. Violet, for instance, is composed from red and blue, and orange from red and yellow.[2] Given the hue-saturation-brightness characterization of colors, this discussion concerns the structure only within one dimension of colors as experienced. I call this the *unique/binary hue structure*. How it differs from the primary-secondary color distinction taught in schools and used in industry is discussed in the next section.

The fact that there are two notions of structure related to hues as they are experienced raises two questions: *Do both described structures exist?* And, if they do, *what is their relationship to each other*? The received view among philosophers is that the unique/binary hue structure exists. If it does, then a shift from one unique hue to another advances through hues which both unique hues contribute to. This shift happens gradually as the contribution of one unique hue is decreased and the contribution of another is increased. One consequence of this is that the unique/binary hue structure simultaneously also organizes hues into similarity and dissimilarity relations. Hence, the existence of the similarity structure of hues follows from the existence of the unique/binary hue structure. However, this does not hold when reversed the other way around, as the mere similarity structure of hues does not distinguish different types of hues (such as unique and binary hues). In other words, we can

[1] The structure of phenomenal color space concerns colors as *experienced*. Therefore, it should not be confused with different color models that make use of primary colors from which other colors can be combined.

[2] Rather than adding "unique" for each occurrence of "unique red", I simply refer to it as "red" (and inter alia for other unique hues) in sections 2 to 5, which focus on the unique/binary hue structure.

have the similarity structure of hues without the unique/binary hue structure, but not *vice versa*.

For the past two decades, the described view has played a significant role in philosophical debates about the nature of colors. Indeed, one can argue that ever since the appearance of Larry Hardin's book *Color for Philosophers, Unweaving the Rainbow* (1988), color philosophy has been dominated by two problems: (i) how to account for the unique/binary hue structure, and (ii) how to account for variation among normal color perceivers. The significance of both problems comes from the fact that they are difficult to account for without making reference to the experiences of the perceiver. Thus, they challenge the (commonsense) view that colors are the objective properties of the surfaces of objects (e.g. Bradley & Tye 2001; Byrne & Hilbert 2003; Hilbert 1992)—for example, the objective properties of objects do not exhibit any structure resembling the unique/binary hue structure. Given the central role of the notion of the unique/binary hue structure in color philosophy (for example, Hardin 2003 referred to it as a "major objection" against color objectivism), it is surprising that philosophers have not cast doubt on its existence and have instead focused on somehow accommodating it (e.g. Bradley & Tye 2001; Byrne & Hilbert 2003; Cohen 2003; Johnston 1997). Indeed, the only current exception appears to be Wayne Wright (2013; forthcoming), who briefly revisits some of the evidence mentioned in sections 3 and 4.

In this paper, I revisit the reasons why philosophers endorse the view according to which the unique/binary structure is the basic structure exhibited in all trichromat human perceivers' color experiences. It is concluded that none of these reasons are justified, despite their acceptance among philosophers. Accordingly, there are no undisputed reasons to endorse the view (not that it is necessarily false). The argument advances as follows. Section two discusses some clarifying issues concerning the unique/binary hue structure. Then, in the following three sections, the phenomenological, psychophysical, and neurophysiological reasons to endorse the structure are reconsidered. After concluding that these reasons cannot provide the needed justification, one possible conception of the structure of hues is sketched out in the section six.

2. Clarifying the unique/binary hue structure

Before elaborating on ways to justify claims of the existence of the unique/binary hue structure, let us explicate what is meant by the structure. Following Hardin's argumentation

(1988), which has become the received view on the matter, we need to clarify three issues. To begin with, the unique/binary hue structure supposedly describes the structure of hues as we experience them. That is, even if hues (and other dimensions of colors) are reducible to physical properties, both structures described in section one primarily describe how a hue phenomenally appears to us, and nothing more: a hue appears to be either a unique hue or a binary hue. Following Juan Suarez and Martine Nida-Rümelin's terminology (2009), we can express this as follows: *Binary hues are phenomenally composed*—phenomenally, they appear to be composed of two different hues. *Unique hues are not phenomenally composed* and thus they do not have a trace of other hues.

Consequently, the issue at hand does not concern mixing color pigments—e.g., combining secondary colors from primary colors as painters do. If it did, then the question of whether some hue is unique or binary would be subordinate to the chosen pigment and color model (like the RGB color model and the CMYK color model). Subsequently the status of, say, red and blue as unique hues would become questionable. Indeed, we can mix almost any hue from the various normally used pigments (and lights), but this does not mean that we experience the resulting hue as being composed of these pigments (and lights).[3]

Assuming for a moment that unique and binary hues exist, the second issue that requires clarification is the most general one: What is the nature of phenomenal composition? What is the nature of the relation that separates unique and binary hues from each other? Given that the issue of phenomenal composition does not concern mixing color pigments and lights, it is insufficient to simply state that a phenomenal composition is something that is composed out of something. Rather, the factors of the composition need to be present in the binary hues in some sense, as otherwise we could not experience them as composed. (As an analogy, consider feeling warm bath water, which we do not experience as composed of hot

[3] It is often taught that red, yellow, and blue are the only basic hues and that other hues can be mixed from them. The previous may explain paint-bias (Miller 1997), which is the common error of excluding green from the unique hues since it is true that green can be mixed from yellow and blue when the discussion concerns commonly used pigments. Yet this does not imply that green is any more a phenomenally composed color than red.

and cold water. This does not mean however that we could not tell that the temperature of the bath water is closer to, say, hot water than cold water.[4])

So in a phenomenal composition, the factors of the composition need to be present in experience. For the case at hand, this means that binary hues need to be phenomenally composed of unique hues, because otherwise binary hues would appear to be phenomenally composed of something else. In fact, if the unique hues were not present in experiences, then the arguments analogous to those used in relation to pigments could also be used here. So when we experience phenomenally composed hues we experience them as being composed of two unique hues that are also in some sense present in the experience.

Thirdly, and importantly, the unique/binary hue structure has been postulated as a structure that holds for all normal trichromat human perceivers and their experiences of hues (see for example Hardin 1988; Johnston 1992; Suarez & Nida-Rümelin 2009). That is, it is thought to be necessary that some hues are experienced as phenomenally composed while others are not. Given that the physiological structure underlying color perception is similar among all normal human trichromats, it would indeed be startling if some hue, say violet, turned out to have the binary hue structure only contingently.

Given these three clarifications, we can conclude that the claim is that our experiences of hues come in two varieties: those that are phenomenally composed and those that are not. The unique hues, which form the latter variety, figure in as independent parts of the phenomenal composition. The result of this composition is a binary hue. The relation of phenomenal composition obviously plays an important role here because binary hues could not exist without having a structure of being phenomenally composed of unique hues—without appearing as composed of unique hues. Thus, it is a necessary property of binary hues, if they exist, that they are phenomenally composed. With these issues of the unique/binary hue structure clarified, let us began considering what reasons we have to believe that the structure really exists.

