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Testing the Cross-Cultural Generality of Hering's Theory of Color Appearance

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Abstract

This study examines the cross-cultural generality of Hering's (1878/1964) color-opponent theory of color appearance. English-speaking and Somali-speaking observers performed variants of two paradigms classically used to study color-opponency. First, both groups identified similar red, green, blue, and yellow unique hues. Second, 25 English-speaking and 34 Somali-speaking observers decomposed the colors present in 135 Munsell color samples into their component Hering elemental sensations—*red*, *green*, *blue*, *yellow*, *white*, *and black*—or else responded "*no term*." Both groups responded *no term* for many samples, notably purples. Somali terms for yellow were often used to name colors all around the color circle, including colors that are bluish according to Hering's theory. Four Somali Grue speakers named both green and blue elicitation samples by their term for green. However, that term did not name the union of all samples called *blue* or *green* by English speakers. A similar pattern was found among three Somali Achromatic speakers, who called the blue elicitation sample *black* or *white*. Thus, color decomposition by these Somali-speaking observers suggests a lexically influenced re-dimensionalization of color appearance space, rather than a simple reduction of the one proposed by Hering. Even some Somali Green-Blue speakers, whose data were otherwise similar to English, showed similar trends in *yellow* and *blue* usage. World Color Survey data mirror these results. These within- and cross-cultural violations of Hering's theory do not challenge the long-standing view that universal sensory processes mediate color appearance. However, they do demonstrate an important contribution of language in the human understanding of color.

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1. Introduction

The variation among perceived colors is very nearly continuous. The spectral composition of light is a continuous variable, the responses of the three cone types are continuous functions of the spectrum of the light that excites them, and human observers can distinguish millions of individual lights by their spectral composition. We do not have individual names for all of these colors. Instead, we group them into many fewer named categories, which people use to communicate about color. The relation between colors and the terms that name them lies at the intersection of two fields of study: color science and linguistics.

1.1. Color-opponency in color and language

The color science and linguistic sides of this relation have long been associated. On the color science side, the classic theory of the mental representation of color appearance is due to Evald Hering (1878/1964). Hering's theory states that color appearance is based on six elemental color sensations (*Grundemphindungen*). These are the four hue sensations: redness, greenness, blueness and yellowness, plus blackness and whiteness, all mediated by three mutually orthogonal, color-opponent processes: red–green, blue–yellow, and black–white. The four elemental hue sensations are associated with their corresponding "unique hues" (*Urfarben*), and any chromatic color can be described by single or binary combinations of those unique hues. For example, a color that evokes only redness is the unique hue associated with "red." One color can evoke redness-and-yellowness ("orange"), while another color can evoke blueness-and-redness ("purple"). The elemental hue sensations associated with the opposite poles of the two chromatic dimensions have "mutually exclusive sensory qualities" (Hurvich & Jameson, 1957), and colors cannot contain sensations from the opposite poles of either of the two chromatic dimensions. That is, no color can evoke both redness and greenness or both blueness and yellowness. Hering believed that these opponent pairs were encoded in the physiology of the visual system by means of (then very new and controversial) inhibitory processes.

Thus, color appearance can be understood conceptually within the framework of a three-dimensional Hering space in which the coordinates of each visible color represent the magnitudes of responses in the three putative color-opponent channels, and the sign of the response on any given axis of this space specifies which of the mutually exclusive pairs of elemental sensations has been evoked. So, if red is +, then green is −, and all reddish colors are + and all greenish colors are −; if yellow is +, then blue is −, and all yellowish colors are + and all bluish colors are −. The neutral colors are 0, and they fall between red and green and between blue and yellow (Hering, pp. 49–50). At a minimum, this framework implies that the three Hering dimensions (red–green, blue–yellow, and black–white) are both necessary and sufficient to represent the color appearances of all visible lights.

On the linguistic side, the terms used to describe the elemental color sensations, *black*, *white*, *red*, *green*, *blue*, and *yellow*[1], identify six basic color categories that Berlin and Kay (1969) included in a "universal inventory" of 11 color categories that become successively lexically labeled as color lexicons evolve from simple to complex. A simple lexicon might have terms for only black, white, and red; a more complex lexicon might have terms for all 11 categories. The existence of cross-cultural regularities in the patterns of color naming has been largely substantiated by subsequent statistical analyses of the World Color Survey color naming database (Kay, Berlin, Maffi, Merrifield, & Cook, 2010; Kay & Regier, 2003; Lindsey & Brown, 2006, 2009; Regier, Kay, & Cook, 2005). Kay and McDaniel (1978) attributed these regularities of color naming patterns to the enhanced salience of a common set of perceptual landmarks, which they identified with Hering's elemental color sensations. Hering himself, almost surely referring to modern Indo-European languages when quoting Aubert (1865), noted that "language has long since singled out red, yellow, green, and blue as the principal colors" (Hering, 1878/1964, p. 48).

1.2. Previous tests of Hering's color-opponent theory

Hering's theory has been examined and tested extensively ever since he proposed it. Empirical support for Hering's theory rests largely on three psychophysical paradigms that have focused primarily on the hues of test lights: (a) the determination of individual unique hues, where observers adjust the hue of a test light to introspectively isolate each of the elemental color sensations; (b) hue-scaling, where observers are asked to introspectively report on the proportions of redness, greenness, blueness, and yellowness they see in colored stimuli; and (c) hue cancellation, where observers determine the amount of light of a fixed color evoking one dominant Hering sensation (say, blueness) that is needed to exactly cancel any hint of the opponent-color sensation (in this case, yellowness) when added to each of a set of test lights.

Empirical results have generally supported Hering's theory (e.g., Boynton & Gordon, 1965; Fuld, Wooten, & Whalen, 1981; Gordon, Abramov, & Chan, 1994; Jameson & Hurvich, 1955, 1959; Sternheim & Boynton, 1966). However, more recent work based on other considerations has called into question the importance of Hering's formulation in understanding human color appearance. Principal among these is that Hering supposed that color-opponency is physiologically based, yet no one has so far identified the neural substrate for Hering's color-opponency anywhere in the brain (e.g., Bohon, Hermann, Hansen, & Conway, 2016; Conway, 2014; Komatsu, Ideura, Kaji, & Amane, 1992; Lennie, Krauskopf, & Sklar, 1990; see also reviews by Shevell & Martin, 2017; Zaidi & Conway, 2019). Another problem is that simple models based on linear transformations of cone responses into putative Hering channels fail dramatically (Knoblauch & Shevell, 2001). Particularly, the unique-hue locus for the blue–yellow dimension of color space is dramatically nonlinear (Burns, Elsner, Pokorny, & Smith, 1984; Dimmick & Hubbard, 1939; Wuerger, Atkinson, & Cropper, 2005), and it depends on luminance and adaptation (Cicerone, Krantz, & Larimer, 1975; Larimer, Krantz, & Cicerone, 1975; however, see

Chichilnisky & Wandell, 1999). The privileged status of Hering's unique hues has also been challenged: They are not particularly "colorful" (Witzel & Franklin, 2014); they are not particularly salient in visual search (D'Zmura, 1991; Wool et al., 2015), although one report found unique-hue salience in another kind of experiment (Kuehni, Shamey, Mathews, & Keene, 2010); their locations in color space do not always correlate with the location of best color discrimination on the spectrum locus (Holtsmark & Valberg, 1969) or within named color categories (Bachy, Dias, Alleysson, & Bonnardel, 2012; Witzel & Gegenfurtner, 2018; however, compare Danilova & Mollon, 2012; Danilova & Mollon, 2014); unique-hue settings are not less variable than binary hue settings (Bosten & Lawrence-Owen, 2014); individual differences in binary hue settings are not well correlated across observers with differences in unique-hue settings (Malkoc, Kay, & Webster, 2005); and color-opponent representations of color appearance other than Hering's may also be possible even among speakers of modern Indo-European languages (Bosten & Boehm, 2014; von Goethe, 1810/1840).

1.3. Overview of the present study

Here we address a separate, but related, issue regarding Hering's framework for color appearance: its close association with observers' lexical representations of color. As Brindley (1970, p. 208) pointed out, the interpretation of classic behavioral tests of Hering's theory is weakened by the close correspondence between putative subjective internal sensory representations of visual stimuli (e.g., redness, greenness, etc.) and the lexical color categories in modern Western languages (red, green, etc.). Do the Hering color terms in these languages serve merely as lexical labels for reporting innate universal sensory representations of color, or are these sensory representations critically dependent upon the lexical color categories?

To address this question, we compared the responses of monolingual Somali-speaking and US English-speaking observers on two behavioral assays for Hering's theory: In the first experiment—the unique-hue task—English and Somali observers selected color samples closest in appearance to Hering unique red, green, blue, and yellow from a circular array of 40 Munsell colors spanning a high-chroma color circle (Hinks, Cárdenas, Kuehni, & Shamey, 2007). In the second experiment, a different sample of English- and Somali-speaking observers performed a variant of hue-scaling which we call "color decomposition." In this task, observers identified the Hering elemental sensations evoked by Munsell test stimuli using words in their native language for these sensations. However, unlike hue-scaling, color decomposition does not require observers to introspect upon the proportions of these sensations.

