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Considering the Prevalence of the "Stimulus Error" in Color Naming Research

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Abstract

In "*Does the Basic Color Terms discussion suffer from the Stimulus Error?*" Rolf Kuehni describes a research stumbling block known as the "stimulus error," and hints at the difficulties it causes for mainstream color naming research (Kuehni, This Issue). Among the issues intrinsic to Kuehni's "stimulus error" description is the important question of what can generally be inferred from color naming behaviors based on bounded samples of empirical stimuli. Here we examine some specifics of the color naming research issues that Kuehni raises. While we share Kuehni's view regarding potential problems caused by the "stimulus error" and his concern regarding its prevalence, Kuehni's commentary seems primarily aimed at stimulating a general discussion of color naming research implications, because the articles he critiques do not actually commit the "stimulus error" in any serious sense. Based on Kuehni's comments, we further examine some of the relevant empirical and theoretical implications for cross-cultural color naming research.

Keywords
individual differences, unique hues, stimulus error

Introduction

In his commentary on *Journal of Cognition and Culture, 5(3-4)*, special issue on Culture, Cognition and Color Categorization (abbreviated below as *JCC 5(3-4)*), Rolf Kuehni suggests that authors Bimler (2005), Jameson (2005), Roberson, Davies, Corbett, & Vandervyver (2005), and Sayim, Jameson, Alvarado & Szeszel (2005) all commit some form of color science "stimulus error" (Kuehni,

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This Issue, p. 113-117). The "stimulus error" Kuehni describes is summarized by the following two statements:

(1) It is well known that physical measures of color stimuli do not correspond to measures of perceptual color experience.
(2) Color naming researchers make the classic "stimulus error" when they specify or use stimuli standardized in terms of physical measures **and** assume that perceptual color experiences on such stimuli are equally standardized (in other words, they forget (1)).

In Section 1 below we first examine the basis for Kuehni's claim that authors in *JCC 5(3-4)* commit some form of this "stimulus error" and we resolve those concerns in a straightfoward manner. In Section 2 that follows we explore some of the general issues Kuehni raises concerning the "stimulus error," including some principles from opponent colors theory, and discuss some of the important implications these bring to cross-cultural color naming research.

SECTION 1: Do Bimler (2005), Jameson (2005), Roberson et al. (2005), and Sayim et al. (2005) commit the "stimulus error"?

Kuehni (This Issue, p. 114-115) describes five instances from *JCC 5(3-4)* to support the claim that the articles of Bimler (2005), Jameson (2005), Roberson et al. (2005), and Sayim et al. (2005) all commit the "stimulus error." In the articles cited one can trace these five "stimulus error" instances to one of two sources: Either (A) a "stimulus error" occurs through quoting or discussing the existing literature while addressing a derivative or secondary point, or (B) a "stimulus error" follows from the general failure of modern empirical psychology to gain direct access to the qualitative experiences of research participants. As detailed below, the cases Kuehni cites do not amount to serious, inexcusable, instances of the "stimulus error." However, because both (A) and (B) paths of slippage are likely to be common in color naming research, the instances of "stimulus error" Kuehni lists are detailed below.

Reason (A): Committing a "stimulus error" by quoting or discussing the existing literature

The present authors admit to maintaining, or replicating, "stimulus errors" inherent in the existing literature, and acknowledge that the occurence of such "stimulus errors" in well-accepted ideas in the literature underscores the legitimacy of the question posed in the title of Kuehni's commentary. Consider the following cases where a "stimulus error" is replicated due to Reason (A).

With regard to Bimler (2005) Kuehni states:

> *… in his survey of the 'state of the art' in the discussion of basic color categories in the recent special issue of this journal (Vol. 5, No 3-4, 2005) Bimler states (p. 270): [1] "For our purposes, each color percept comprising the visual environment can be mapped onto a point within the solid that represents the gamut of physically-realizable surface colors." Later (p. 281) he writes: [2] "In practice the primary hue names are not the points of a perceptual compass; plotted as directions in the isoluminant plane they do not map out at equal angles"* (This Issue, p. 114-115).

In quote [1] Bimler uncontroversially suggests that an individual's surface color percepts can be linked to a color space of surface spectral reflectances. In quote [2] Bimler correctly implies that Unique Red (UR) and Unique Green (UG) are neither opposite to each other, nor orthogonal to the polar Unique Blue-Unique Yellow axis (UB-UY) in any color space that accommodates the psychological facts of color mixing and the realities of trichromatic vision. Early developers (e.g., Ewald Hering (1920) and Wilhelm Ostwald (1916)) and the modern proponents of the Swedish *Natural Color System* (e.g., Hård, Sivik & Tonnquist 1996) have shown that it is possible to define a *phenomenological* color space in which UR and UG form the two poles of an axis that is orthogonal to the UB-UY axis, but such models do violence to actual perceived similarities among hues, and they do not predict a wide range of color mixture results. Thus, in the worse case Bimler is simply working within the conventional practices found throughout the color naming literature, and thereby maintains "stimulus errors" inherent therein.

Similarly, Kuehni attributes a "stimulus error" to Jameson (2005) even though it stems from an existing view in the literature that Jameson is in the process of criticizing in the same passage that Kuehni quotes (Kuehni, This Issue, p. 115).

Of the Roberson et al. (2005) article Kuehni states:

> *The analysis of the data of Roberson et al. (pp. 349-386) was done based on tiles, i.e. stimuli, not on perceptions (admittedly the only possibility at the current stage of knowledge).*

In fact, the study of Roberson et al. (2005) uses a rigorously formalized perceptually based color space (i.e., *CIELAB*) which aims to minimize "stimulus error" that otherwise would have been intensified by using other non-perceptually based stimuli.[1] If Kuehni believes that the "stimulus error" Roberson et al.

[1] CIE (Commission Internationale l'Eclairage) is the international organization responsible for setting standards for color and color measurement (translates as "International Commission on

commit through the use of *CIELAB* is not excusable, then he may not excuse hundreds of other existing empirical studies which use that stimulus space as a perceptual model.