3. Reflecting on one's own experiences

One possible way to justify the claim that some hues are phenomenally unique and some are phenomenally composed is by reflecting on our personal experiences. After all, the datum of

[4] This analogy is obviously not perfect, given that warmth is not a circular qualitative space while colors are. Nevertheless, this difference does not have a bearing on the issue of phenomenal composition.

the structure lies within our hue experiences and one would thus assume our experiences to be a major source of support for the existence of the unique/binary hue structure. However, the issue is not so simple: Although there has been extensive research on what wavelengths or color patches people pick out as unique red, green, blue, or yellow, there has not to my knowledge been any systematic studies on the issue of whether all people and cultures experience all of these hues, and no other, as unique. That is, it has not been systematically studied whether there could, for example, be a person that perceives orange as a unique hue, or a culture where it is held that green is a binary hue. Hence, there are no studies directly confirming or refuting the structure—rather, the evidence is thought to come indirectly from other linguistic, psychophysical, and neurophysiological studies (e.g., the World Color Survey, hue scaling, etc.), and these will be discussed in the following sections.

Many find the structure plausible however and fortunately we do not need to prove its existence for the purposes of this article. Instead, we can focus on the question of whether reflection upon our experiences provides us with good enough reasons to hold the unique/binary hue structure as it has been pictured. I take it that this would be the case if our judgments concerning our experiences were in general reliable and if there were no real disagreements concerning the unique/binary hue structure. Conversely, if there are reasons to doubt our introspection, and/or if there is substantial disagreement regarding the structure, then simply taking one's own experience of the hues as a truth that holds for all perceivers is unjustified. In what follows, I argue that the history of the phenomenal hue structure is a history of substantial disagreements.

To begin with, according to Gage, Democritus has already proposed "that yellow and green are two species of the same genus of hue." (1999, 12) Democritus's proposal was also accepted by Goethe, the first person to systematically study colors as they are experienced and a man who considered his color theory to be his most important contribution to the study of color. After decades experimentally studying colors as they are experienced, he presented his theory. It included the notion of three primary colors and three secondary colors (Goethe 1810). The three primary colors were red, blue, and yellow. Their afterimage-opposite colors (the colors that one perceives as afterimages from viewing primary colors) were green (for red), orange (for blue), and violet (for yellow). That is, Goethe concluded that green is not a unique hue, but rather has the same status as orange and violet. Furthermore, in Goethe's theory, the color pairs were different than what they are thought to be in the unique/binary hue structure.

In his highly influential book Handbuch der Physiologischen Optik (1867), Hermann Ludwig Ferdinand von Helmholtz argued that all colors can be produced by a combination of three lights (an idea put forward by Thomas Young). Importantly for the discussion at hand, Helmholtz argued furthermore that all color sensations are simple sensations because we cannot separate different elements of color in them. That is, Helmholtz did not reduce color sensations to three primary colors. In this way color vision differed from hearing for example, in which pitch and timbre can be separated. If any, the notion of structure suggested by our color vision was the similarity structure of colors.

The unique/binary hue structure was finally presented in its current form by Ewald Hering (1878), who had found Helmholtz's color theory lacking. Considering the current almost unanimous consensus, it is surprising that Hering's theory was not straight-forwardly accepted. Instead, it was seen as a rival to Helmholtz's theory, and both theories received much support. For the discussion at hand, it is most interesting to note that this dispute was not resolved by phenomenological reflection. Indeed, it is possible that the debate could have carried on to this day if Leo Hurvich and Dorothea Jameson (1957) had not provided quantified data of opponent-processes, since these were considered to support Hering's view.[5] The opponent-processes will be discussed in section five.

The history of color vision science thus illustrates how, at least for a period of 80 years, phenomenological reflection was not sufficient to convince many color vision researchers of the veracity of the unique/binary hue structure. One of the most philosophically interesting participants in this disagreement was Franz Brentano (1979), who argued that all greens are in fact phenomenally composed of blue and yellow—green is not a unique hue. What is remarkable about this philosopher's argumentation is that he clearly states his focus on colors as they are experienced, not on colors as mixed from pigments. Furthermore, like Goethe, Brentano also concentrated on this issue for many years and replied to objectors' claims that his introspection is poor by referring to his artist friends who

[5] The third prominent theory of color during the first part of the twentieth century was Christine Ladd-Franklin's (1916, 1929) theory of color sensations. It unified Helmholtz's and Hering's theories by incorporating the ideas of three types of receptors (Helmholtz) and four opponent colors (Hering). Ladd-Franklin was first to provide an explanation of the evolutionary development of color vision in humans too. Her theory is not elaborated on because it can be seen to anticipate Hurvich and Jameson's theory of opponent-processes and the interest towards Ladd-Franklin's theory decreased significantly once their theory was presented.

shared his doubts on the uniqueness of green. Thus, the status of unique hues was also controversial in early 20th century philosophy.

In summary, there has been considerable disagreement about the unique/binary hue structure, and its universal acceptance has not been studied systematically. Furthermore, this disagreement is not due to confusing the issues of mixing pigments and phenomenal composition. It is instead a result of many years of research conducted by some of the field's greatest experimenters. This does not mean that we are always or commonly mistaken when we reflect upon our experiences, nor does it mean that the unique/binary hue structure could not be a necessary structure of hues. Nevertheless, the previous discussion suggests that there is a real possibility that our conception of unique/binary hues is mistaken to the extent that phenomenological reflection is not sufficient to justify the existence of the unique/binary hue structure.

One could perhaps object to this by arguing that they are certain that the unique/binary hue structure is correct on the basis of their own phenomenal reflection. This objection is unmotivated, however, because the structure was postulated as a necessary structure exhibited by the color experiences of all normal human color perceivers. Hence, when one says that his phenomenological structure confirms that the structure is true, he is saying that it also holds for the experiences of those whose phenomenological reflection tell them otherwise. This raises the following question: what makes some peoples' experiences concerning the unique/binary hue structure more justified than others'? Goethe, Brentano, Helmholtz and his followers, for instance, most likely thought that their conception was right and those endorsing some other notion of the structure of hues were wrong. Given that people disagree on their judgments concerning their color experiences even when they result from a thorough phenomenological reflection, it is unlikely that proponents and opponents of the unique/binary hue structure are swayed by disagreeing views when the disagreement is based on the phenomenological reflection.[6] Then again, if neither side is mistaken, then the issue

[6] It is interesting to note that the same conclusion can be drawn from the history of describing the colors of the rainbow. If making judgments about one's own color experiences were easy, one would assume that this is a matter in which people would have approximately the same opinions. Yet, the number of colors perceived in the rainbow have been claimed to be three (e.g., Aristotle, later Thomas Young), six (e.g., Aëtius, Ammianus Marcellinus), seven (Sir Isaac Newton's assistant), eleven (Sir Isaac Newton), and too many to count (e.g., Ovid, Virgil) (Gage 1999; Newton 1704/1952).

would depend on the perceiver, and whether some hue is unique or binary would be a contingent matter—not a necessary one as the modal claim holds.