While English is classified as an 11-basic-color-term language, traditional Somali has only three to four color terms: *black*, *white*, *red,* and possibly *green* (Berlin & Kay, 1969). However, extensive cross-cultural contact beginning in the early part of the 20th century, especially with speakers of Italian and English, has expanded the modern Somali lexicon (Brown, Isse, & Lindsey, 2016; Maffi, 1990). Modern Somali, like most world languages that have been studied, shows prominent individual variation in color naming, even within dialects, with some Somali speakers omitting some or all of the newer color terms. In previous work (Brown et al., 2016), we showed that individual Somali color lexicons, like those in the World Color Survey ("WCS"; Kay et al., 2010), tend to fall into about four distinct classes of color naming system called "motifs" (Lindsey & Brown, 2009). The motifs differ primarily in how the cool colors (blues and greens and some purples) are named. In the "Dark" and "Gray" motifs, the cool colors are named *black* and *gray*, respectively. In the "Grue" motif, they are named using a single "*green*-or-*blue*" chromatic color term (called "*grue*" in the literature). In the "Green-Blue" ("GB") motif, there are distinct terms for *green* and *blue*. The motifs are structurally similar to some of the color naming systems identified as diachronic "stages" in Berlin and Kay's color term evolutionary sequence (Berlin & Kay, 1969; Kay et al., 2010). However, unlike the stages, two or more of the motifs are observed synchronically within most WCS languages.

We exploited this prominent diversity in color naming among Somalis to tease apart within- versus cross-cultural effects of color lexicon on our behavioral assays of Hering theory. We examined responses in individuals who (a) spoke *different* languages but expressed the *same* motif (English vs. Somali GB), (b) spoke *different* languages and expressed *different* motifs (English vs. Somali non-GB), and (c) spoke the *same* language (Somali) but expressed *different* motifs (GB vs. non-GB). For example, would observers speaking different languages, but who identified the same glossed color categories "red," "green," "blue," and "yellow," make the same unique-hue settings? What about color decomposition? We expected that English and Somali-GB observers would perform in a manner consistent with Hering's theory. However, it was not clear how Somali observers who lack the full complement of Hering terms (i.e., terms for the red, yellow, green, blue, black, and white elemental sensations) would handle the Munsell test samples. For example, if Somali Grue speakers can successfully introspect the greenness and/or blueness in the test stimuli, then, in principle, they could use their *grue* color term to report the presence of either or both of these sensations in the color decomposition task. But suppose Somali *grue* is not conceptually linked to both greenness and blueness in any simple way. How might these observers respond? One possibility is that they will be unable to report the decompositions of stimuli requiring a greenness or blueness verbal response, as required by Hering's theory, or they might respond idiosyncratically and inconsistently to these stimuli. But another possibility is that their responses might reveal an entirely different understanding of color appearance based on the semantics of color categories for which they do have words. Such an outcome would pose a serious challenge to the universality of Hering's theory.

2. Experiment I

Both Hering's theory of color perception and the hue decomposition paradigm rely heavily on "unique" hues, which are defined as the colors that excite only one of the four color-opponent processes. They are a red or a green that is neither bluish nor yellowish, and a blue or a yellow that is neither reddish nor greenish. In this first experiment, we examined the colors selected under the classic unique-hue protocol by Somali-speaking and English-speaking observers. First, each observer provided a list of his/her own color terms, thus guaranteeing that the correct terms were used for the rest of the experiment. Then the observer identified the unique hues corresponding to the chosen terms for the red, green, blue, and yellow elicitation samples.

The color-name elicitation phase, both in this experiment and in Experiment II, was necessary because of the considerable diversity in terms Somalis use to name the red, green, blue, and yellow elicitation samples. Previous work in Somali color naming (Brown et al., 2016; Lindsey, Brown, Brainard, & Apicella, 2015) showed that red, for example, can be called *guduud* or occasionally *casaan*. Most Somalis use the term *cagaar* to mean green, though some will use *doog* or the Arabic term *aqdar*. Yellow has many terms in Somali, but most informants use *jaale* or *huruud*.

2.1. Methods

2.1.1. General

The observers in Experiments I and II were tested under a protocol approved by the Institutional Review Board of the Ohio State University and following the tenets of the Declaration of Helsinki. Experimental sessions were conducted entirely in the observer's native language, using the services of a professional interpreter for the Somali observers. This interpreter had 4 years of experience as the interpreter of Somali color naming in our laboratory at the time of this study and was a co-author on our previous report (Brown et al., 2016). Consent forms and other paperwork were printed in the observer's native language. However, many Somali observers could not read the forms easily, and in those cases, the interpreter explained the study in Somali before consent was given. Each session began after the observer understood the study and gave his/her informed consent to participate. Each observer was tested individually and was screened for possible color vision deficiency using HRR pseudoisochromatic plates (Bailey, Neitz, Tait, & Neitz, 2004) before the experiment began.

2.1.2. Observers

Ten Somali-speaking observers, aged 50.5 ± 16.6 years (mean, *SD*; six females and four males), were recruited from the Somali community of Columbus, Ohio, and were tested at the Somali Senior and Family Center in Columbus, OH. The demographic profiles of the Somali observers (their ages, occupations, and where they had lived in Somalia) were similar to those of the informants in our previous study (Brown et al., 2016). All Somali observers were native, monolingual speakers of the standard dialect of the Somali language, and they reported living in the United States for an average of 7.4 years (*SD* = 3.8), after a stay of several months to many years in one or more other African countries before immigrating to the United States. In all, 68 native American English-speaking observers (44 females and 24 males) were recruited from introductory psychology and optometry classes at the Ohio State University for participation in the first experiment.

2.1.3. Stimuli and procedures

In the first phase of Experiment I, color terms were elicited with a set of 23 Munsell samples (Glossy Edition). This stimulus set was designed to include good examples of the color categories in the World Color survey, as well as a range of other saturated and desaturated colors, and had been used to elicit color terms from Somali and US observers in a previous study (Lindsey et al., 2015). Broadband 5000K fluorescent lamps (Phillips F32T8950; CRI = 90) illuminated the test samples, which were mounted on small gray cards (500 cd/m^2, Color-Aid 4.5). Samples were presented individually in a fixed order (listed in Lindsey et al., 2015), and the observer provided a single monolexemic color term for each sample. The terms assigned to the red, green, yellow, and blue samples were selected for use in the second phase.

In the second phase of Experiment I, the observer viewed a palette of 40 Munsell color samples. These highly saturated (high Munsell chroma) colors showed uniform gradations in hue, with overall reflectance (Munsell value) varying as necessary to include good examples of red, green, blue, and yellow that were near the corresponding focal colors in English (Sturges & Whitfield, 1995). The samples were: 2.5R–10R 5/12, 1.25YR 7/12, 5YR–10YR 7/12, 2.5Y–7.5Y 8/12, 10Y 8/12, 2.5GY 8/12, 5GY 7/12, 7.5GY 6/12, 10GY 5/12, 2.5G–5G 5/10, 7.5G 5/12, and 10G–10RP 5/10. Samples were presented in a circular array on the Color-Aid 4.5 gray surface, using the same illuminant as in the elicitation phase of the experiment. Using the observer's own terms for the colors elicited in the first phase, the experimenter instructed the observer to select the sample from the array that came the closest to satisfying each of the following sets of criteria: (a) the *blue* sample that contained no *red* or *green* color in it, (b) the *yellow* sample that contained no *red* or *green*, (c) the *red* sample that contained no *blue* or *yellow*, and (d) the *green* sample that contained no *blue* or *yellow*. The four target colors were tested in random order. The observer was allowed to pick up individual samples and hold them next to other samples in the array for color comparison.

Based on the color terms provided in the elicitation phase, all but one of the Somali observers in the present study used distinct terms for the red, green, blue, and yellow samples, and all four chromatic unique hues were determined for these observers. The remaining Somali observer used *grue* for green and blue, so he provided unique yellow (neither red nor grue) and red (neither yellow nor grue) choices only.

2.2. Results

The unique red, green, and blue selected by Somali GB and US English-speaking observers were very similar (Fig. 1); median selections were the same (7.5R 5/12, 2.5G 5/10, and 10B 5/10, respectively), and mean selections differed from the medians by <1 Munsell hue step. The unique red and yellow selected by the single Somali Grue speaker was similar to those of the Somali GB speakers (asterisks in Fig. 1). Median and mean