Regarding the "stimulus error" from Sayim et al. (2005) that Kuehni criticizes: The passage Kuehni cites consists of a very simple statement of empirical fact concerning individual variation in unique hue empirical settings and uses constructs that are widely accepted in the literature.

Our "stimulus error" explanation, and the suggestion that well-entrenched concepts from the area may inherently contain the "stimulus error," is not a weak rationalization to excuse or camouflage major flaws in our empirical studies. Rather, the cases cited as "stimulus errors" are, as Kuehni suggests, the best one can do when working within the constraints of the current state of knowledge and technology.[2] It is worth noting that within the four articles Kuehni critiques a substantial degree of recognition of the "stimulus error" trap is seen in either the theory or the design of the experiments that the articles describe.

For example, the Jameson (2005) article argues for an *Interpoint Distance Model* (*IDM*) of individual color categorization which explicitly aims to remedy the over generalization of stimulus space measures used as psychological models. Towards this goal Jameson (2005) emphasizes the IDM's use of an "idealized [perceptual] color space" (p. 319, 320, 328, 337), acknowledging "a metric across cognitive space is difficult to construct even though it may exist" (p. 321). Jameson (2005) explains that in the IDM color is modeled "… in a way that is intermediate to a metric geometry (assuming trade offs between [psychological] dimensions) and a topological space" (p. 322), and in this way differs from the typically employed metric stimulus spaces (*i.e.*, CIE) and other color order systems typically employed (*i.e.*, Munsell Book of Color, Optical Society of America space, etc.). Of the IDM, Jameson (2005) also suggests "… Category partitions depend on chromatic biases and the distribution of colors in appearance space. IDM partitions of visible color space greatly depend on the stimulus domain under consideration, and partitions are expected to vary as stimulus domain variation impacts color differences inherent in the spatial extent of the categories

Illumination") and developer of the CIE XYZ (1931) model, which is the first of a series of mathematical models produced by the CIE that describe color in terms of synthetic primaries based on human perception. The primaries are imaginary mathematical constructs that model our eyes' response to different wavelengths of light. The CIELAB system that Roberson et al. (2005) used aims to approximate a perceptually uniform color metric.

[2] Color characterization, however, is ever improving as the CIE is nearing the publication of an improved color space model that again builds on previous versions, aiming to better serve as a perceptually uniform model of color. While this will not eliminate the "stimulus error" trap, it will make such transgressions somewhat less costly.

represented across color order systems" (p. 325). Finally, Jameson (2005) states "IDM partitioning operates from a generalizable abstraction of color appearance space (similar to Davidoff's (1991) internal color space) rather than from a specific color order system (i.e., Munsell, OSA or other surface color space; or a CIE light mixture space)" (p. 338). Thus, just as Kuehni's "stimulus error" critique demands, Jameson implies "… a true, generally valid perceptual color space is, of necessity, independent of stimuli …" (Kuehni, This Issue, p. 115).

In addition to Jameson's (2005) recognition of the "stimulus error" issue, a central question of the Sayim et al. (2005) study is the examination of whether one empirical measure of color naming should be widely assumed to serve as a proxy for color perception structural relations. Thus one aim of the Sayim et al. study is to clarify a well-established point of view that inherently invokes the "stimulus error".

Further examples of the present authors' efforts to forestall the "stimulus error" can be listed, but the intended point has been sufficiently made. That is, while working within the context of some of the established constructs and paradigms of the area researchers are on slippery ground, and in the course of discussing or working with certain accepted ideas may replicate a "stimulus error" in what otherwise is a relatively "stimulus error"-free research endeavor.

Reason (B): Color naming research without direct access to qualitative experience

Relevant to Kuehni's commentary, a different way to commit the "stimulus error" is to speak about subjects having the same (qualitative) experience when they exhibit the same objective behavioral measures. For example, suppose that Subject J and Subject K exhibit equivalent performance on some perceptual task. Both, let us say, select a physically identical stimulus as a unique hue, or exhibit identical similarity mappings for the same set of physically specified color stimuli. Are we then entitled to say that they have an equivalent perceptual experience of what are known to be physically identical stimuli? It depends. If what we mean is that for some appropriate subset of behaviorally tractable tests the subjects display an equivalent set of *discriminations*, and if from this we infer they have the same or similar *experiences*, then there is little to complain about. What we mean, in this context, is that in so far as we believe the subjects experience color, and in so far as we can measure experience using experiments that track behavior, we cannot distinguish between Subject J and Subject K. Here the perceptual psychologist can fall back to patterns of behavior and choice to provide the exact meaning of any comparisons made between Subject J and Subject K, and talk of the subjects' experiences is a shorthand that is understood as such.

Suppose, however, one were to push the issue further and note that while such disciplinary practices are understandable, even unavoidable, we really *cannot* *know* what another's experience is like. It is possible, as philosophers have pointed out, that Subject J's experience is altered in some systematic and behaviorally intractable way, relative to Subject K. Or perhaps, to move to the outer fringes of philosophical thought, it is possible one of the subjects really has *no experience at all*, though he exhibits appropriate behavior and is, in a now infamous expression, a philosophical "zombie." The perceptual psychologist should respond to this challenge by simply accepting it. One cannot know these things, even if they are less than empirically plausible. The perceptual psychologist need go no further than the exact, behaviorally tractable, account of what she says, leaving the truly puzzling aspects of qualitative experience to the philosopher's analysis (see Seager 1999, for a survey of contemporary philosophical positions on qualitative experience).

With regard to human color naming research then, when a psychologist empirically observes that, for example, a leaf from a tree is described as "green" by Joe, and then Sue also empirically describes the color of the leaf as "green," the psychologist can truly only report that the same empirical descriptor was used by these two individuals and cannot draw any verifiable inference about the equality of Joe's or Sue's *internal color experience*.

Similarly, across languages, if Sam from a foreign ethnolinguistic group describes the color of the same leaf with the empirical descriptor "neerg," and on diverse occasions uses "neerg" exactly as Joe uses "green" under identical empirical circumstances, then the psychologist may report that for these two individuals from different cultures, "green" and "neerg" are semantically equivalent, but still nothing can be concluded with certainty about the equivalence of the *inner color experiences* linked with "green" for Joe compared with "neerg" for Sam.