4. Linguistics and psychophysics to the rescue?

Possibly due to the above-mentioned problems and Hardin's influential book (1998), philosophers have usually drawn justification for the unique/binary hue structure from psychophysics rather than merely their own color phenomenology. This has been done in two very different ways. On the one hand, philosophers have justified the existence of the unique/binary hue structure by relying solely on psychophysical studies. On the other hand, some of the arguments for the structure link psychophysics to the underlying neurophysiology of chromatic processing.[7] The first approach will be discussed below and the second will be discussed in the next section.

One can identify at least four different arguments for the existence and primacy of unique hues that are based solely on linguistic or psychophysical studies. It is safe to say that for a long time each of them provided justified reasons to maintain the notion of the unique/binary hue structure. However, the situation has changed considerably during the past decade. In what follows, I will outline these arguments and the ways they have recently been challenged (further sources can be found in the references).

To begin with, the special status of red, green, yellow, and blue as unique hues has been argued for on the basis of *hue-scaling* (e.g., Abramov & Gordon, 1994). This is a method in which participants of the study are presented with a stimulus and their task is to estimate the percentage of different hues that this stimulus consists of. For example, a subject could be presented with a turquoise stimulus and she might report that it is 40 percent blue and 60 percent green. Hue-scaling has been considered to support the notion of unique hues because the results suggest that the four points of the hue circle—those of unique hues—are

[7] As the discussion on Helmholtz implied, he was explicit in not linking properties of chromatic processing with hues as experienced. Instead, unique hues became explicitly linked to neurophysiological mechanisms only after the opponent-processes were discovered in LGN. As will be discussed shortly, such an idea is no longer generally endorsed, as there is no physiological evidence for the existence of primary axes of opponent processes that match unique hues.

such that they are reported to consist of only one hue (e.g., some point in the hue circle would be 100 percent blue). Agreeing with this, Israel Abramov and James Gordon (1994, 468) state that they "find it virtually impossible to think of canceling or scaling all hues in [terms other than red, green, yellow and blue] and ultimately this is the principal justification for using [red-green] and [yellow-blue] as axes."

The support that hue-scaling experiments provide for the unique/binary hue structure suffers however from the fact that the studies have not included a proper control condition—either the subjects of the studies have been asked to use terms red, green, yellow and blue, or, if other hues are used, then these hues have not been as far apart on the hue circle as the aforementioned colors. This shortcoming was noted by J. M. Bosten and A. E. Boehm (2014), who asked their participants to report the hue of the stimuli by using the terms teal, purple, orange, and lime. Their results showed that the subjects performed this task just as well as when they used the terms red, green, yellow, and blue. Thus, when the proper control condition is taken into account, the hue-scaling does not support the idea that red, green, yellow, and blue (or any other four hues) have a special status as unique hues and that all other hues are binary.[8]

Secondly, it has been suggested that the studies on *color memory* provide evidence for the primacy of unique hues (Heider 1972; Heider & Olivier 1972). This is because color chips of unique hues are remembered better than those of binary hues in some studies. Possibly the most discussed population to exhibit this pattern is the Dani people, a tribe still classified as having a stone-age culture investigated by Eleanor Heider and Donald Olivier (1972). Dani people are particularly interesting because they have only two terms for colors. Hence, the fact that they were better at remembering the unique hue samples than the binary hue samples cannot be explained by linguistic biases.

While the performance of Dani people is consistent with the notion of the primacy of unique hues, Jules Davidoff, Ian Davies, and Debi Roberson (1999) were unable to replicate these results with the Berinmo people, another stone-age culture. Quite the contrary, the Berinmo people remembered best those color chips that were in accordance with their color terms. Given that these people have five terms to describe colors, none of which

[8] Moreover, Bosten and Boehm's results showed that what subjects identified as a unique hue shifted significantly as a function of the color terms used in the instructions. This in part causes one to "question subjects' abilities to identify certain hues as unique." (Bosten & Boehm 2014, A385)

correspond to terms in used in the English language[9], the same rationale that supports the notion of the primacy of unique hues in the case of the Dani people speaks against it in the case of the Berinmo people.[10] The authors also hypothesized that if color "categories always form around natural fault lines in perceptual colour space, it should be relatively easy to learn another language's colour categories" (1999, 204). Their results however did not provide any justification for this hypothesis.

Related to color memory, one might assume that if binary hues are composed of unique hues, our ability to identify binary hues would be less precise and stable than our ability to identify unique hues. That is, in tasks where we need to choose, say, a unique green color patch among a number of color patches, we would more consistently choose the same color patch than we would if we were asked to choose a binary hue (e.g., "a purple that is not too red nor too blue"). This is not the case, however. Instead, unique hues and binary hues show the same degree of within-individual variability and we are no better at reliably identifying unique hues than other hues. (Malkoc, Kay & Webster 2005; Bosten & Lawrance-Owen 2014)

The third argument for the unique/binary hue structure originates from the *color naming* study by Sternheim and Boynton (1966). In their study, Sternheim and Boynton investigated the primacy of unique hues by asking people to describe entire hue circle with as few color terms as possible. Their argument was that in order for a hue to be what they called 'elemental', its use must be both sufficient and necessary to describe the whole color circle. Their results showed that color terms for red, yellow, and green were elemental (each of them was required to describe the entire hue circle), whereas orange was not. Accordingly, the conclusion to be drawn is that unique hues are more basic than binary hues in these psychophysical experiments. (See Wooten & Miller 1997, for an overview of many other studies using similar methods.)

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[9] For example, they do not separate blue and green, but they have a separation that does not exist in English (see the study for details).

[10] It is worth noticing that, while the graphical multiscaling result gave reasons to accept the presented interpretation of the original Dani experiment (Heider & Olivier 1972), the interpretation can be questioned too. This is because the statistical measures used by Heider and Olivier gave conflicting results by also suggesting that the performance of the Dani people is best explained by linguistic and cognitive factors. For some reason, the first measure was accepted while an explanation for the second measure is still missing.

While Sternheim and Boynton's results appear to support the notion of unique/binary hue structure, the details of the study make one wonder why it has received so much prominence in philosophers' argumentation. Ignoring the fact that they were not able to show that blue is a unique hue (other studies showed this), a crucial methodological problem in this study is that the subjects were likely to be native English speakers. (The study was done in Rochester, USA, and the nine subjects were high-school, undergraduate, and graduate students.) As Bill Wooten and David Miller (1997) comment, with very few exceptions, other similar studies have also been done with American English speakers (those that they refer to are not exceptions). Accordingly, one could easily imagine that subjects from other language groups might use different terms to describe the color circle. For example, both the Dani and Berinmo people mentioned above can describe the whole color circle perfectly fine without the color terms used by English speakers! Hence, they would perform flawlessly in the color naming studies without appealing to terms referring to four unique hues.