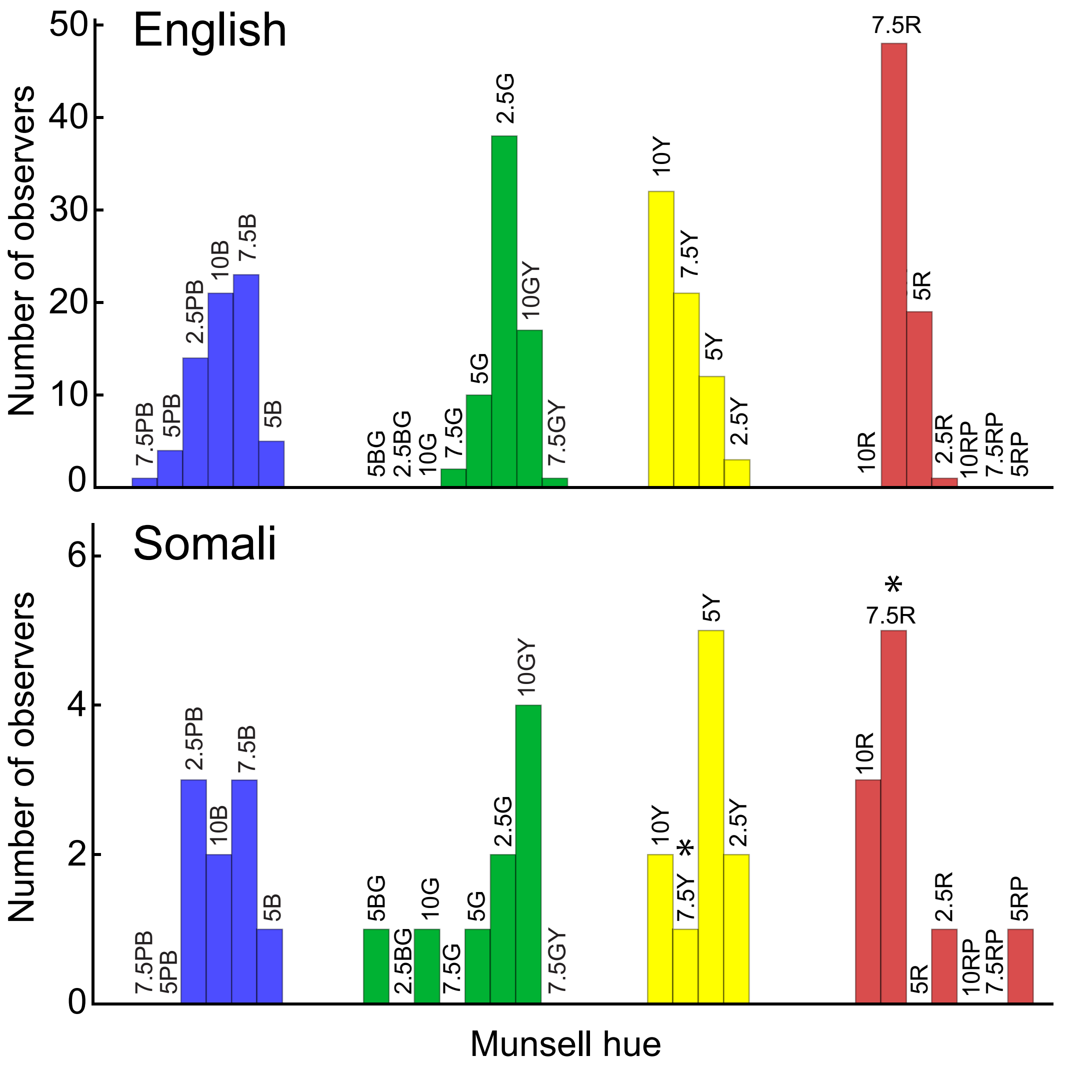


Fig. 1. Unique-hue selections by English- and Somali-speaking observers, with Munsell samples (designations above the bars) in spectral order from purple (left) to red (right). Asterisks: data from the single Somali Grue observer.

Somali selections for yellow were both one Munsell hue step redder (5Y 8/12 vs. 7.5Y 8/12) than those of US observers. Mann–Whitney tests for differences between English speakers' and Somali speakers' unique-hue distributions differed only for yellow (p = .010), which remained marginally statistically significant at p < .04 when corrected for four repeated comparisons.

Somali-speaking and English-speaking observers chose closely similar color samples for the unique-red, unique-green, and unique-blue instructions. Even the distributions for unique-yellow, which differed statistically significantly across the two groups, overlapped extensively, with the Somali range of unique yellow exactly coinciding with the range of the unique-yellow selections of the English-speaking observers. Thus, these results are similar to those of Webster et al. (2002), who reported that the unique hues of Indian and US observers were similar, and that the variation across groups was less than the individual variation within groups on this task.

3. Experiment II

Experiment I showed that Somali-speaking observers, like US English speakers, can easily choose colored samples based on unique-hue instructions, and that these choices are about what one would expect for terms naming the Hering elemental hue sensations. Therefore, we were in a position in Experiment II to ask how observers apply the color terms for those unique hues to colors of a wider range of hues, chromas, and values.

For each of a series of test colors, observers were asked to mentally decompose its color appearance into the elemental color sensations of Hering's theory of color appearance. Observers then reported the component sensations using their own terms for *red*, *green*, *blue*, *yellow*, *black*, and *white* in their native languages. This color decomposition procedure differed from the standard hue-scaling procedure in five important ways.

1. Each session began with a preliminary color naming phase in which observers provided names for an elicitation set of color samples, which included good representatives of unique red, green, blue, and yellow stimuli, as well as white and black categories (Lindsey & Brown, 2014). This was necessary to classify the Somali observers according to their motifs. Also, previous work, including Experiment I and Brown et al. (2016), showed that there are several different terms for these colors in modern Somali, and it was important that observers in this study used their own personal color terms.
2. Observers reported only the Hering elemental color sensations that they saw in a given colored stimulus, using only the six Hering color terms in any combination they chose, rather than using a rating scale to express the proportions of Hering elemental sensations that were present in the stimulus (see also Boynton & Gordon, 1965; Thomson, 1954, for a similar approach). This simplified protocol was necessary because of time constraints in using a large number of samples and testing Somali observers with the help of an interpreter.
3. More responses were permitted than is typical for hue-scaling studies. Both *black* and *white* were allowed, since those were the terms that Hering used, and previous work showed that some Somali observers use achromatic terms to name green and/ or blue stimuli. This is in contrast to the typical hue scaling procedure, where hue terms have been used with saturation (e.g., Gordon & Abramov, 1977, 1988), *white* but not *black* (Sternheim & Boynton, 1966), or none of these options (Fuld et al.,

1981). Based on previous work (Lindsey et al., 2015), "*no term*" was allowed, if the observer did not think that the test color could be named, even partially, with any combination of their six permissible terms.

4. Observers did not receive any extensive instruction or practice, and especially no feedback, on the color decomposition task. This constraint allowed us to see how observers responded spontaneously to the stimulus set, without the potential bias induced by extensive preliminary instruction and practice (see also Gordon & Abramov, 1988, who used both naive and practiced observers).
5. The stimuli were a subset of the printed Munsell color samples used in the World Color Survey that spanned a broad range of hues, lightnesses, and colorimetric purities. This is different from most hue-scaling experiments, where the stimuli were typically either spectrally narrowband lights presented as aperture colors (e.g., Gordon & Abramov, 1988) or moderately saturated colors spanning a color circle, presented on a computer monitor (e.g., Bosten & Boehm, 2014). In two previous systematic studies of hue scaling involving non-spectral aperture colors, colorimetric purity was varied by mixing monochromatic lights with white (Abramov & Gordon, 2005; Kulp & Fuld, 1995).

3.1. Methods

3.1.1. Observers

Thirty-four color-normal Somali-speaking observers, aged 42 ± 18 years (mean, *SD*; 19 females and 15 males), participated in Experiment II, which was conducted in the laboratory. Fisher's exact test analysis showed no association between age and gender (significance level = 0.457). As in Experiment I, their demographic profiles were similar to those of the informants in Brown et al. (2016). Their occupations in Somalia ranged from camel herders (15%) to government workers (6%). Other occupations included: owners/employees of small businesses (32%), tradespeople (6%), housewives (12%), and farmers (6%). Twenty-four percent of them left Somalia as schoolchildren. Virtually, all spent some time in one or more refugee camps located outside Somalia before immigrating to the United States.

Twenty-six US English-speaking undergraduate observers also participated in the color decomposition task in a laboratory setting. One English-speaking observer tested positive for red–green color blindness, and his data were excluded from analysis. The remaining 25 English-speaking observers (13 females and 12 males), aged 19.8 ± 4.3 years, were raised in the United States in English-speaking homes, and none learned to speak a second language before the age of 12 years.

3.1.2. Materials

The stimuli were 145 Munsell colors, Glossy Edition, which was a subset of the 330 color samples comprising the World Color Survey stimulus set (Fig. 2a; Brown et al., 2016). The elicitation color set consisted of 10 colors extracted from this test set

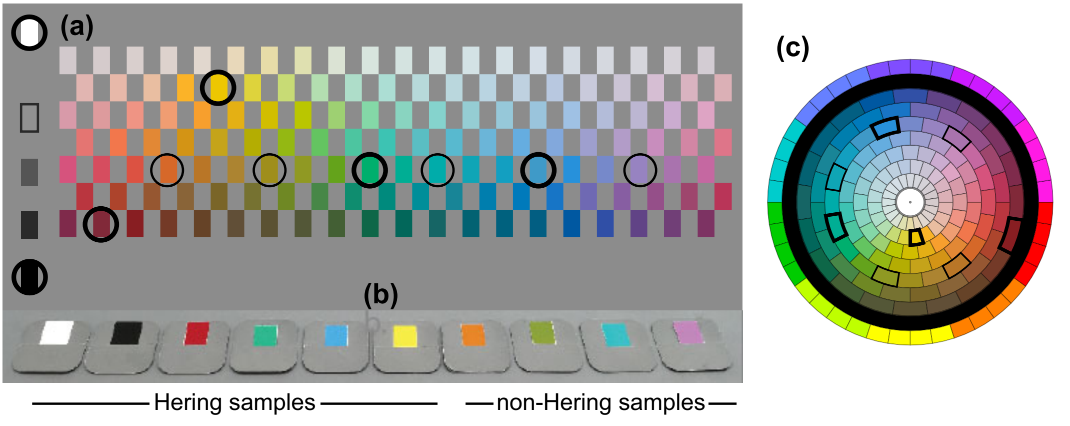


Fig. 2. Stimuli used in the color decomposition task. (a) One hundred and forty-five Munsell test color samples, shown in their traditional locations within the World Color Survey stimulus diagram. Black circles: 10 colors comprising elicitation color set; bold circles are the Hering samples. (b) Photograph of the elicitation sample set, arranged according to Hering and non-Hering color samples. (c) Chromatic stimuli from "a," shown in radial diagram format. Munsell hue (2.5R through 10RP) varies progressively counterclockwise from the rightward direction; the outer colored ring codes the Munsell hue groups. Munsell value varies from 9.5/(white; center of each panel) to 3/(darkest samples tested; outer ring). Black borders: elicitation samples; bold borders, the Hering samples.

(highlighted in Fig. 2a,c and shown in Fig. 2b). Six of these "Hering samples" were target colors designed to elicit the observer's Hering terms. These were good examples of the corresponding English color categories (Berlin & Kay, 1969; Lindsey & Brown, 2014; Sturges & Whitfield, 1995). There were also four additional "non-Hering samples": orange, olive, cyan, and purple, which were included in case they might be necessary to help classify the motifs of the Somali observers.