Thus, without *direct access* to qualitative experience the psychologist has only the ability to describe how individuals differentially respond to tested stimuli, and, through the shorthand of reporting results, stimuli may become a proxy for perception, and the "stimulus error" is easily made. While this form of stimulus error is understandable, may be detected throughout psychology, and in some cases is unavoidable given the limits imposed by even the most modern tools of the psychological science, it is still an inferential leap that should be avoided as Kuehni suggests.

There are, however, ways to proceed and avoid such inferential leaps. That is, although for color psychology the metric structure given by the color stimuli themselves may not be adequate to serve as a reliable external proxy of internal psychological experience, there are methods to properly infer features of internal psychological color experience. An example of this is found when similarity structure mappings are considered for two observers with known color perception abilities. For example, Shepard and Cooper (1992) took nine color names (e.g., blue, red, gold, etc.) and asked normal color vision observers to rank the 36 pairs of names in order of dissimilarity. They also asked the observers to rank 36 pairs of actual colored samples of 'chips', with nine chips corresponding to the names (e.g. a red best-example matched the name "red"). The combined judgments were analyzed with multidimensional scaling. The results are a diagram summarizing the similarity metric, such that items are graphed in close spatial proximity when they are more cognitively or perceptually similar, and more distant when they are dissimilar. This sort of relational correspondence analysis, which capitalizes on the relative structure among stimulus relations as measured behaviorally, is a valid form of assessment that when correctly used can be comparatively free of the "stimulus error."

In light of the explanation provided by Reasons (A) and (B) described above, the degree of "stimulus error" slippage that truly occurs in the four articles Kuehni critiques is not excessive (nor abnormal) for the research area. As a general matter, however, the present authors agree with Kuehni's suggestion that it is philosophically correct to keep the constructs of subjective internal experiences separate from the formal definitions of the objective measures of behavior and the objective stimuli that invoke those internal experiences. The present authors are wary of the "stimulus error," acknowledge Kuehni's caution, and agree that less "stimulus error" would be a very good thing for the advancement of color naming research.

SECTION 2: Extending Kuehni's analysis of the "stimulus error" to determine its prevalence in color naming research

In addition to his critique of authors in *JCC 5(3-4)*, Kuehni raises two further issues that relate to the "stimulus error" definition described in the *Introduction* above, both of which generally bear on the color naming research area. Altogether (with points (1) and (2) described earlier) the four points Kuehni (This Issue) raises are summarized as follows:

(1) Physical measures of color stimuli do not correspond to measures of perceptual color experience.

(2) Color naming researchers make the classic "stimulus error" when they specify or use stimuli standardized in terms of physical measures **and** assume that perceptual color experiences on such stimuli are equally standardized (in other words, they forget (1)).

(3) The exceptions to (1) are an individual's unique hues percepts (for Hering's opponent colors) which can be linked to stimulus measures for a given

individual. Unique hue percepts are internally uniform, and comparable across individuals.

And,

(4) The exceptions to (2) are the *focals* of Hering fundamental color categories (Red, Green, Yellow, Blue, plus Black and White), found by color naming. These actually do correspond to perceptual color and can be related to color stimulus metrics.

On these four points, we believe that Kuehni is correct about (1) and (2) (as Section 1 describes); is wrong about (3); and in (4) he verges on the "stimulus error" himself. In the pages that follow we explain the significance of these four points both in the context of the articles in *JCC 5(3-4)*, and in the larger context of the color naming literature.

Is the "stimulus error" common in color psychology research?

The question of whether the "stimulus error" is generally seen in color psychology research is implicit in Kuehni's commentary, and to properly address it some historical background is needed.

In his study of spectral light Isaac Newton observed:

> *"For the Rays to speak properly are not coloured. In them there is nothing else than a certain Power and Disposition to stir up a Sensation of this or that Colour."* (Newton 1704, p. 124-125).

In short, there is nothing intrinsically "red" about the visible long-wavelengths, and nothing "blue" about visible short-wavelengths. Color does not occur in the wavelengths themselves; it is a product of the organism viewing the wavelength, and the red and blue we may see are strictly rooted in human physiology.[3]

Newton's observation presages the color "stimulus error" problem. The "stimulus error" is the conflation of subjective experience with objective stimulus measures. In the context of color naming research, the "stimulus error" is com-

[3] Thus, when a particular long-wavelength stimulus and a particular short-wavelength stimulus are viewed by some terrestrial animal (which differs physiologically from a human) as well as by a human individual, the non-human animal will almost certainly manifest color experiences distinctly different from the red and the blue that humans experience, as the latter are strictly tied to human physiological processing.

mitted (as Kuehni suggests) when a color space like the CIE (see footnote 1) is used as a *psychological* model for color-naming behaviors. Kuehni's point on this matter is uncontroversial because the CIE models are by design only abstractions of LMS spaces (i.e., defined by primaries resembling the output of three retinal cone types) and conscious color experience clearly only occurs after much additional neural processing beyond retinal coding. Psychophysicists accept that the CIE space is strictly a light mixture space which a standardized human retina would stipulate, and was not intended as a *psychological* model of individual color experience (Kuehni 2003). Nevertheless, psychologists may properly use it for its precise, human-specific, descriptions of stimuli in empirical research, but not as a color appearance model (further details of the various CIE spaces are beyond the scope of this discussion. For details see Kuehni, 2003).