Another language that does not show preference towards separate terms for four unique hues is Kwakw'ala. This case is fascinating because many Kwakw'ala speakers are bilingual and speak English as their second language. Accordingly, they know the distinction between yellow and green. Even so, they prefer to use their own term which applies to both yellow and green (Saunders & van Brakel, 1997). Thus, one would assume that they do not describe the hue circle with the terms yellow and green. Furthermore, van Brakel (1994) lists 57 languages that have only one word for yellow and green, and hence it is hardly a rare occurrence that the two colors are treated as one.

The general lesson to be drawn from the above examples is that there are different ways to describe color appearances, and not all of them support the notion of the existence of the unique/binary hue structure. Indeed, psychologist Kimberly Jameson (2005, 94) has recently argued that "one can describe color appearances [the hue circle] equally well as ratios of only red, yellow, and blue (as Goethe and others have proposed), similar to the way they are typically described using ratios of red, yellow, blue, and green." Accordingly, she (2005, 95) concludes that philosophers' argument for four unique hues (in this case Hardin's) is not very compelling, for the same argument "could be developed for the alternative set of primaries suggested."

Finally, one could argue for the existence of the unique/binary hue structure on the basis of *the uniformity of color categories* in different languages. Indeed, color terms in many languages are rather similar and based on this Brent Berlin and Paul Kay (1969) suggested that there must be universal constraints on their development. More precisely, they suggested that these constraints relate to black, white, and the unique hues in particular. A debate followed about whether such universal constraints explain the development of color terms. The two sides of this debate were the *relativists* (according to whom color terms are constrained only by linguistic, cultural, and cognitive influences) and the *universalists* (according to whom the biological chromatic processes determine that color terms are universal among all humans). However, as Paul Kay and Terry Regier mention, the universalist hypothesis, which they endorsed at this point, has “gained considerable acceptance over the years” (2003, 9085). One of the people Kay and Regier refer to is Hardin.

Nevertheless, as in the previous cases, the debate about this topic has changed considerably during the past decade. First, Kimberly Jameson and Roy D’Andrade (1997) suggested that the uniformity of color terms follows not from strong universal constraints related to unique hues, but from soft constraints concerning the irregularities of the color space in general (especially constraints on how saturated certain hue and lightness combinations can be). The idea was that the development of color terms is influenced by constraints determined by the overall asymmetrical shape of the color space and that the developed terms would provide the most optimal way to classify the color space. Ten years later, Regier, Kay, and Khetarpal (2007) formalized this third alternative, which is between the universalist and relativist alternatives, and found that the World Color Survey data support it. A few years later, they argued (2009, 885) that these constraints for color categories “do not flow from a limited set of privileged focal colors. Instead, in a natural generalization of the universal-foci account, all colors are focal (perceptually salient) to some degree.”[11] That is, there are some universal ways to classify color space—based on the shape of the color space, not unique hues—and because our color terms aim to classify them in the most optimal way, the color vocabularies of different languages tend to be similar.

The previous argument is in accordance with the re-assessment of the World Color Survey done by Rolf Kuehni (2005) and Jameson (2010). As Kuehni reports, only 38.2 percent of the 110 languages investigated in the World Color Survey included color terms for all four unique hues. For example, 36.4 percent had a term with a combined meaning for green and blue. Based on Kuehni’s study, Jameson (2010) argues that the World Color Survey does not in fact provide support for the view that color naming and color categories

[11] Indeed, excluding yellow, unique hues are not more salient in search tasks than binary hues. (Wool et al. 2015)

derive their structure from the unique hues. Accordingly, she concludes that this widely accepted view should be altered. As Kay and Regier's case illustrates, some former universalists have already changed their minds on this issue.

On the whole, what I have been arguing is that the previous decade has witnessed a mini-revolution in psychophysics related to color perception as regards the unique/binary hue structure. While the various lines of argumentation were previously thought to support the existence of the structure, each of them is now seriously challenged. Rather than supporting the notion of unique/binary hue structure, many nowadays think that the results of four different types of experiments demonstrate only linguistic, cultural, and cognitive influences (Davidoff, Roberson) or soft universal constraints that are not based on unique hues (Alvarado, D'Andrade, Jameson, Kay, Regier). Therefore, it is safe to say that psychophysics does not provide satisfactory means to justify the existence of the unique/binary hue structure.

The previous argumentation does not of course disprove the existence of the unique/binary hue structure. Instead, it only shows that the most prominent arguments used by philosophers and (previously) most psychophysicists to support the notion are no longer accepted by many prominent psychophysicists. Hence, perhaps it is time for philosophers to also reconsider these cases with an open mind.

5. Neurophysiological considerations

5.1. The Hurvich-Jameson Model as a Neurophysiological Justification

Given that the notion of unique/binary hue structure is not firmly grounded with purely psychophysical results, grounding it by combining psychophysics with neurophysiology could perhaps work better. One motivation for this approach is that we already know much about color perception. For example, we now know that colors are represented at the retinal level by excitations in three different cone types and that this stage is followed by a *second stage of chromatic processing* in which these cone excitations are combined.

Traditionally, the processing in the second stage is explained by means of the Hurvich-Jameson opponent-process theory. It is this theory that philosophers (and scientists alike) almost unanimously refer to when they seek a neurophysiological justification for the unique/binary hue structure. The most recent philosopher to discuss the Hurvich-Jameson opponent-process theory and its merits is Paul Churchland (2005). Another reason he is particularly relevant for our purposes is his extension of the previous discussions by arguing that the opponent-process theory forms a basis for new predictions that can be tested and verified. Churchland argues that this predictive power provides an additional motivation for embracing identities between color experiences and the states of opponent processes. Following his terminology, I refer to opponent processes as described in the Hurvich-Jameson opponent-process theory with “the H-J network” and the theory of such processes with “the H-J model”.

The basic idea behind the H-J model is that hues and their phenomenological structure reflect how they are neurally processed among normal human trichromats. In accordance with this idea, the H-J model was proposed mainly as an explanation for two features of our color phenomenology. The first feature is the topic of this paper: there are two fundamentally different kinds of hues, unique and binary hues. The second feature is that unique hues form two opponent-color pairs (red-green and blue-yellow pairs) or color-appearance axes. The two hues in a pair cannot be combined to form binary hue: while a binary hue can be composed of, say, red and blue, no naturally perceived binary hue is composed of red and green or blue and yellow.