3.1.3. Procedures

After securing informed consent and eliciting demographic information, and after testing the observer's color vision using the HRR plates and the D-15 panel, the 10 elicitation color samples were presented one at a time in random order to determine the observer's own color terms. For each sample, the observer provided a single monolexemic name that he/she commonly used in his/her native language to denote that color (Table 1). A few observers replied "don't know" for one or more of the non-Hering samples. Then the orange, olive, cyan, and purple/lavender color samples were set aside, and the red, green, blue, yellow, black, and white samples were placed on the side of the table, in view of the observer, to remind him/her which color terms were allowed. The color samples were provided as a mnemonic aid instead of written color terms because many Somali-speaking observers could not read the English or Somali color names. Observers were unaware of the purposes of the study at the time of test, but they were debriefed after testing was done.

In the color decomposition phase of each session, each of the 135 remaining Munsell color samples was presented one at a time, in a fixed pseudorandom order. The observer

Table 1
Terms applied to Hering elicitation stimuli

Target	English	Somali		
	All (25)*	GB (27)*	Grue(4)*	Achromatic (3)*
Red	*red (25)*	*guduud (26)* *casaan (1)*	*guduud (4)*	*guduud (3)*
Green	*green (25)*	*cagaar (27)*	*cagaar (4)*	*cagaar (2)* *boore (1)*
Blue	*blue (25)*	*buluug (27)*	*cagaar (4)*	*madow (2)* *dameeri (1)*
Yellow	*yellow (25)*	*jaale (20)* *huruud (4)* *yallow (2)* *maroon (1)*	*jaale (4)*	*huruud (1)* *jaale (1)* *casaan (1)*
Black	*black (25)*	*madow (27)*	*madow (4)*	*madow (3)*
White	*white (25)*	*cadaan (26)* *cadays (1)*	*cadaan (4)*	*cadaan (2)* *dameeri (1)*

*Numbers in parentheses indicate numbers of observers.

was instructed to name each test color using any combination of the Hering color terms elicited in the first phase of the session, or *no term*. Thus, each test sample could receive anywhere between zero and six Hering color terms. The observer was instructed to provide a particular Hering term if and only if the appearance of the test sample showed a color quality or qualities that could be named using that term. Colors that showed multiple color qualities could receive multiple color terms. Colors whose appearance could not be named using any of their Hering color terms, alone or in combination, should receive the response *no term*. We emphasized that Hering term selections should be based on color appearance alone and that observers should ignore how paint pigments could be mixed to produce the target color. Finally, observers were instructed to base their responses on the meanings of their Hering terms and to ignore the appearances of the mnemonic samples used to elicit these terms.

3.2. Results

3.2.1. Elicitation sample color names and Somali motif assignment

All 25 color-normal English-speaking observers responded *red*, *green*, *blue*, *yellow*, *black*, and *white*, respectively, to the six Hering color term elicitation samples. The Somali observers generally provided some combination of the high-consensus terms *guduud* for red, *cagaar* for green, *buluug* for blue, *jaale* or *huruud* for yellow, *madow* for black, and *cadaan* for white, although there was some variation in the actual color terms among Somali observers (Table 1). Somalis called the purple/lavender elicitation sample *barbal* (purple, $N = 12$), *guduud* (red, $N = 11$), *binki* or *basali* (pink, $N = 6$), *gereen* (green, $N = 1$), or *no color* ($N = 6$), but never any Somali term for *yellow*.

In all, 27 Somali observers used distinct terms for all six Hering elicitation stimuli, and they were classified as members of the GB motif of Lindsey and Brown (2009). Every Somali woman but one expressed this motif. However, not every Somali observer used distinct terms for all Hering samples (Brown et al., 2016). Four Somali observers used a single chromatic color term, *cagaar* (the dictionary term for green in Somali), to name both the blue and green elicitation samples. They were assigned to the Grue motif. Finally, an Achromatic motif was defined for three Somali observers (two men and one woman) who would have fallen into the Gray or Dark motifs of Lindsey and Brown (2009). Two of them used *madow* (the dictionary term for black in Somali) as their term for the blue and black samples, and one used *dameeri* (a common term for gray; see Brown et al., 2016) as their term for both the blue and the white elicitation samples. There was no gray elicitation sample, so we do not know what motif the latter observer would have been assigned to, if a gray sample had been available in the elicitation set.

As in previous work (cf. Brown et al., 2016), the Somali motifs were related to the ages and genders of the observers. After grouping observers' ages by decade, Fisher's exact test revealed an association between age and motif (significance level = 0.01), with the GB motif predominating among younger observers and the Grue motif being used by older observers. The GB motif was more commonly used by women ($N = 18$), than by men ($N = 9$), and every Somali woman but one used the GB motif (significance level = 0.016). We have argued elsewhere (Brown et al., 2015) that this demographic profile, with the GB motif predominating among young women, is consistent with diverse color naming being associated with ongoing language change. There was also a weak but statistically significant association between occupation and motif (significance level = 0.043), with housewives, students, most business people, farmers, and government workers using the GB motif.

3.2.2. Number of color terms used in color decomposition

The four different groups of observers (English speakers and the Somali speakers in the three motif groups) differed in how they combined chromatic color terms, achromatic color terms, and *no term,* to name the chromatic Munsell stimulus samples (Fig. 3). A one-way analysis of variance for each panel in Fig. 3 showed that the overall frequency of use of each combination of term types was always different from zero (after centering the motif dummies, the intercepts were different from zero: $F_{1,55} > 16.75$, $p < .0002$ in each case). However, the groups differed in how many chromatic samples were named using single chromatic terms only, mixed chromatic and achromatic terms, and achromatic terms only ($F_{3,55} > 7.4$, $p < .0005$ in each case), or using multiple chromatic terms only ($F_{3,55} = 3.872$, $p = .014$), but not in the number of samples called *no term* ($p = .088$). Planned post-hoc analysis, with Bonferroni correction, revealed that English speakers were significantly different ($p < .03$) from one or more Somali groups in each case where the ANOVA revealed a statistically significant difference among groups. Also, achromatic terms only occurred most frequently in the data sets of Somali speakers in the Achromatic motif.

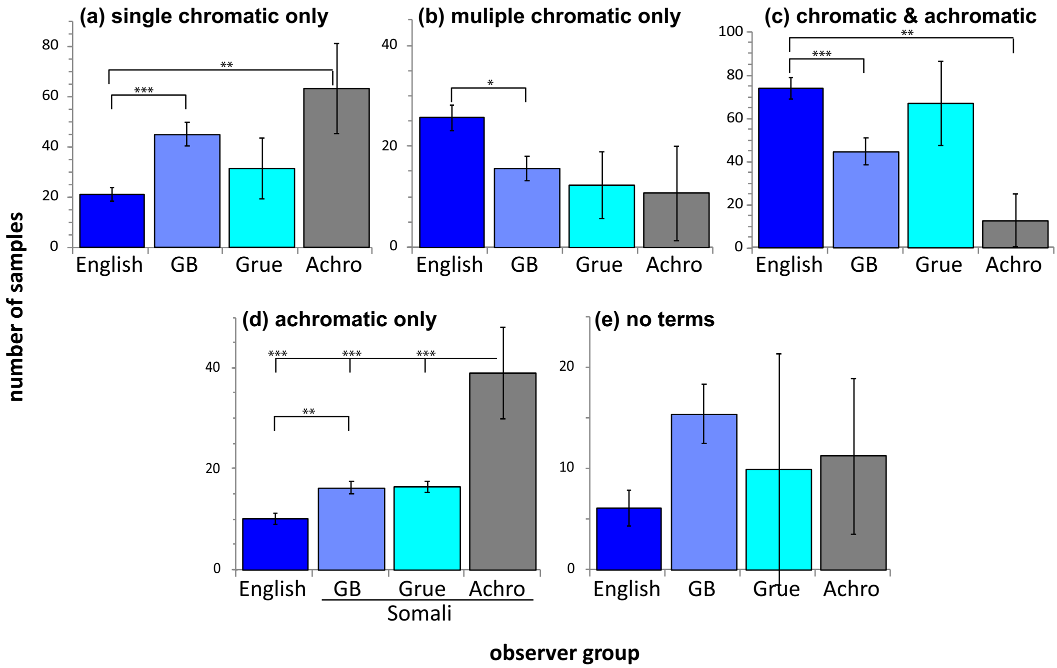
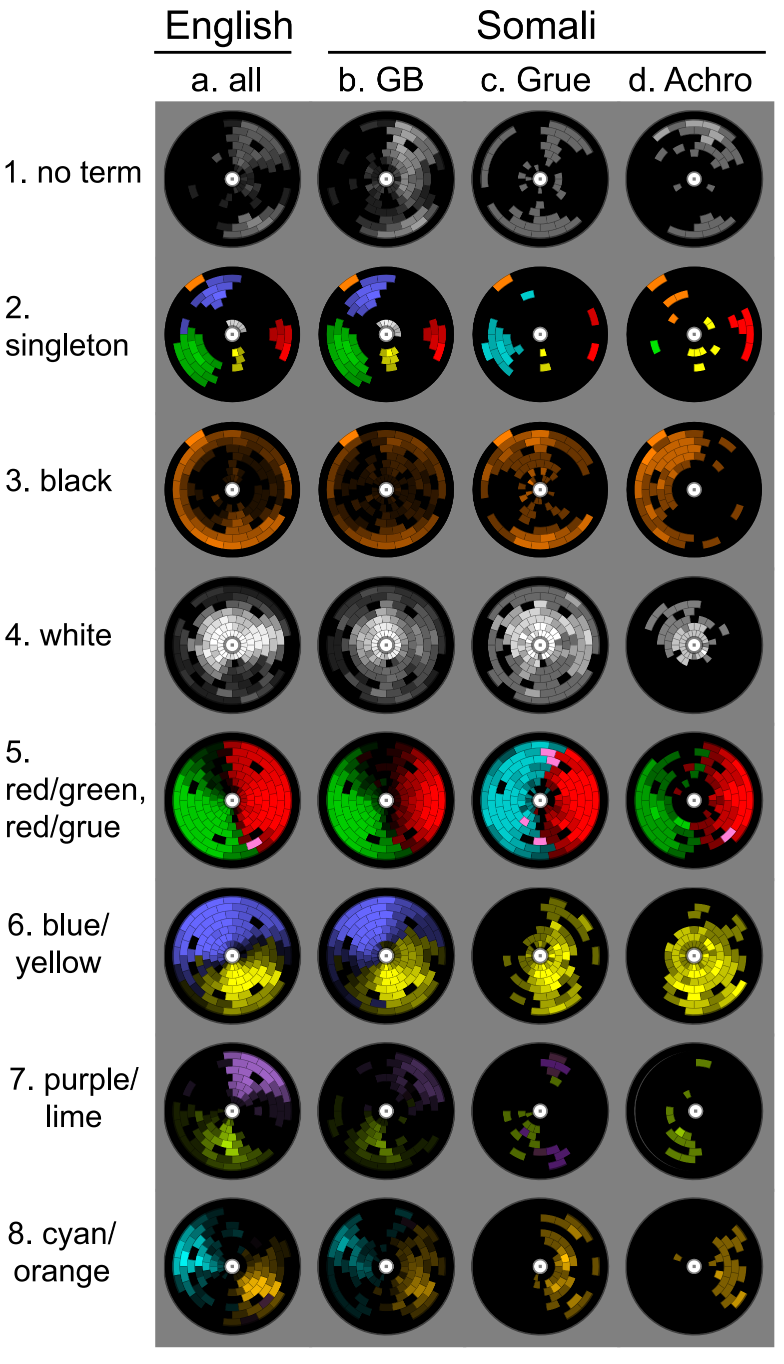