The issue becomes less clear, however, when the discussion moves to perceptually based color order systems (e.g., the Munsell Book of Color or *MBC*). Perceptually based color order systems are collections of physical stimulus samples (e.g., colored papers) which depict wide ranges of colors like those one might imagine when one thinks of the *idea of color*. Typically such systems contain arrays of specific colors: Such as an array of discrete variations on "red" (varying in both lightness/darkness and purity/dilution), and also similar arrays of discrete samples of oranges, yellows, greens, and so on, all varying along the same parameters, continuing around the hue circle. The physical samples in such collections are typically ordered in a three-dimensional color solid in which the continuum of lightness from light to dark is broken into discrete steps along one axis, the continuum of hue is broken into steps along a circle, and purity varies by discrete steps along radial arms each meeting the central brightness axis at one end and the hue circle at the other end. Such stimulus spaces are *perceptually based* when some attempt has been made to order the discrete steps in these three dimensions according to some form of psychological similarity. For example, in the MBC, the distances separating adjacent hue steps aim to be equal in perceptual distance around the entire circle. Therefore the distance between two adjacent green samples in one portion of the ordered MBC hue circle is perceptually equivalent to the distance between adjacent pairs of orange neighbors found in a different portion of the MBC hue circle. However, because of difficulties inherent in establishing such perceptual metrics, it is not the case that such perceptual-step uniformity is achieved across all three dimensions (a fact that by itself that forebodes "stimulus error" dangers). Thus it is as if "the distances between levels of lightness were in furlongs, the distance between levels of saturation in stadia, and the distance around the hue perimeter in paces, and no table of equivalences was provided" (Jameson & D'Andrade 1997, p. 297). All perceptually based color order systems have some form of this perceptual metric problem (e.g., see Indow 2003). Nevertheless, because perceptually based color order systems are *based on human perceptions*, it might seem okay to commit the "stimulus error" and assume that the metrics of the stimulus space equal the perceptual metric of the observer; or that the similarity metric (and observable stimulus qualities) present in such spaces are equivalent to similarity (and qualia) inside the heads of experimental subjects. Unfortunately, this assumption remains problematic because (a) the stimulus measures in such standardized spaces may not model (or even approximate) measures of psychological relations experienced by normal color perception observers, and (b) there is no real equality between external stimulus and internal experience because even perceptually based color order system stimuli can evoke different (personal) experiences in different observers. Such effects relate to Kuehni's suggestions that broad variability is found between stimulus and individual experience, and across individual experience (Kuehni, This Issue, p. 114).

The bad news is that the human internal color space is actually non-euclidean, and existing color difference formulas that represent color differences in terms of three color attributes or color dimensions are both inaccurate and approximate. Unfortunately, the best tools available to psychologists are the three-dimensional stimulus-space models that do not appropriately capture subjective differences between stimuli (Indow 2003). This difficulty has long been known, of course: Perceptual color space mapping results show a non-linear relationship between perceptual color space and stimulus spaces, as well as local and global differences in the metrics obtained in different regions of the perceptual color space (Indow & Aoki 1983, Indow 1988). The work of Nickerson (1957, 1943) also showed the lack of correspondence between the additive vector representation of mixtures of light and the perceptual constant-hue loci in the subjective space of color.

In view of this difficulty, what is a color-naming empiricist to do? To collect and communicate data, bounded samples of stimuli must be standardized, conclusions need to be drawn from the patterns emerging from observers' responses to those stimuli, and comparisons need to be made between various populations to relate their underlying psychology. Unfortunately, the best a color researcher can do to escape this seemingly infinite regress into the subjectivity of perceptual experience is to tread lightly across their data fields to avoid committing the "stimulus error" and aim to avoid an over generalization of empirical findings to internal psychological experience. For color naming researchers who view a physiologically determined or uniformly shared color experience as the primary basis for color naming regularity, the path is likely to be fraught with "stimulus error" traps. For color naming researchers who undertake the ambitious empirical goal of assessing diverse linguistic cultures, the path is further obstructed because the tendency to intermingle stimulus measures with psychological experiences may be greater when experimenters do not share a native cultural-competence with the diverse populations they assess.

We consider it likely that Kuehni's insinuation that color naming research widely suffers from a case of "stimulus error" may, unfortunately, be accurate. Fortunately, psychologists have developed some approaches – currently in use in color naming research – for avoiding the "stimulus error" (comparisons of the relative structure of stimulus relations measured behaviorally that was discussed briefly above). At this juncture, however, it is useful to consider Kuehni's (This Issue) suggestions for sorting out the "stimulus error" problem in color naming research.

Can the Unique Hue construct circumvent color naming research "stimulus errors"?

To offset the discouraging picture painted by his "stimulus error" discussion, Kuehni points to the Unique Hues – or the empirical realization of Hering's opponent-color *Urfarben* – as a possible point of departure from the problem of color experience subjectivity. The Unique Hues, he suggests, stand out by being more tractable (as summarized by items (3) and (4) presented at the beginning of *Part 2* above), and:

> "… the unique hues, allow a glimpse into inter-observer variability of the way that a given stimulus is experienced under a particular set of conditions" (Kuehni This Issue, p. 114).

In light of his other research, here we believe Kuehni is suggesting that although physical measures of Unique Hue settings are known to vary substantially across normal individual observers (Kuehni 2001, 2004, 2005a, 2005b, Miyahara et al. 2004, Webster et al. 2000), there is something personally *real* and psychologically salient about Unique Hue subjective experiences for each individual. The evidence for this *realness* is the robustness with which an individual can replicate his or her personal unique hue settings across time and repeated trials, even though they may differ dramatically from those of another individual.

Kuehni also adds that "Investigations of this [inter-observer Unique Hue setting] variability have a considerable history but the findings have usually been disregarded as facts that are unpleasant for the psychophysical dogma. The findings are of considerable importance for the on-going discussion about basic color terms" (Kuehni, This Issue, p. 114).

In this way Kuehni implicitly questions whether the construct of Unique Hue is appropriately represented in psychological theories of color perception and color naming.[4] To explore this question, and because neither special issue *JCC 5(3-4)* nor Kuehni's commentary say much about the origins and history of the use of the Unique Hue construct in the color naming literature, a brief overview the construct's introduction and transformation in the area is needed.