The H-J model explains the features mentioned above by maintaining that signals of three cone types are combined in three different channels. Two of these channels process chromatic information in an opponent fashion and one processes brightness information. Importantly, the H-J model maintains that the activation levels along the chromatic channels correspond with the color-appearance axes and that we perceive unique hues when one chromatic opponent process channel is inhibited or excited and the other is in equilibrium. Since there are only two chromatic opponent channels with two ways to differ from equilibrium, the channels can signal four unique hues. All other hues result from the activation of both channels and are consequently composed of two unique hues. Thus, unique hues are special since they have a representation in the H-J model—they reflect the activation within an opponent channel—whereas binary hues are represented only by means of unique hues. As opponent processes can signal at best only one hue at a time, the H-J model can also explain the existence of opponent-color pairs. The H-J model therefore appears to be successful in explaining the previous two features of our color experiences.

The H-J model was first developed as a theoretical explanation for the features of our color phenomenology. In 1960s, it received support from the physiological findings according to which chromatic processing in LGN and V1 function in opponent fashion. Churchland argues that we can further strengthen the case for the H-J model since the model can also be used to predict the existence of color experiences we cannot normally experience. Simplified, the idea is the following: When we look at some color for a long time, related opponent cells become fatigued. When we move our gaze to another color, this fatigue is expressed in the opponent cells' tendency to signal the opposite color. For example, if we stare at a blue patch for some time and then move our gaze to a white surface, the surface looks yellowish. This well-known phenomenon related to adaptation becomes interesting due to Churchland's claim that by choosing two colors—those that we become adapted to and those that we later look at, suitably—we can perceive colors whose presence opponent processes cannot signal in normal situations. Examples of these colors are a redder red than we can normally perceive and a maximally dark black that is simultaneously blue. What is significant here is that Churchland predicted these color experiences based on the H-J model. Since everyone can easily test and verify that these predictions hold (see Churchland 2005 for details), this appears to provide an additional motivation for Churchland's claim that every color experience can be identified with some state of the H-J network. Consequently, what we have here is an empirically well-grounded theory that incorporates the notion of unique/binary hue structure.

Before more critically examining how well the H-J model succeeds in explaining our color experiences, it is important to explicitly recognize that the theoretical attractiveness of deploying opponent processes in establishing the existence of the unique/binary hue structure lies in their structural similarity to the unique/binary hue structure. The H-J model explains the alleged unique/binary structure of hues by appealing to the idea that neural processes related to chromatic processing exhibit the same structure as the unique/binary hue structure. Obviously, this explanation is only successful if we accept that the structure of phenomenal color experiences mirrors the structure of chromatic processes. I will not question this assumption. I am in fact quite willing to accept it here as the argumentation in the rest of the paper is built upon it. Hence, for the present purposes, I agree with Churchland that our color phenomenology could be explained or reduced to our chromatic processing and that the structure of the latter is exemplified in the former. Accordingly, the question we need to answer is whether the H-J model is a correct model of our conscious color perception.

Despite the strong explanatory appeal of the H-J model and the fact that it appears to be empirically well-grounded, the psychophysical data does not in fact conform to it. To begin with, Hurvich and Jameson argued for the H-J model partly because of the results obtained in hue cancellation experiments, a procedure that provides quantitative data of opponent-colors. In the hue cancellation experiments, subjects are asked to adjust the amount of fixed light so as to cancel its complementary color from the target light. For example, a subject can be presented with a target light and asked whether it is bluish or yellowish. If it is bluish, then the subject adjusts the amount of yellow light until it "cancels" the blue component from the target light, resulting in a light that is white, red, or green. The amount of yellow light reveals the strength of the cancelled blueness and can be used to plot the opponent-processing curve. Hue cancelling experiments, however, begin with identifying the wavelengths that corresponds with unique hues for each subject. Thus the experiment *assumes* the special status of unique hues although there is no reason why the task could not be performed based on other hues (e.g., purple could be cancelled with lime). Accordingly, any claims about the neurophysiological opponent-process mechanisms based on hue cancelling experiments are not justified on the sole basis of psychophysical experiment.

Second, although the activation in opponent channels was long thought to correspond with the color-appearance axes, many scientists have agreed that the evidence that has emerged since J. Krauskopf et al.'s study (1982) suggests otherwise. Michael A. Webster et al. (2000, 1553), for example, have argued that "[t]he LvsM and SvsLM axes are often loosely described as 'red–green' and 'blue–yellow' axes, respectively, yet the discrepancies between the cardinal cone-opponent and color-appearance axes are large." In other words, the physiological recordings of opponent processes do not correspond with the unique hues. Instead, color experiences that correspond with the inhibitory and excitatory levels of opponent processes are better described as purple, orange, greenish-yellow, and cyan (DeValois et al. 1997). Given that the hypothesis in the H-J model states that unique hues are processed in the opponent channels, then purple, orange, etc. should be unique hues. Since this is not the case, hues cannot be identified with the known states of opponent processes (or the H-J network) even if one in general agrees that our color experiences are reducible to the states of neural processes.

Another discrepancy between the H-J model and empirical data is that the experienced unique hues are not linearly arranged as true axes because they are not opposite in the color space—a unique hue stimulus cannot be made grey by cancelling it by adding its opponent unique hue. Thus, E. J. Chichilnisky and Brian A. Wandell (1999, 3444), for example, write that "[w]hile the presence of a nonlinearity is certain, its form is not, so linear opponent models remain in use in spite of the empirical evidence." Hence, opponency in general does not concur with psychophysical data in this respect either.

Finally, the explanatory power of the H-J model was based on the postulation that the hues form opponent color pairs because they result from a single underlying process—the special status of unique hues and the opponent hue pairs resulted from the fact that they were phenomenal expressions of single opponent processes. Contrary to this postulation, Michael A Webster et al. note that "judgments of red and green or blue and yellow scale differently with eccentricity, suggesting that they do not depend on a single underlying process. The independence of the color-opponent poles is further suggested by the observation that red versus green or blue versus yellow are not collinear within cone-opponent space." (2000, 1553) In other words, Webster et al. argue that experiences of red and green or blue and yellow do not result from a single process (a conclusion that would also explain why the unique hues are not arranged linearly in color space). If this is true, then the H-J model cannot account for them, even in principle. In consequence, *this finding suggests that the postulation of some new stage of color processing may be necessary*.

In short, we have seen four different but possibly interrelated flaws in the attempt to justify the unique/binary hue distinction with the H-J model. *First*, the H-J model cannot be justified solely on the basis of hue cancelling experiments. *Second*, unique hues do not correspond with the activation in known opponent processes. *Third*, unique hues are not linear in a sense that a unique hue can cancel its opponent hue in hue-cancellation experiments. *Fourth*, the unique hues as opponent hues may not follow from a single process, as the H-J model would anticipate. Given these discrepancies, the properties of the H-J network are not similar enough to those of the unique/binary hue structure to lend support to the existence of the structure.