Fig. 3. The average number of chromatic test samples (±SEM) named in a particular way by English-speaking observers and Somali-speaking observers in the GB, Grue, and Achromatic motifs. Notice that the ordinate ranges vary across panels. (a) Exactly one chromatic term and no achromatic terms. (b) At least two chromatic terms and no achromatic terms. (c) At least one chromatic and at least one achromatic color term. (d) Achromatic terms only. (e) *No term*. Pairwise statistical significance: $*p < .05$; $**p < .01$; $***p < .001$. The data pooled across all panels contain each sample named by each observer exactly once.

Fig. 4. Consensus in Hering color term usage. Radial plots of color decomposition responses to 135 chromatic color samples (approximate colors shown in Fig. 2c) and black and white elicitation samples. False colors code the type of term, and false color luminance codes the fraction of informants using the term on an approximately perceptually linearized relative brightness scale ([term used by # observers]/[total # observers])$^{0.65}$. Black areas: term type not used. Columns a–d, language/motif. Rows 1–8, patterns of color decomposition. "1. no term:" samples not named, false-colored white. "2. singleton:" usage of single term (*red*, *green*, *blue*, *yellow*, *black*, or *white*) only. "3. black:" *black* used alone or in combination with other Hering terms, false-colored orange. Consensus in naming the black elicitation sample is shown as the orange sector on the outermost ring of the radial plots in rows 2 and 3. "4. white": *white* used alone or in combination with other Hering terms, false-colored white. The white elicitation sample is shown as the white disk in the center of each diagram. "5. red/green, red/grue," "6. blue/yellow:" Hering terms alone or in combination with other terms. "7. purple/lime," binary combinations of *red*-plus-*blue* or *red*-plus-*grue* compared with *yellow*-plus-*green* or *yellow*-plus-*grue*. "8. *cyan/orange*," binary combinations of *green*-plus-*blue* compared with *red*-plus-*yellow* (false-colored yellowish-orange). Pink: areas of overlap across observers, where different observers chose different terms, and at least 33% of observers chose the minority term. In panel d2 only, the terms for blue were *madow* for two observers and *dameeri* for the third; these have been pooled and coded orange.



3.2.3. Patterns of color decomposition

Polar plots of consensus in Hering term usage by all the observers tested in this study are shown in Fig. 4. In each of these plots, WCS chart hue varies with angle around each

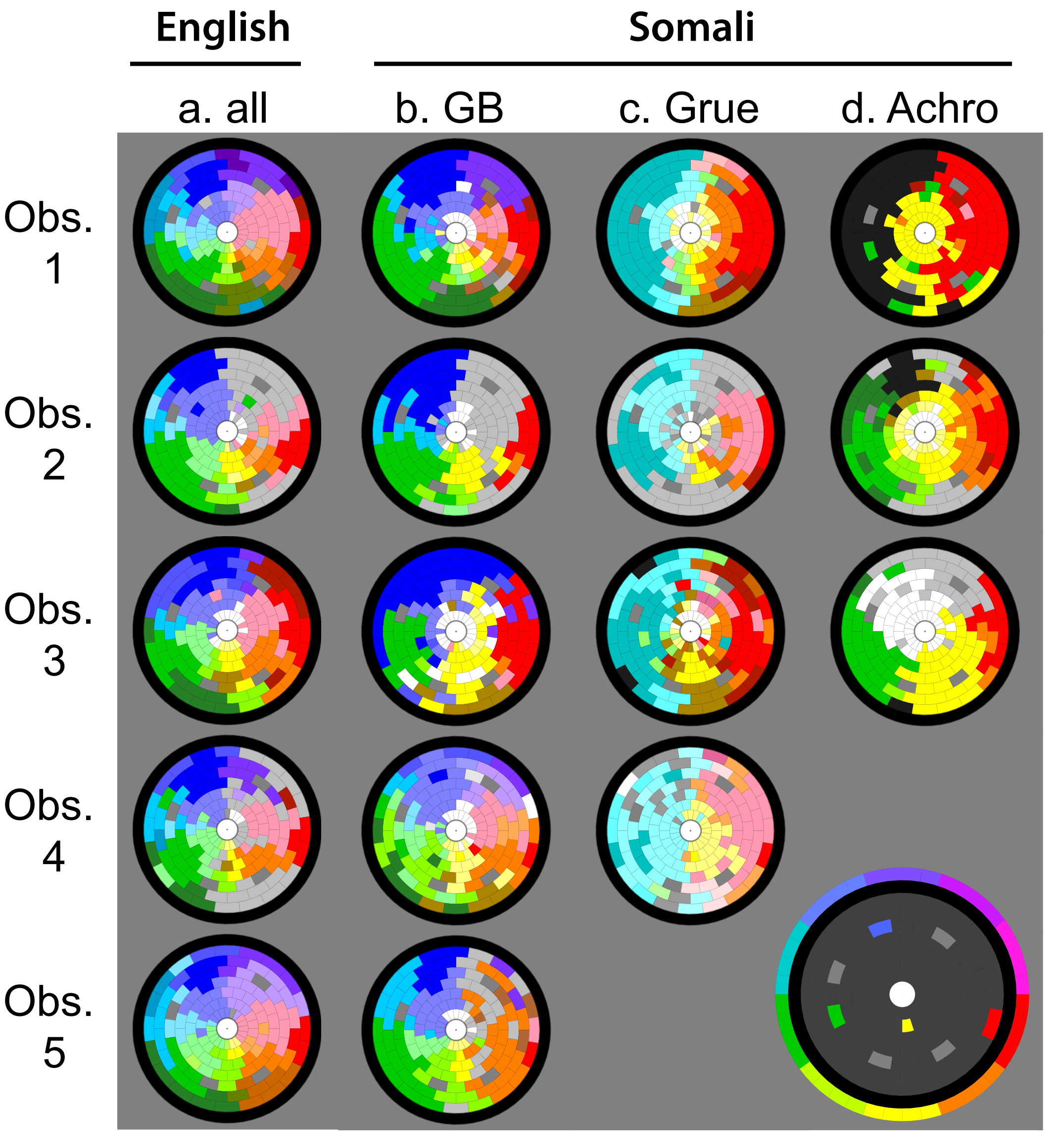


Fig. 5. Examples of individual color decomposition results applied to chromatic colored samples. False colors indicate the color terms used (Detailed false color keys in Supplemental Materials Figs. S1.3 and S1.4). Lower right: key shows Munsell hue group false-color-coded around the rim and elicitation samples in the interior of the plot (false colors: the positions of the Hering elicitation samples; gray, the positions of the non-Hering elicitation samples). Columns a–d, language/motif groups. Rows 1–5, individual observers within each group. Responses to the red, green, blue, and yellow elicitation samples were added into the rest of the data set. Saturated red, green, blue, and yellow false colors: unitary Hering color terms; other saturated hues: binary combinations of these terms; light colors: corresponding hue term plus *white*; dark colors: corresponding hue term plus *black*. Light gray: *no term*. Middle gray: *black*-plus-*white*. Dark gray: non-Hering elicitation samples.

concentric circle of the plot, and value varies radially from light (closest to center, including the white sample which is the central white disk) to dark (farthest from center, including the black sample, which is the orange sector in the outermost ring in rows 2 and 3; true colors and their nominal Munsell hue designations shown in Fig. 2c). Each row of polar plots in Fig. 4 emphasizes a different aspect of the Hering color decomposition results, and each column shows results for one language/motif observer group. See the figure caption for more details. More traditional Mercator-like projection plots of results from all study participants are shown in Supplemental Materials S1. Fig. 5 shows the representative examples of individual data.