A brief account of the introduction and use of the Unique Hue construct in color naming research:

German Psychophysicist Ewald Hering (1920) is credited with asserting that only four hue terms – *red, green, yellow*, and *blue* – *rot, grün, gelb* and *blau* for Hering, of course – are necessary and sufficient to describe all colors. These terms describe four fundamental colors Hering called *Urfarben*, or Unique Hues.[5]

Sometime later the construct of Unique Hue was empirically expressed as the hue cancellation paradigm (Jameson & Hurvich 1955). In this way, for example, unique yellow or UY was operationalized as a pure yellow that is neither reddish nor greenish tinged. This operational definition involving cancellation is achieved equally well whether tuning mixtures with dials (known as the *Method of Adjustment*: e.g., cancel red and green from UY by adjusting dials linked to red and green content of a field) or by a force-choice task in a psychophysical staircase procedure (e.g., press one of two buttons for a series of presented stimuli indicating either (a) too much red, or (b) too much green. The stimulus point where (a)-(b) reversals are seen across several staircases is the point defined as UY). Unique Hues have also been obtained using surface color papers, but the criterion of identifying a yellow that is neither reddish nor greenish has always remained essential to pinning down a yellow Unique Hue.[6]

When the Unique Hue construct was widely popularized in psychology (around the time when the opponent process response properties of cells in the visual pathways had been identified, but before it became apparent that their

[4] Omitted from this entire discussion (and from Kuehni's commentary) is the issue of whether the opponent color pairs that Hering postulated (Red versus Green and Yellow versus Blue) also relate to opponent neurophysiology cancellation pairs linked to early levels of cortical processing of the color code (i.e., when opponent colors are additively mixed they give rise to a neural signal that produces a neutral achromatic appearance). Jameson & D'Andrade (1997) criticize this idea at length.

[5] In the discussion that follows emphasis is given only to the *Urfarben* associated with the chromatic hue circle, and the Black and White *Urfarben* are not discussed. In addition, there is a good chance that the hue category regions glossed by Hering's *Urfarben* terms differed from that denoted by the contemporary English glosses. This bears noting because it exemplifies difficulty inherent in a language-based definition of Unique Hue categories.

[6] Unique Blue (UB), Unique Red (UR) and Unique Green (UG) are operationalized in a similar way to that described for Unique Yellow (UY).

response profiles did not correspond to the Hering color opponencies as expected) was not long from its adoption as the foundation for the most widely received theory of cross-cultural color naming (Berlin & Kay 1969). In the Berlin-Kay formulation (as well as in contemporary versions of the theory) Unique Hues were linked to color category best-exemplars, or "focals," (see Kay & Regier 2003, Regier, Kay & Cook 2005). For a time they were thought to reflect fundamental neural response categories of visual processing (Kay et al. 1991), although this link to physiology has been more recently supplanted by *cognitive* salience (Kay 2005).

Eleanor Heider-Rosch first related unique hues to color category prototypes (Rosch Heider 1971, 1972a; 1972b; Rosch Heider & Olivier 1972). Regardless of one's view of prototype theories, Rosch's work can be seen as a step to move psychological salience from stimulus properties to an *internal* cognitive prototype (or a step away from the "stimulus error"). Later, after much work and numerous cross-cultural assessments, the Unique Hue construct from psychophysics became widely synonymous with constructs in color naming theory such as *Landmark Colors, Chromatic Fundamentals*, or *Elemental Colors* (e.g., MacLaury 1997).

What is important to note here is the progressive shift in the concept of Unique Hue from its classical definition to its broader current use in color naming investigations. This shift has rendered the originally construed Unique Hue construct and the divergent concept of Hering color category *focals* as very different things at a number of levels. It is important to understand this difference because, first, it explains why we believe Kuehni is wrong about item (3) and is at risk as described in item (4) (as described at the beginning of Section 2), and second, it helps us evaluate the appropriateness and use of the Unique Hue construct in color naming research.

How is the Unique Hue construct typically generalized in color naming research?

To understand the comparability of color naming "*focals*" and *Unique Hues* we need to consider their use in the color naming literature. For example, on page 116 of his commentary, Kuehni essentially asks: Are stimuli selected as focal colors for "red" "green" "yellow" and "blue" categories identical to the stimuli selected as unique hue perceptions (within expected error)? This is reminiscent of some of Kuehni's earlier analyses (Kuehni 2005a, 2005b) and is representative of the kind of comparison widely found in the color naming literature.

For example, in discussing the largest corpus of color naming data – the World Color Survey (WCS) data (Cook, Kay & Regier 2005) – MacLaury merges the two different constructs of Unique Hue appearances with *focal* stimulus samples:

"*… the distribution of [color category] foci as well as its stepped contour reveal a widely recurrent response to perceiving the closest approximations to unique hues attainable with chip pigments…*"; and, "*The 4 favored columns [identified as Hering's Unique Hue categories] contain 2,543 of the 10,644 chromatic foci, that is, 24%. Pure chance would amount to 10%…*"; and, "*What explains the 76% of chromatic foci that do not fall on unique hues?*" (MacLaury, 1997 p. 202).

More recently other analyses of World Color Survey data also link the the Hering primaries with theory of color category "focals":

"*… there exist universal constraints on cross-language color naming related to these 11 basic color percepts, particularly to the six Hering opponent primaries, black, white, red, yellow, green, and blue…*" (Kay & Regier 2003 p. 9085).

And,

"*… the most reliable and widespread of these [category] clusters correspond to the six Hering primaries: white, black, red, yellow, green, and blue – suggesting that these points in color space may constitute a universal foundation for color naming. These foci in color space have also appeared to be cognitively privileged, in nonlinguistic tasks with speakers of languages that have dissimilar color naming systems*" (Regier, Kay & Cook 2005 p. 8386).

And,

"*The Kay and Maffi model takes universal constraints on color naming to be based on presumed universals of color appearance – for example, on opponent red/green and yellow/blue phenomenal channels…*" (Kay 2005, note 5, p. 52).

In the passages quoted above the use of the construct of unique hue by non-psychophysicists clearly deviates significantly from the classical psychophysical sense (Jameson & Hurvich 1995, Hering 1920) which has links to a specific psychophysical cancellation paradigm.