With the H-J model rejected, one may wonder about the status of the color experiences predicted by Churchland, which supposedly provided additional motivation for the H-J model. Fortunately, all that is required to explain them is a theory that explains both the structure of our color space and how adaptational processes in color processing are realized. In effect, this theory would describe the effects of adaptation in the same way as the H-J model, but in relation to color space and not opponent process axes. That is, an effect of adaptation would be a change in color experience that points in the opposite direction of the adapted color in color space. In this way, the theory could explain the new colors brought to our attention by Churchland and provide a basis for predictions concerning them. Consequently, the success of Churchland's predictions made on the grounds of the H-J model were not based on the model itself. Instead, the success was due to the fact that the H-J model provides sufficient description of the color space as well as an explanation of adaptational processes that adequately describes the effects of adaptation.

Then again, although the H-J model describes both the adaptational processes and the alleged structure of color space, this does not mean that one theory must provide us with both these descriptions. Instead, it could be that one theory accounts for the processes related to adaptation while the other describes the structure of our phenomenal color space. One empirically plausible alternative, and the one that I endorse, is the following: the H-J network accounts for the adaptational processes and it is succeeded by a third chromatic processing stage that accounts for our color experiences. In this case, the third stage might inherit some features of the previous stages (such as adaptational effects). Accordingly, predictions based on the earlier stages provide evidence for their existence, but not for the idea that they would be the final stages of chromatic processing. Thus, the situation would be similar to one in which we make predictions about color experiences based on the known properties of photopigments in the retina (or the lack thereof in dichromats' retinas). In this case, successful predictions do not explain everything about our color experiences, and they do not allow us to reduce color experiences to the cone activations. This also explains why the H-J model is unsuccessful in justifying the existence of the unique/binary hue structure. If the processes related to the H-J network precede those related to our conscious perception, then there is always room for structural transformation after these processes. As a result, opponent processes cannot justify claims about the unique/binary hue structure any more than processes related to three cone types could justify claims about the existence of only three unique hues.

The alternative above is not only a theoretical option, since opponent processes in LGN are wavelength-based processes while our conscious perceptions of hues is not about perceiving wavelengths. Accordingly, Stanley J. Schein and Robert Desimone (1990), for example, have argued that chromatic processing takes place in V4 and shares only some features with preceding chromatic processes. In a similar fashion, Semir Zeki (1983; 1998) has argued that the processing of color constancy, and thus the processing related to our conscious color experiences, happens in V4, although V2 could also be involved. Of course, some retinal processes may well be and probably are involved in this, but our conscious perception, which demonstrates color constancy, is not constituted by opponent processes. It is therefore not only possible but also very probable that the chromatic information that opponent channels (the H-J network) convey does not correspond with our phenomenal color experiences, nor does it need to. For this reason, it should not be surprising if known opponent processes do not yield support for the existence of the unique/binary hue structure.

5.2. What do the Cortical Processes tell us about the Structure of Hues?

The previous discussion leads to the conclusion that if we want to have a neurophysiological justification for the existence of the unique/binary hue structure, what we need is an account of the correlates for our conscious perceptions of hues and see how they are organized rather than how the processes occurring before them are organized. Presumably, these correlates should be found in the cortex, in areas V1, V2 and/or V4, or maybe even beyond. The rationale for focusing on these areas is that the presence of their hue-selective neurons suggests that they have at least an important—if not constitutive—role in processing related to our phenomenal hue experiences. (In the chain of chromatic processing, the known opponent-processes exist before these areas and cannot thus be used in arguments that concern the constitutive characteristics of our color experiences.)

The best correspondence between hue experiences and neural processes has been found in V2 by Youping Xiao, Yi Wang, and Daniel Felleman, who discovered that colors are represented by the location of the peak activation the colors produced in cortical area V2 in macaque monkeys (2003). The area where colors were represented corresponded with the DIN color system (German standard color chart). More precisely, this correspondence was only in the order of the hues, not between a hue circle of the DIN system and locations of response activation peaks. Hues in the DIN system follow each other in the same order as their response activation peaks in the cortex. The authors wrote:

> the peak regions of the responses to different colours [in V2] were spatially organized in the same order as colour stimuli are arranged in the DIN (German standard colour chart) colour system. Nearby regions represented colours of a similar hue. (Xiao et al. 2003, 535)

The conclusion Xiao et al. (2003, 537) draw from their results is that “the observed organization of the peak responses in the order of the hue had a biological origin.” The form that the response activation peaks took was a “band organized in an L-shape.” (Xiao et al., 2003, 536) This means that, physiologically speaking, there exists nothing that resembles the unique/binary hue structure. On the contrary, since no one location has more importance than the others, there appears to be no reason to suppose that some hues would be unique hues. For instance, aqua (turquoise), orange, and violet had only one location peak, as did unique hues. Hence, if considered physiologically, hues that are traditionally considered as binary do not contain any more independent factors than unique hues. Furthermore, the DIN system does not perceptually emphasize any unique hues. In short, no level of description of Xiao et al.’s results provide justification for the existence of the unique/binary hue structure.

Xiao et al.’s results are notable for the discussion at hand for four reasons. First, they provide a prime example of a physiological description of color processing that is structurally organized in a way that resembles our hue experiences. Second, this processing occurs in an area of the cortex where the activation is often thought to correlate with our phenomenal experiences. Third, there is no experience-independent way to justify the claim that response activation peaks of unique hues would somehow be more fundamental than the response activation peaks of binary hues or that binary hues would really have composed structure. That is, what we have here is a case in which the activation related to experiences of unique and binary hues does not mirror the unique/binary hue structure. Fourth, the DIN color system is a version of the similarity structure of hues, and the neural processes Xiao et al. found in V2 accordingly parallel the phenomenal similarities and dissimilarities described in this structure of hues. These observations therefore point to the conclusion that our phenomenal hue experiences exhibit only the similarity structure of hues.

This conclusion receives support from Webster et al.’s aforementioned finding that opponent hues (red-green and yellow-blue) do not result from a single underlying process. It also concurs with the fact that the recorded activations in the most promising areas do not support the idea that red, green, yellow, and blue are unique hues. On the contrary, Peter Lennie et al. (1990) and Russell DeValois et al. (1997) have convincingly argued that hue sensitivities in V1 are scattered uniformly. Similar results have been found for V2 (Kiper et al. 1997) and V4 (Schein & Desimone 1990). Thus, the visual cortex does not appear to show preference for any fundamental color axis.