English-speaking observers: Although most English-speaking observers named most of the samples successfully, *no term* responses also occurred frequently (Fig. 3e). As shown in Fig. 4a1, these were concentrated in the purple and/or lavender (8/25 = 32% of observers) and brown regions of the diagram (9/25 = 36% of observers; e.g., Fig. 5a2), as defined by the modal responses of English-speaking informants in Fig. 5 of Lindsey and Brown (2014). The Hering terms *red*, *green*, *blue*, and *yellow* were often used alone ("singletons," shown in Fig. 4a2), with high consensus for colors near the elicitation samples that had been called *red*, *green*, *blue*, or *yellow* in the preliminary phase of the experiment. Notice that singleton usage of Hering terms in the color decomposition task is not the same thing as the unique-hue responses elicited in a traditional hue scaling experiment. In this task, the distribution of singleton responses depends not only on the observer's unique hues but also on their willingness to deploy single terms when one Hering sensation dominates but other, less salient sensations may also be present.

Black responses by English speakers were reserved mainly for the darkest achromatic samples, including the single black sample (orange sector in the outer rings of Figs. 4a2, a3), and *white* was applied with high consensus to the light samples (Figs. 4a3,a4), including the single white sample (central white disk throughout).

The *red* and *green* responses are generally well separated in the English data set. All the samples receiving *red* or *green* responses from English speakers, either alone or in combination with other terms, are shown in Fig. 4a5. *Red* and *green* were often combined with other chromatic (*yellow* or *blue*) or achromatic Hering terms (*black* or *white*). As expected, *red* was deployed across reddish, orange, and purple/violet portions of the color chart, while *green* was deployed across yellowish, greenish, and bluish portions of the chart. There was some overlap in red and green non-singleton responses, in that a few samples were called *red* by some observers and *green* by others (false-color-coded pink in Fig. 4), but *red* and *green* were only very rarely used together (0.8% of responses).

The English "blue/yellow" radial plot (Fig. 4a6) shows that *yellow* was deployed across orangish, yellowish, and greenish portions of the color chart, and *blue* was deployed across greenish, bluish, and purple/violet portions of the chart. English *blue* and *yellow* responses were generally well separated, and green samples were never called *blue*-plus-*yellow*.

According to Hering, colors that fall between the unique hues will be named by particular binary combinations of the corresponding non-opponent Hering terms. The English "purple/lime" plot (Fig. 4a7) shows the use of *blue*-plus-*red* and *yellow*-plus-*green*. As expected, *red*-plus-*yellow* was chosen in the orangish regions of the WCS chart, while *blue*-plus-*green* was chosen for cyan-colored samples (Fig. 4a8). Most English-speaking observers who named purple/lavender samples with a distinct color term combination did so using *blue*-plus-*red*, sometimes with *white* as well, although purple samples sometimes elicited the *no term* response instead (e.g., Fig. 5a2).

The English-speaking observers were a demographically and educationally homogeneous group, so the diversity of their responses was somewhat surprising. It is unlikely that the deviations from the expected pattern that is shown in Fig. 5a1 were due to observers deliberately providing systematically misleading responses. All observers were unaware of the purposes of the study, the test sample size was large (135 colors), and samples were presented in pseudorandom order. It would have been difficult for observers to remember their unexpected responses to previous samples in one region of the chart while providing typical results for color samples in other regions of the chart.

Somali-speaking observers: Somali observers were divided into the GB, Grue, and Achromatic motif groups based on how they named the blue sample during the elicitation phase of the experiment. Observers in the GB motif group (N = 27) always used the Somali term *buluug* for the blue sample. Grue observers (N = 4) used a single term (*cagaar*) to name both the blue and the green elicitation samples, and Achromatic observers (N = 3) used a term for black or white to name the blue elicitation sample. The color naming results of these three groups are shown in the respective columns in Fig. 4, columns b–d (see Fig. a2–a4 for Mercator-like presentation of the individual data).

Somali GB observers. In spite of the demographic diversity of Somali GB observers (Section 3.2.1), the patterns of consensus in their color decomposition were qualitatively similar to those obtained from the English-speaking observers (cf. Fig. 5 columns a and b). The semi-circular mutually exclusive distributions of *red* versus *green* and *blue* versus *yellow* usage were similar across English and Somali GB observers (cf. Figs. 4b5 and 4b6 to Figs. 4a5 and 4a6), although English *red* responses covered somewhat wider ranges of samples than the corresponding Somali responses. Somali GB singleton responses were generally similar to what was seen in English (cf. Fig. 4b2 to 4a2), and the overall patterns of binary usage of terms for lime (*green*-plus-*yellow*), orange (*red*-plus-*yellow*), and cyan (*green*-plus-*blu*e) were generally similar to those obtained from English speakers (cf. Fig. 4a7 to Fig. 4b7 and cf. 4a8 to 4b8), albeit with lower frequency (Fig. 3b). Somali GB observers rarely called purple samples *red*-plus-*blue* (Fig. 4b7; cf. Fig. 5b1 to Fig. 5b2–b5), but, remarkably, *yellow*-plus-*white* sometimes extended into the lavender range (e.g., Fig. 5b3). These results are considered in Section 4.3.

In the Somali GB data set, as in the English data set, green samples were never called *blue*-plus-*yellow* (cf. Fig. 4a5 to Fig. 4a6 and cf. 4b5 to 4b6). Together with the infrequent use of *red*-plus-*blue* to name purple in Somali, these results suggest that both

English-speaking observers and Somali-speaking observers were obeying the instructions and introspecting on the color sensations contained in the samples, rather than following the rules for mixing paints.

Somali Grue observers. The responses of the Somali Grue observers are particularly interesting in light of Hering's theory because these observers did not use distinct terms for the Hering green and blue sensations.

As expected, the singleton responses of the Grue speakers (Fig. 4c2) fell into three distinct regions of the chart: red, yellow, and grue (which is color coded cyan in Figs. 4 and 5), with singleton *grue* covering the green and blue elicitation samples, but otherwise falling exclusively in the green area of the chart. Although all Grue observers called the blue elicitation sample *grue* as well, the high consensus terms for the blue test colors (other than the elicitation sample) were *grue* combined with an achromatic term (cf. Fig. 4c3 to 4c4). Figs. 4c5 and 4c6 show the distributions of *red/grue* and *yellow*, respectively. Only one of the four Grue speakers (Fig. 5c2) failed to name all the samples. This observer, like many of the English-speaking and Somali GB-speaking observers (Figs. 5a2 and 5b2), had difficulty mainly in naming purple/lavender and brown samples (cf. Fig. 4, panels a1,b1, and c1).

If Grue color decomposition reflected nothing more than a reduction in the number of available Hering terms, we would expect that the samples that were called *grue* by Somali GB observers would include both the samples that English speakers called *green* (Fig. 4a5) and those that they called *blue* (Fig. 4a6). Contrary to that prediction, *grue* was almost never used to name purple samples, which were clearly bluish to most English-speaking observers.

So, although the term "*grue*" is a portmanteau of the terms "*green*" and "*blue*," the response *grue* clearly did not mean "*green*-or-*blue*." Instead, purple samples were often called *yellow*, in combination with an achromatic term (Figs. 4c3, 4c4 and 5c1, 5c4) or *red* (Figs. 4c8 and 5c3, 5c4). Also as noted, there is an absence of singleton usage of *grue* across the entire blue region of the chart, except, of course, for the blue elicitation sample. This suggests that the Grue speakers perceived blues as shades of a color category that is focused in the green region of color space.

Somali Achromatic observers. Somali Achromatic observers constitute a small, diverse class of observers. All three used an achromatic term to name the blue elicitation sample as well as many test samples that are generally given a chromatic term by other Somali observers. One of them (Fig. 5d1) used an achromatic term to name both blue and green elicitation samples. The other two (Fig. 5d2,d3) used a common Somali chromatic term (*cagaar*, the dictionary translation of *green*) to name the green elicitation sample.

Overall, Somali Achromatic observers provided terms for most colors: *No term* was not significantly more prevalent for them than it was for the other observers (Fig. 3e; cf. Fig. 4d1 to Fig. 4a1–4c1). Their use of singleton terms was a bit scattered (Fig. 4d2), but their use of *red* and *green* was similar to Somali GB speakers (cf. Fig. 4b5 to 4d5). Also, Achromatic observers used the binary combinations *yellow*-plus-*green* and *yellow*-plus-*red* to name the colors of lime and orange samples, respectively (Figs. 4d7 and 4d8). Thus, Somali Achromatic observers, like the English speakers, showed a good understanding of the color decomposition task.

Nonetheless, the Somali Achromatic observers, like their Grue counterparts, used their Hering *yellow* term in regions of the color chart not predicted by the color-opponency provision of Hering's theory. This can be seen both in singleton usage (4d2), and in cases where *yellow* was combined with other terms (4d6; see also Fig. 4d8). In fact, the use of *yellow* by one or more observers is evident around all 360 degrees of the polar stimulus plot for Achromatic observers.

4. Discussion

A major challenge in interpreting behavioral tests of Hering's theory has been the close correspondence between Hering's primary sensations and the basic lexical color categories—*red*, *green*, *blue*, *yellow*, *black*, and *white*—found in modern Western languages (Brindley, 1970, p. 202). Indeed, Hering himself argued that this correspondence between color sensations and color terms was prima facie evidence for his theory of color appearance (Hering, 1878/1964, p. 46). In this report, we have addressed Brindley's concerns by examining the effects of differences in color lexicon on observers' unique-hue and color-decomposition responses.

4.1. Unique-hue settings

The unique-hue settings by the English- and Somali-speaking observers in this study are entirely consistent with one another and with Hering's theory. However, this Somali sample was small, and only one of the Somali observers (a Grue speaker) expressed a motif other than GB in their color naming. A second possible problem concerns the nature of the unique-hue task itself. There is a close correspondence between red, green, blue, and yellow unique hues identified by English speakers and the best examples ("focal colors") of their corresponding color categories, when selections are made from the same color palettes (Kuehni, 2005; Miyahara, 2003; however, see Kuehni, 2001, for an exception). Furthermore, the focal colors have been shown to be universal across languages (Regier et al., 2005). Therefore, the English and/or Somali speakers might have based their unique-hue selections on the best examples (among the colors displayed) of their red, green, blue, and yellow color categories, rather than on the specific contributions of Hering's elemental sensations.