Relevant to such uses of the Hering opponent colors as a basis for theories of color category emergence, and the uses of Unique Hue appearances as a model for color category "focals," is that only 41 of the 110 languages in the WCS contain categories comparable to all four English language terms "red", "green", "yellow" and "blue" (Kuehni, 2005b, p. 411). In the absence of the descriptors necessary for tasks seeking unique hue category focals in such populations, it is difficult to begin to know if a correspondence with Unique Hue perceptions might exist in these languages.

Moreover, across the roughly 40% of WCS languages that actually possess all four Hering terms, aggregate focal ranges vary enormously (even after weeding out aberrant outlier subjects), with the green focal range overlapping the yellow and blue focal ranges in some cases (Kuehni, 2005b). Based on the data Kuehni (2005b) reports, we simply cannot say with certainty that a focal (aggregate) chip corresponds to a given individual's personal unique green setting; since settings can vary widely, even between trained observers, the opposite may well be true.

Kuehni suggests that Unique Hue *results* are important for the basic color term discussion. We agree with him on this, but in a way that differs from how it has been historically considered important in the color naming literature. That is, first, we consider the large variation across individual Unique Hue settings as a problematic basis for pan-human universal shared color category "focals". Second, because the classic definition and the Unique Hue task are defined by primitives representing the linguistic terms "red", "green", "yellow", and "blue", it is difficult to imagine how any of the standard procedures could be used to establish Unique Hue settings for individuals in any ethnolinguistic group that lacks the appropriate linguistic glosses (and this problem is substantial). Presumably individuals from such linguistic groups could be trained to carry out the empirical task, but does not this undermine the assertions that Unique Hues are "necessary and sufficient," universally psychologically salient reflections of pan-human chromatic fundamentals?

We believe that this problem arises from the original cultural relativity of the Unique Hue construct as generalized in some color perception and color naming research. Such generalizations need to be examined and properly addressed by color naming researchers, and are a contributing factor (if not the source) of many of the "stimulus error" deficiencies found in the color naming literature. It is worth noting that while very few studies have made cross-cultural comparisons of psychophysical Unique Hue settings (no doubt discouraged by the difficulties inherent in conducting such studies), one recent study has compared Unique Hue settings from English-speaking Americans and Eastern Indian speakers of Tamil and Marathi (Webster et al. 2002). The results included small but consistent differences between the different populations in the stimuli that they selected as unique hues. However, the results reported for the Eastern Indians speakers were from a small subset of participants drawn from the larger Indian sample, and it is not clear whether the subjects were bilingual, or whether they were instructed in either Indian or English language during the experiment (at one point the article seems to suggest bilingualism and that instructions were in English, Webster et al. 2002, p. 1953). This is mentioned not to raise doubt about the study, but to suggest that the empirical results are not yet sufficient to establish whether it is valid to generalize the language-based primitives of the Unique Hue task to linguistic populations that do not naturally express them. To prove that differences in Unique Hue experience across cultures is the larger part of the explanation for differences in color term use, one must guarantee that the generalization of the Unique Hue task equally applies in the non-English language populations tested. Alternatively, if other studies were carried out and showed difficulties in such generalizations, then the implied salience and utility of the Unique Hue setting construct for cross-cultural color naming research could be open to question.

Beyond Hering's Unique Hues: Can contemporary uses of the Unique Hue construct be made appropriate for color naming research?

In his discussion of the salience of the four Unique Hue points in the color continuum Kuehni states "No information is available for the stretches of hue changes between these points because of the lack of objective definition…" (Kuehni This Issue, p. 114). The issue of necessitating an *objective* definition of any distinctive hue points in the color continuum is a crucial to color naming theory, and is one, we believe, that can be analyzed in a way that is both more appropriate for color naming research, and allows the accommodation of Kuehni's suggestion of "… two additional hue-related basic color terms, orange and purple." (p. 116).

Such an analysis, however, requires a clear separation of the psychophysically defined construct of Unique Hue from the ideas of unique hue that color naming researchers might appropriately employ. To explore this idea we further dissect the Unique Hue definition below. As mentioned earlier there is an undeniable linguistic component to the "necessary and sufficient descriptor" criterion for a Unique Hue (which for the moment we can set aside). A second component inherent in the Unique Hue definition is the operational definition of *exclusion*, or *cancellation*, of all reddish and greenish tinge from UY (for example). It is this *exclusion operation* that Figure 1 addresses.[7]

Figure 1 presents a schematic representation of a standard Newtonian color circle ranging from red (at top) and continuing clockwise through the spectral colors to blue, extra-spectral purple and closing the circle at red again. Hering's concept of phenomenologically opponent colors are indicated by the points for Unique Red (UH), Unique Yellow (UY), Unique Green (UG) and Unique Blue (UB). These form two conceptually orthogonal polarities, intersecting at a neutral point within the conceptual color appearance solid. Being complements or opponents in Hering's theory, each pair of Unique Hues are conceptually

[7] Here the term "exclusion" in the Unique Hue setting task is opted for rather that the term "cancellation" used in other research (Jameson & Hurvich 1955). This is done to differentiate the Unique Hue procedure from a different, often discussed, color cancellation procedure involving the additive mixture and nulling of complementary hues to produce a neutral appearance.