One line of argument against the aforementioned conclusion is to maintain that the neural correlates for hues in the visual processing should be found later than in V2. Given the hierarchical nature of visual processing, this is a reasonable objection. Furthermore, it has even been argued that the neural basis for unique hues has been found in these areas. Indeed, Cleo M. Stoughton and Bevil R. Conway (2008) showed how globs (regions of the posterior inferior temporal cortex that respond to colors) have preferences towards red, green, and blue while the explicit representation of yellow was weak. However, John Mollon (2009, R442) pointed out that this outcome may have been a consequence of using a monitor that distorted the stimuli and concluded that "it remains the case that no one has shown a cortical origin for the unique hues". Conway and Stoughton (2009) largely agreed with this possibility. Even more tellingly, in a study published the same year, Conway argued that globs' hue preferences are arranged in accordance with perceptual color space: "the tuning of sequentially encountered neurons … shifted gradually through small sections of the perceptual color space (red–orange–yellow–green–blue–purple–red)" (Conway & Tsao 2009, 18038). That is, hue sensitive neurons in the subsequent processing stream to V2 are likewise tuned to all or almost all hues (they do not show any preference for unique hues) and are organized as in the similarity structure of hues.[12] Hence, if cortical processes tell us anything about the structure of hues, it only supports the notion of the similarity structure.

6. What if the unique/binary hue structure does not exist?

The phenomenological reflection, psychophysical results, and neurophysiological data do not provide even remotely undisputable justification for the existence of the unique/binary hue structure. Yet, many have found the notion of unique hues credible, which is demonstrated by the fact that even philosophers who hold color objectivism have not contested it. Thus, despite the previous facts, if pressed they might say that some hues do appear unique and some binary—some hues even appear to function as opponent color pairs. In this section, I try to address these issues. It is not my purpose to provide a decisive account of them, but only to *sketch one possible account* of how these intuitions could be explained with the similarity structure of hues (and thus without invoking the unique/binary hue structure).

In order to do that, let us begin by elaborating on the similarity structure of hues. The basic idea is that the hues could be arranged by means of the similarity and dissimilarity relations.[13] When they are so arranged, they form a continuous circle: if we start going around the circle in either of the two possible directions, hues similar to each other come one after another until we arrive back at the hue we began with. In this circle, no point

[12] This is in accordance with the earlier study showing that the preferred hues of color-selective neurons (those that respond almost only to colors) cover nearly all color space and thus show no preference for unique hues (Komatsu, Ideura, Kaji & Yamane 1992).

[13] For a very thorough discussion on how this could be done, see (Clark 1993).

is more important than any other point. Hues make up the continuum of hues and all of them have phenomenally equal status. Considered within this framework, no hue is strictly speaking phenomenally composed from other hues.

This does not mean, however, that we could not isolate some areas in the circle and consider their relationship to other points in the circle. As an analogy, consider the case of the temperature of water. Although few people, if any, can tell whether the water is 43 or 44 degrees Celsius based on their sensory experiences, most can say that it is somewhat warm in both cases. We can also distinguish this water from water that is cold, merely cool, or hot.[14] The same holds for hues: we can isolate some areas in the hue circle that we then regard as *basic hues* and we can estimate their relationship to other hues or areas in the hue circle. In other words, the similarity structure of hues does not exclude the possibility that we can estimate how close hues we experience are to each other—indeed, the whole structure is organized by means of such comparisons—and this does not assume that basic hues are unique in the sense described above.

The previous explanation raises the question of what the nature of the basic hues is. Fortunately, the discussion in sections four and five suggests an explanation for basic hues. *First*, their basis lies in the similarity structure of hues, which in turn has a biological origin. *Second*, basic hues cover an area of the similarity structure of hues, not determinate points, and are unlikely to have precise boundaries. *Third*, the operation of estimating the relationships of hues is a cognitive one, which suggests that areas of the hue circle that are relied upon to form a basic hue depend in part on cognitive factors. *Fourth*, since some hues show basicness over others in the color naming tasks, one is led to conclude that color terms play a role in determining the basic hues as well. This possibility is emphasized by the fact that the referents of ordinary color terms cover areas of the hue circle, not some determinate points, and basic hues would hence resemble them in this respect. In addition to the above mentioned psychophysical evidence for the discussed close connection of color terms to color naming and color categories, this also concurs with the evidence that the color categories of a language can have an influence on even simple color discriminations (Winawer et al. 2007).

[14] It should be remembered that this analogy is only partial because warmth does not form a circular qualitative space. This difference is not crucial here, however, because the issue at hand concerns similarity judgments, not the linearity or circularity of a quality space per se, and we can make such judgments for both colors and warmth.

Accordingly, *the basic hues are comprised of areas in the hue circles that are cognitively and linguistically important*. Thus they do not receive their basicness solely from their phenomenology, but also from their role in cognitive and linguistic operations—this again emphasizes the difference between the criteria of a basic hue and a unique hue.

With this conception of basic hues, in which they are partly constituted by our cognition, we can explain the phenomena that arguably gave support for the existence of unitary-binary hue structure without simultaneously invoking that structure. First, we can explain the special status of some hues over others. Since some hues are basic due to their cognitive importance and prominence in color language, they become more significant than the others and are also better recognized and remembered. Another aspect of this explanation for uniformity concerns the limitations of our memory and the requirements of our cognition. The choices and number of basic hues reflect what and how many basic hues we can make use of.[15] Arguably, the basic hues would be rather different from each other in these cases since they would then be the easiest to use and remember. Accordingly, basic hues would be those that are relatively far away from each other in the phenomenal hue circle (as red, green, yellow, and blue in fact are). In practice, this would mean that our color terms, and subsequently basic hues (since they are partly constituted by color terms) would be a nearly-optimal way to classify the phenomenal hue circle. This idea extends the one discussed in relation to color categories and the World Color Survey according to which "the need to maximize informational content of the available terms will dictate the region of color space to which [color terms] are applied." (Jameson & Alvarado 2003, 133; see also Jameson & D'Andrade 1997; Regier et al. 2007)

Second, the notion of basic hues also provides us with an explanation for why some hues are considered binary hues. Although no hue is strictly speaking phenomenally composed, we occasionally use other color terms to describe them (like in the case of yellowish-green). For instance, since hues that are not basic are still close to basic hues in the hue circle, we need to use basic hues to describe them. In other words, they come to be described by two hues, which in turn make us regard them as composed hues. Thus, it is our language that suggests that some hues are composed.

[15] At the same time, this plasticity of the basic hue categories would explain the larger color vocabulary of visual artists and their reluctance to regard only red, green, yellow, and blue as basic hues (and unique hues). Since most people do not need such a refined color vocabulary, they consider fewer hues as basic hues.

Third, if red, green, yellow and blue are basic hues for a person, we can also explain why red and green (or blue and yellow) are not perceived together in normal circumstances.[16] Since we have here four basic hues and the hue circle forms a continuum that runs from one basic hue to another, any given point in the hue circle can be close to only two basic hues. If we make the plausible assumption that the binary hue becomes defined through those basic hues that are closest to it, then no binary hue can be simultaneously red and green because blue is between these hues in one direction and yellow is between them in the other.[17] This would also provide an explanation for why Brentano considered green a binary hue: his basic hues did not include green, and hence green became defined through blue and yellow. Likewise, if we divide color space in a fine-grained way, such as by making orange one of the basic hues, then no hue can simultaneously appear red and yellow. Instead, these hues would appear to be either reddish-orange or yellowish-orange, which explains how someone (like the author) could have these kinds of hue experiences.