4.2. US and Somali no-term *responses*

In Experiment II, a substantial fraction of both Somali-speaking and English-speaking observers gave *no term* responses, most commonly to samples falling in the purple/lavender and brown regions of this test palette. This result was robust, and it constitutes a violation of the *sufficiency* (or completeness) provision of Hering's theory: that every color must be nameable using only the terms for the six elemental color sensations. Previous investigations have shown that purple and brown are named color categories both in English (Berlin & Kay, 1969; Lindsey & Brown, 2014; Sturges & Whitfield, 1995) and in

Somali (Brown et al., 2016), although they are not traditional Somali categories and are often named using loanwords. So some observers in the present experiments might have considered purple and/or brown to be elemental in some way that is related to their color lexicon, and contrary to Hering's theory. Prior empirical studies of English *brown* have generated mixed results (Fuld, Werner, & Wooten, 1983; but see also Buck & DeLawyer, 2012, 2014; Quinn, Rosano, & Wooten, 1988). Purple has generally been shown not to be elemental, although more recent studies of hue-scaling (Bosten & Boehm, 2014, Fig. 3e) and partial-hue matching (Logvinenko & Beattie, 2011, observer CB) do report the occasional observer who does treat purple as elemental.

The frequent use of *no term* by Somali-speaking observers is in line with the findings of previous work on unconstrained monolexemic color naming (Lindsey et al., 2015), where *don't know* was a permitted response, but the frequent use of *no term* by English speakers was unexpected. Demographic factors such as age and life experiences might explain the significant rates of *no term* use by Somali observers, but they do not readily explain why English speakers used *no term* as often as they did. Previous studies of English speakers only occasionally reported that participants had difficulty with the task in hue-scaling experiments (e.g., Bosten & Boehm, 2014, Fig. 3e; Emery, Volbrecht, Peterzell, & Webster, 2017a, Section 2.1). Perhaps the differences between those results and ours are due to our color decomposition task. However, we suspect that the differences are mainly due to the more diverse palette of colors we tested and the availability of *no term* as a valid response in this study.

4.3. *Somali* yellow *responses*

The Somali terms for *yellow* gloss nominally to the English term *yellow*, and the unique yellow chosen by our small sample of Somali GB speakers in Experiment I corresponds closely to the unique yellow chosen by English speakers. However, in the color decomposition task, the extension of *yellow* was markedly greater for Somali speakers than for English speakers. The top row of Fig. 6 compares *yellow* responses across the four language/motif groups studied here. For English speakers (Fig. 6a), a contour can be drawn through the white samples at the center of the polar plot that divides color space into two mutually exclusive regions of *blue* and *yellow* responses (the white line was chosen to divide blue from yellow in Fig. 4a6; see also the English monolexemic data in Fig. 6e). The results from Somali GB speakers showed that a few of their *yellow* responses extended into the pink/lavender region of the chart, and thus well into the blue area defined by English-speaking observers. In stark contrast to the English data, *yellow* wraps completely around the 360 degrees of the polar plots in the Somali Grue and Achromatic data sets (Fig. 6c,d). No matter how the white contour in these panels is drawn, whether it is straight or curved, as long as it passes through the center of the diagram, that contour cannot segregate *yellow* responses from any conceivable set of opposite color-opponent responses like *blue*. This is inconsistent with the color-opponent structure of Hering's color space. It is also inconsistent with any other theory of color appearance based on color-opponent dimensions that include yellow as one of the primaries (e.g., von Goethe, 1810/1840). Notice also that the

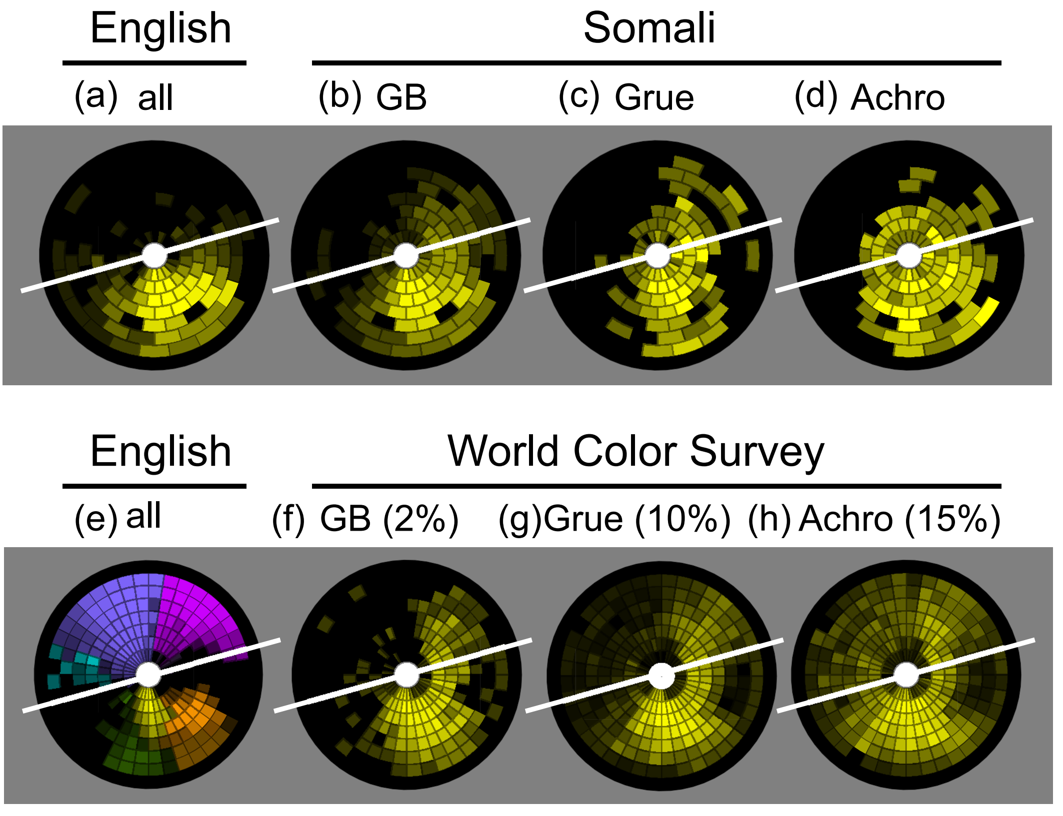


Fig. 6. Consensus plots of the use of *yellow* here and in previous work. Top row: panel a, English *yellow* data from Fig. 4a, row 6, and panels b–d, Somali *yellow* data from Fig. 4b–d, row 6. Bottom row: Data from experiments where only single color terms were allowed. For clarity, overall data in each panel are scaled linearly to a maximum of 1.0 for the panel as a whole, then compressed with an exponent of 0.65. Panel e, English color naming patterns classified as the yellowish colors (*lime* or *olive*, *yellow*, *orange*, and *brown*), and the bluish colors (*cyan*, *blue*, and *purple*), from Lindsey and Brown (2014). Panels f–h, WCS color naming patterns classified as *yellow*-or-*orange* by cluster analysis (see Lindsey & Brown, 2006 for details); percentages are the fractions of informants in each motif group (Lindsey & Brown, 2009) whose data are shown because they used *yellow*-or-*orange* to name bluish samples. White lines divide each diagram into bluish and yellowish domains.

360-degree extensions of *yellow* in Figs. 6c,d entirely enclose white (the origin of the polar plots in Fig. 6), so Somali *yellow*, as used by both Grue and Achromatic speakers, is not a well-formed color category in the sense of Regier, Kay, and Khetarpal (2007).

Other examples of this extension of *yellow* have been observed previously both in Somali monolexemic color naming (Brown et al., 2016) and in the WCS data set (see examples in the individual data shown in Supplemental Materials S2, Fig. S2.1). Subsets of yellow data from the WCS that exhibit the extended pattern of *yellow*, organized by motif (Lindsey & Brown, 2009), are shown in Fig. 6f–h. Much like the present *yellow* responses, these WCS *yellows* extend throughout the high lightness/low saturation areas, including into the purple/lavender areas, of the WCS chart. The obvious similarity

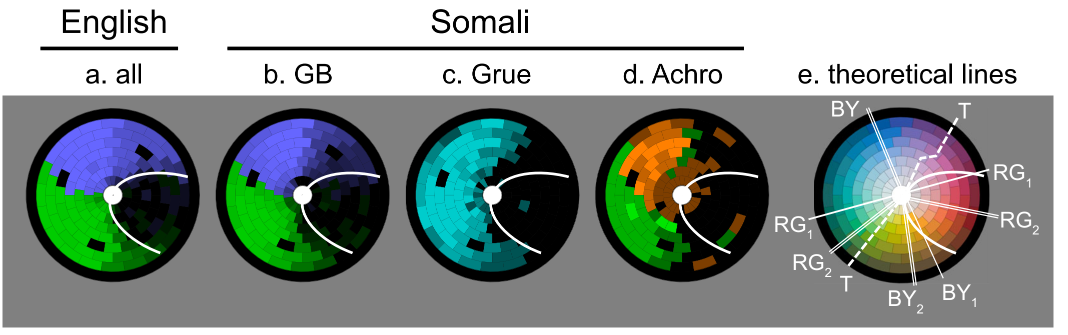


Fig. 7. English and Somali terms for *green* and *blue*. The union of (a) all samples called *green* or *blue* in English is compared to (b) the union of all samples called *green* or *blue* by Somali GB speakers, (c) the samples called *grue* by Somali Grue speakers, and (d) the samples called *green* or *achromatic* by Somali Achromatic speakers. The curve in (a) is repeated in each panel. (e) Contours dividing color space according to various theories of color vision. T, tritan contour, is taken from the tritan confusion line passing through white in CIE xyY space. RG_1, the line dividing blue from yellow (Fig. 6) and RG_2, the line passing through the middle of the singleton *red* and *green* samples via *white* (Fig. 4a2), are two estimates of the null set for the Hering blue/yellow process. BY_1, the line separating *red* from *green* (Fig. 4a5), and BY_2, the bent line passing through the middle of the singleton *yellow*, *white*, and *blue* samples (Fig. 4a2; BY_1 and BY_2 converge to BY on the blue end), are two estimates of the null set for the Hering red/green process.

between the present Somali data and the results from so many other languages suggests that the present results are not due to some peculiarity of the Somali education system or due to the life experiences of these Somali observers.