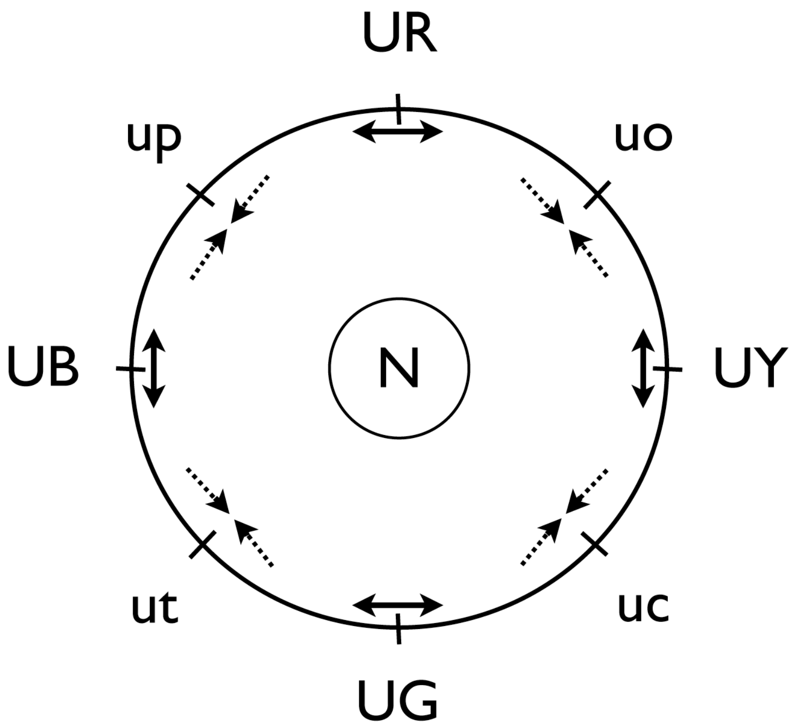

Figure 1: A schematic representation of the Newtonian color circle. Hering's opponent colors are denoted by 'UH' (Unique Red) , 'UY' (Unique Yellow), 'UG' (Unique Green) and 'UB' (Unique Blue). The solid two-headed arrows placed at the four Hering hue points diverge from the points on the hue circle at each unique hue location to represent the canceling, or exclusion, operation inherent in instructions of the standard unique hue setting paradigm used in psychophysics. Four additional points on the circle are represented by lowercase letters: 'uo' (Unique Orange), 'uc' (Unique Chartreuse), 'ut' (Unique Turquoise) and 'up' (Unique Purple). These suggest additional unique hues possible when the definitions of Unique Hue are considered, and a one word instruction change is made to the Unique Hue setting task. The dashed arrows converge at each of the four points of lowercase scripted hues to represent a **balance** operation using adjacent Unique Hues. It is important to note that the relationships represented here are not suggested as a physiological model of processing underlying any of the colors represented.

incompossible (Bimler 2005). Note that in Figure 1 the solid two-headed arrows placed at the four Hering hue points diverge to represent the *exclusion*, or cancellation, operation inherent in instructions of the standard Unique Hue setting psychophysical paradigm. In addition to the Hering hues, four additional points are represented on the circle by lowercase letters: Unique Orange (uo), Unique Chartreuse (uc), Unique Turquoise (ut), and Unique Purple (up). These colors form "non-cardinal" axes in the conceptual color appearance solid, meaning that like the Hering opponent colors they too are complementary color pairs. These non-cardinal colors are considered much less significant by contemporary theories, and are not considered psychologically salient colors in the original Hering opponent-colors model, despite psychophysical evidence for their salience (reviewed below), and despite their conceptual opponency. Note that in Figure 1 the dashed arrows that converge at each of the four points of lowercase-text hues differ from the arrows for the Hering hues, and that they converge onto their non-cardinal hue location to represent a balance operation, as opposed to an exclusion operation.[8] The balance operation is suggested here as a variant on the instructions of the standard unique hue setting paradigm and is further discussed below.

The unorthodox suggestion of these *alternative* Unique Hues (*uo, uc, ut* & *up*) actually provides a path for homing in on an objective definition of Unique Hues as needed for psychological color naming research – that is, one free of the Hering-based linguistic "descriptor" criterion and the language-category based exclusion criterion. Thus a purely objective definition, arguably more appropriate for color naming research, is that such experiences need only satisfy criteria of empirical robustness and consistency within-individual under both classical and non-classical Unique Hue setting paradigms.

Similar alternative Unique Hues were proposed facetiously by Justin Broakes (1997), although he abandoned the idea and discounted the psychological significance of these alternatives on the grounds that (unlike Hering hues) they are not necessary and sufficient descriptors of all color experiences. Of course, the language-based "descriptor" criterion for color salience is problematic for universalist models of color categorization, and is unlikely to be linked in a causal way to perceptual experience (which should properly place it outside the realm of perceptual psychophysics), and raises questions about its value as a modeling construct.

[8] Note that Figure 1 depicts only the Hering phenomenological, or experiential, opponent colors, and **does not** depict pairs of color-opponent neural processing signals (Red signals opposing Green and Yellow signals opposing Blue) that are typically held to blend to give a neutral achromatic white point (N) as opponent color theory dictates (see Jameson & D'Andrade 1997 for a discussion).

Note that support exists in the experimental psychophysics literature for non-cardinal hues with measures of empirical robustness that rival Unique Hue robustness. Research shows that the salient axes of color space are not restricted to those suggested by the Hering-Young-Helmholtz theories, but involve a number of neurophysiologically equivalent mechanisms tuned to non-cardinal directions in the perceptual color space. For example, the findings of D'Zmura, 1991; D'Zmura & Knoblauch, 1997; D'Zmura & Lennie 1986; Krauskopf, Williams & Heeley, 1982; Zaidi & Halevy, 1993; Webster & Mollon, 1994, all suggest that humans possess chromatic detection mechanisms that have preferred directions spanning a wide range of spectral bandwidths. In many of these studies the non-cardinal directions are just as empirically robust and psychophysically salient as the Hering color directions. Recently, when Malkoc et al. (2005) used hue cancellation and focal naming to determine binary-hue settings (e.g., blue-green) as well as unique hues (e.g., pure blue or green), both classes of hue exhibited comparable variance across individuals. This too can be interpreted as support for the suggestion of alternative unique hues. Thus a full understanding of the cognitive processes underlying color appearance and color naming requires a richer model than merely a variant of Hering color opponency, although the acceptance of this within the field of vision science has not yet widely extended to psychological research.