Finally, it was suggested in section 5.1. that the H-J model describes the second stage of chromatic processing and that, although this provides a possibility that the structure of color space is transformed after the known opponent processes, the properties related to the opponent-processes can have bearing on the following stage of processing that constitutes our phenomenal experiences. Although this suggestion can be assessed only when we know more about the cortical processing of chromatic properties, the suggestion would explain two things.

First, as discussed above, the hue cancellation and adaptational processes are often linked to the opponent processes. If such processes constitute the second stage of chromatic processing and if some of the phenomena related to it are passed on to the next stage of chromatic processing, then hue cancellation and adaptational processes can also be accounted for in the provided framework. For example, if red and green (or any other colors that are opposite in the similarity structure of hues) produce incompatible activation in opponent-processes, and such activation explains, say, why experiencing green causes an

[16] They can be perceived together in special circumstances (Crane & Piantanida 1983) and this has been used in an argument against color objectivism (e.g., Arstila 2003).

[17] As an analogy, consider a line in which we arbitrarily mark some basic points. Every non-basic point is then close to only two basic points and becomes defined in relation to them and not to the other basic points. The same thing holds for color space, and that is why every "composed" hue can only be composed of two hues.

after-image of red, then the effect can also be explained within the current framework—it is simply that the story of adaptation does not concern the final stage of chromatic processing.

Second, it would mean that the similarity structure of hues would be weakly constrained, but not determined, by the opponent processes. This in turn would explain why humans normally have similarly asymmetrical color spaces. Because basic hues would thus have some biological constraints, this adds to the provided explanation of why there is uniformity in basic hues for perceivers both within one language group and across different language groups. That is, the soft constraints of the uniformity of color terms that Jameson and D'Andrade suggested would result from the transformation from the second stage of processing to the third stage of processing. In other words, the reason some areas of the hue circle form a basic hue may be that the similarity structure of hues is preceded by the opponent-processes in the chain of chromatic processing.

As mentioned above, this suggestion can properly be assessed only when we know more about the cortical processing of chromatic properties—at this point, the neurophysiological details of the suggestion remain unclear. It is worth noting, however, that the suggestion receives support from the study by Malkoc, Kay and Webster. They (2005, p. 2167) argue that while there is "compelling evidence for the dissociation between the dimensions of color appearance and precortical color organization [i.e, the second stage of processing that consists of opponent processes]", the statistical analysis between the opponent processes and color appearances (which result from the third stage processing) suggest that (excluding red) the opponent processes relate to what is traditionally considered binary hues, not unique hues. Consequently, they *speculate* that the second stage of color processing weakly constraints the third stage of processing by providing the boundaries of what is traditionally considered unique hue categories.

This explanation of how color terms and related cognitive factors bring about the apparent distinction between unique and binary hues converges with some of the proposed views of categorical perception of colors. It is especially close to Debi Roberson and Jules Davidoff's view (2000; 2005), according to which cognitive and linguistic color categories influence how the continuum of the similarity color structure is categorized. That is, they take the unique/binary hue structure (or basicness of some hues) to be imposed on the similarity structure of hues on the basis of linguistic and cognitive factors, as do I. They base their claim on the results of the similarity judgments, short-term memory, and long-term learning tasks conducted in various language communities. Our difference lies in the fact that, whereas I regard basic hues to be weakly constrained by biological processes, they put forward the relativist notion of color structure and thus in effect reject this constraint.

7. Concluding Remarks

This paper began by presenting the main ideas of two different notions used in descriptions of the structure of hues as we experience them. Since these notions differed, the questions that readily proposed themselves were: do both exist and what is their relationship to each other?

The received view among philosophers maintains that there are four unique hues and that they are organized in opponent color pairs forming so-called color-appearance axes. The unique hues are primary when compared to other hues, since all other hues can be described and composed from these four hues. Furthermore, it was argued that the unique/binary hue structure organizes hues in similarity and dissimilarity relations and thus the similarity structure of hues can be understood to be subordinate to the unique/binary hue structure.

The received view is challenged, however, by phenomenological, psychophysical, and neurophysiological facts, as they do not lend support for the existence of the unique/binary hue structure. Instead, they imply that the retinal and opponent processes are followed by a third processing stage (which takes place at visual cortex), a stage that philosophers have not taken into consideration. One important aspect of this third stage and the dimensions of color appearance it brings about is that it does not incorporate the unique/binary hue structure. Thus although the unique/binary hue structure has played a central role in the philosophy of color, the arguments based on it remain on an empirically implausible view of the color perception and philosophers should focus on the similarity structure of hues instead.

All this is to say that if we follow the common practice among color philosophers to revise our theories in the light of empirical findings, we should conclude that we do not have justified reasons to maintain that unique and binary hues exist. The inverse also applies: we may need to revise the conclusion that the unique/binary hue structure does not exist when we learn more about our color vision. Yet the plausibility of the proposed alternative is supported by the fact that there is some evidence for the influence of cognitive factors on color perception and categorization, and that we can use the similarity structure of hues to explain phenomena related to the unique/binary hue structure without simultaneously invoking the unique/binary hue structure as a necessary structure of hues among normal trichromats.

Let me end this paper by briefly discussing the results in the broader context of color philosophy. According to color objectivism, colors are objective properties of the surfaces of objects (see for example Bradley & Tye 2001; Byrne & Hilbert 2003). This view has been challenged by the large variation among normal color perceivers and the unique/binary hue structure of color space. The challenge from the unique/binary hue structure is that the objective properties of objects do not exhibit any structure that bears resemblance to the unique/binary hue structure. Given the reasons to refute the existence of the structure as understood by the opponents of color objectivism, then "a major obstacle to attempts to motivate some form of realism on the basis of the systematic relations between physical properties and color experience" is removed (Wright forthcoming).

One could argue, however, that color objectivists are now faced with new problems. This is because the objective properties of objects match with the similarity structure of hues only to some extent, but not perfectly. For example, the similarity of surface spectral reflectances does not guarantee the similarity of color experiences (see Byrne and Hilbert 1997; Wright forthcoming, section 2, for this point). Moreover, the surface spectral reflectances do not explain why the color space is asymmetrical—why there are more greens than blues, or why yellows are on average more luminous than blues. Therefore, although color objectivists can avoid the arguments based on the unique/binary hue structure, some of comparable issues can be raised based on the similarity structure of hues. Changes to the current theories are likely required to address these concerns since the best-developed means to account for the similarity structure of hues by color objectivists is based on an idea close to the notion of unique hues (see Byrne 2003; Byrne & Hilbert 2003). Hence, if there are no unique hues, then how can we account for the similarity structure of hues?[18]

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