Finally, purely from the perspective of color naming research, Figure 1's suggestion of alternate Unique Hues that are just as subjectively compelling as the Hering Unique Hues is consistent with the color naming literature and is not so ridiculous. Many color naming studies have made various measures of the salience of other color categories and found them equal to the Hering Hues. Boynton (1997) concluded that "all eleven basic colors are perceptual fundamentals", after failing to find any index of salience which elevated the Hering primaries above 'derived' basic terms such as purple and orange (see also Boynton & Olson, 1990). With regard to the suggestion of a unique purple, clearly Munsell (1966) considered it essential to his color order system since a purple primary is used in the construction of the Munsell Book of Color, in addition to Red, Green, Yellow & Blue primaries. And supporting the suggested salience of unique chartreuse and unique turquoise are the facts that some languages do possess glosses for a salient greenish-yellow color category which functions as a "basic color term" (MacLaury 1997), and a blue-green color category gloss is also very commonly observed (e.g., Roberson, Davies & Davidoff 2000).[9] Finally, if

[9] Although the best exemplars of blue-green categories observed in the world's languages can apparently occur as either a central green, central blue or a central turquoise appearance with almost equal frequency (Lindsey & Brown 2004, p. 293).

we consider the subjective salience of the absolute best examples imaginable of Orange, Chartreuse, Turquoise and Purple, these constructs do subjectively seem to perfectly balance adjacent primaries just as the absolute best examples imaginable of Red, Green, Yellow & Blue seem perfectly undisturbed by their neighboring hues – and to some observers at least the subjective salience in both sets is real and compelling. (Although such subjective, "compelling," criteria are perhaps no better than the strictly language-based criterion of "necessary and sufficient descriptor".)

Based on the above discussion and the empirical evidence summarized above, it is reasonable to argue that the Hering Unique Hues may only differ from the suggested alternative Unique Hues by a single-word instruction in the empirical task. With this awareness, updating of the Unique Hue construct as we suggest here seems more appropriate and objective for use in color naming research (differentiated here from color psychophysics research) compared to the classically motivated Hering Unique Hue construct most often used (e.g., Kay 2005, Kay & Regier 2003).

Are there Difficulties inherent in verifying shared Unique Hue experiences?

One last issue should be considered with regard to the Unique Hue issues raised by Kuehni, summarized as item (3) earlier in Section 2. That is, the present authors disagree with Kuehni's repeated statements that two individual's Unique Hue settings (even those with a substantial physical difference) *must* evoke identical Hering percepts or "common qualia in the majority of human[s]." However, our disagreement with this suggestion mostly stems from (*i*) points raised earlier in our discussion concerning the operational definition of the Unique Hue construct given by the empirical setting procedure, and (*ii*) from the fact that the internal experience of any observer's unique hue setting is a subjective Class B observation (Brindley 1960) which makes it impossible to say anything about the equality of the Unique Hue qualities given by two observers' settings (Mollon & Jordan 1997). Our view is simply that there is no good perceptual argument to support the idea that Hering's Unique Hues should be classed as **perceptually** different from the suggested alternative Unique Hues (shown in Figure 1) if (a) they only differ empirically by an instruction (balance versus cancel), and (b) both classes of hues show comparable empirical robustness. Moreover, if the crux of the distinction hinges on the linguistic "descriptor" criterion, then we consider that the justification has departed the domain of perception and entered the domain of culture and cognition, in which case the foundations of cross-cultural color naming theory and mainstream color naming research (which rely heavily on classical ideas underlying opponent color salience) will require a good deal of updating.

Summary

It should be said that none of the authors that Kuehni targets in his commentary have ever suggested (in *JCC 5(3-4)* or elsewhere) that color vision physiology, or "hardwiring," is an **unimportant** factor, or constraint, in the perceptual processing and individual categorization and naming of color appearance. And it should be noted that none of the criticisms Kuehni directs at the articles of Bimler (2005), Jameson (2005), Roberson et al.(2005), and Sayim et al. (2005) have any deleterious effect on the conclusions made those empirical studies.

The present authors agree with Kuehni that a greater awareness of the "stimulus error" is needed in color naming research and throughout the basic color terms discussion.

These authors also agree that there is something significant about Unique Hue settings: Namely, (1) In the populations in which they have been psychophysically tested they are individually highly reliable, repeatable, and seem psychologically salient, although they are not uniformly shared. And (2) Depending on what ethnolinguistic culture you belong to, they may also be "necessary and sufficient descriptors" of other visible colors. (And the related construct of opponent-color processing has proven to be of value in understanding color vision processing mechanisms.)

Beyond these features it is unclear what utility the construct of Unique Hues brings to *color naming research* (as distinct from *psychophysical* research) because:

(1) A large proportion of languages (e.g., approximately 60% in the WCS) lack at least one of the primary constructs needed to participate in the Unique Hue setting task.
(2) For those that do not have the Unique Hue primary constructs the "necessary and sufficient descriptor" argument is invalid.
(3) Empirical results suggest that other Unique Hue Alternates may be as robust and salient as the Hering Unique Hues.

And,

(4) As a corollary of the "stimulus error" issue: There is no way to verify that one individual's internal experience of, say, a Unique Yellow, is qualitatively equivalent to a different individual's internal experience of Unique Yellow (and there seems to be evidence to suggest they could be different).

Kuehni's suggestion that individuals can have repeatable Unique Hue settings although they may invoke personal meaning, or significant qualitative experience, other than that expected by Hering's model (see Kuehni, This Issue, Note 2, p. 115), seems like a plausible explanation for the empirical robustness of individual Unique Hue settings given the fact that we cannot directly observe what experiences such settings invoke in and across individuals. It also seems like an explanation that is compatible with our hypothesis that other, equally reliable and robust, unique hue alternates might exist, and that a simple change of instruction could produce a Unique Orange just as easily as Unique Yellow. At a minimum a better rationale is needed for justifying either task instruction as a basis for an explanatory theory of color naming.

Finally, although we do not know for certain, the present authors suspect that an updating of the foundations of color naming theory and mainstream color naming research – to better accommodate advances found in the pioneering work of scientist like Boring (1929) and Brindley (1960) – is what Kuehni intended when he raised the discussion of "Stimulus Error" in his commentary on special issue *JCC 5(3-4)*. We certainly hope this is the case, and would be pleased if his suggestion lead to the minimization of all such stimulus errors from the literature, thereby contributing to a correct and complete understanding of color naming phenomena.

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