MacLaury (2001) reported similar patterns in some Mesoamerican languages, and concluded that these patterns were defined as much by lightness and/or saturation as by hue. Bimler (2011) called these “wildcard” categories, speculating, as did MacLaury, that these categories occur early in the evolution of a language community’s color lexicon, where these regions of the color chart have not yet been formally lexically labeled (cf. the “emergence” view of color term evolution proposed by Levinson (2000). *Yellow* is also a relatively recently acquired color term in the Somali language (Berlin & Kay, 1969; Maffi, 1990). There are many terms for *yellow* in modern Somali, and there is great variability across individuals in the range of colors named *yellow* (Brown et al., 2016). This result provides additional evidence that, even today, Somali *yellow* is not a well-established color term. It is possible that, in line with MacLaury and Bimler, Somali observers use *yellow* to signal a perceptual dimension that combines both hue and saturation/lightness (cf. Fig. b–d, above, to Bimler, 2011, Fig. 5d). But, no matter how these color terms are to be understood, they are not currently used in a way that is consistent with Hering’s theory of color appearance, and they suggest a dimensionalization of a color appearance space that is not merely a reduced form of the one proposed by Hering.

4.4. *Somali* grue

By definition, Somali *grue* covers a large area of greenish and bluish colors, including the English green and blue focal colors (Fig. 7), and Somali Grue speakers do not use a distinct term for *blue*. However, the curved white contour that delineates the English blue and green areas in Fig. 7a, and repeated throughout Fig. 7, shows that the large number of purple samples called *blue* (in conjunction with other colors such as *red*) in the English language data set are not called *grue* (alone or in conjunction with any other colors) by the Somali Grue speakers. The use of *blue* by Somali GB speakers in Fig. 7b and the use of achromatic terms for blue by Somali Achromatic speakers in Fig. 7d show a similar pattern. Thus, contrary to the classical interpretation of *grue* (e.g., Kay & McDaniel, 1978), the Somali *grue* term clearly does not name the union of the samples called *blue* and the samples called *green* by English-speaking observers in the color decomposition task.

The curved contour in Fig. 7a was drawn based on lexical considerations, so it has no basis in color theory. The contours in panel 7e show possible color-theoretic partitions of color space (enumerated in the caption). None of these theoretical lines delineates the area of *grue* colors. Thus, the use of *grue* in the Somali color lexicon does not suggest an understanding of color that is a simple reduction of Hering's color-opponent space, or indeed of any of the standard color spaces known to vision theory.

It is certainly true that any speaker who does not use the full quota of six Hering color terms cannot obey the "necessity" requirement of Hering's theory. However, in principle, Grue speakers could still respond in a Hering-appropriate way on the color decomposition task if they simply assigned *grue* to the color appearance of all greenish and bluish colors. For example, they could use *grue* to name greenness in a green sample and, when combined with *yellow*, to name the greenness in a lime-colored sample. Similarly, they could use *grue* to name blueness and, when combined with *red*, to name the blueness in a purple sample. If they did this, *grue* would just be a single term applied to two distinct elemental color sensations, but the color naming of Grue speakers would be otherwise consistent with Hering's theory. Contrary to this reasoning, Somali *grue* extended only part of the way into the region occupied by English *blue* (compare Fig. 7a,c; also Fig. 4c5, 4a6), and Somali Grue speakers only rarely used *grue* to name purple samples (Fig. 4c7). The consensus plots in Fig. 6 reveal the frequent usage of *yellow* to name the purple samples, often in combination with their other Hering terms.

This interpretation of Somali *grue* agrees well with *grue* in other languages. If WCS informants had considered *grue* to be a single term that applied to two (English-like) color categories, one might expect that many individuals would choose two focal colors, one focal green and one focal blue sample, instead of just a single sample. An analysis of the focal color selections by WCS Grue informants (Supplemental Materials S2) showed that, contrary to that prediction, only about 2% of informants chose both a focal green and a focal blue sample. Instead, 82%–84% of them chose single focal colors, most commonly green. Thus, the results of the WCS agree with the Somali results reported here: *Grue* does not name two distinct color categories that happen to have the same name.

Thus, Hering's color space cannot be adjusted to account for the Somali Grue data by simply combining the green and blue categories and assigning a single term to both. This is further evidence that Somali color decomposition describes a color appearance space that is not merely a reduced form of Hering's.

4.5. Other Somali color terms

In view of the fact that Somali *yellow* and *grue* are so different from any terms found in English, it is not surprising that Somali deployment of *red* across the stimulus set is also somewhat different. The range of colors called *red* by many English speakers includes the purple samples, but *guduud*, the Somali term for red, is more restricted (especially in Fig. 4b5). Only English *green* and Somali *cagaar*, when *cagaar* is used to mean green, cover a similar range of samples in English and Somali.

4.6. Human mental representations of color appearance

It is clear from the present results that color decomposition among Somali speakers (and even to some degree among English speakers) was closely associated with their lexical representations of color, rather than tracking the predictions based on Hering's theory. Why is this so?

There is considerable converging evidence that the high-level processing of color is governed by many more than the two (red–green and blue–yellow) or four (red, green, blue, and yellow) chromatic processes of Hering's theory. Evidence of more than four chromatic processes comes from chromatic detection experiments (Hansen & Gegenfurtner, 2013; Krauskopf, Williams, Mandler, & Brown, 1986; Lindsey & Brown, 2003), color appearance experiments (Emery et al., 2017a; Emery, Volbrecht, Peterzell, & Webster, 2017b; Webster & Mollon, 1994), visual search experiments (D'Zmura, 1991), single unit macaque electrophysiology (Lennie et al., 1990; Shapley & Hawken, 2011; Xiao, Kavanau, Bertin, & Kaplan, 2011), and human fMRI studies (Brouwer & Heeger, 2009; Kuriki, Sun, Ueno, Tanaka, & Cheng, 2015). Of particular interest is the Brouwer and Heeger's (2013) human fMRI study revealing correspondences between various cortical neural signals and lexical color categories, but only when subjects were performing a structured color naming task.

We propose that when an observer decomposes the appearance of a color into its named color components, the complex, multi-channel neural representation of color is "read out" into a lower-dimensional perceptual/cognitive color representation (see Emery et al., 2017a for a similar idea). It seems likely that an individual's lexical representation of color plays an important role in the read-out process. In this view, the Hering terms would be the most likely set of terms to mediate this process, if the observer has them in their lexicon. However, even among English speakers, the pattern of the mapping between colors and Hering terms is variable across individuals (Emery et al., 2017b; Malkoc et al., 2005), and observers can perform color scaling using a completely different set of secondary color terms instead of the Hering terms, if they are asked to do so (Bosten & Boehm, 2014).Therefore, it is not surprising that this read-out mapping between the non-linguistic, high-dimensional color code that all people experience, and the color terms in the observer's native language, would vary within as well as across languages and cultures.

How could Hering's "elemental sensations" arise from the semantics governing the red, green, blue, and yellow color categories in European languages, rather than the other way around, as earlier work on the evolution of color naming systems seemed to suggest (Kay & McDaniel, 1978; Rosch, 1972)? One current explanation comes from information-theoretic models that optimally partition color space based on the human perception of color differences and the pragmatic aspects of language. These models suggest that lexical color categories that closely approximate those found in the WCS could arise de novo, without the guidance of innate perceptual landmarks that were once thought necessary to explain the striking regularities in color naming around the world (Gibson et al., 2017; Zaslavsky, Kemp, Regier, & Tishby, 2018). However, this explanation remains incomplete, as there is also evidence that color categorical structure can occur independently from the semantic or pragmatic aspects of language. For example, some form of color categorical structure may exist in pre-linguistic infants (Bornstein, Kessen, & Weiskopf, 1976; Skelton, Catchpole, Abbott, Bosten, & Franklin, 2017). Moreover, a study of the Hadza, a group of Tanzanian hunter-gatherers, showed that, while terms for *red*, *white*, and *black* English-like color categories are well established, terms for other colors —especially *green*, *blue*, and *yellow*—are used in the idiolects of many individuals, even though terms for these colors are not established in the Hadzane language (Lindsey et al., 2015).

Perhaps Hering's color space, complete with all six of his elemental sensations, was universally present in the minds of all our observers, but many of them could not connect their own sensory experiences directly to the ones prescribed by Hering. Bosten and Boehm (2014), following Brindley (1970), have emphasized the highly subjective nature of the classic behavioral tests of Hering's theory. In our color decomposition task, there is no way to know for sure what strategies subjects employed in performing this task, even when the results tracked those expected if color appearance *were* governed by the Hering sensations. These are clearly limitations of the color decomposition task and similar behavioral paradigms, regardless of the language spoken by the observer. However, in view of the mounting evidence against the privileged status of the Hering elemental sensations, it seems likely that the most natural and immediate mental representation of color appearance will be the one informed by the individual's color idiolect.

The precise relationships among the neurophysiology of color vision, the psychophysics of color appearance, and the semantics of color idiolects remain to be worked out. Nonetheless, the results reported here provide cross-cultural evidence that color appearance and the semantics of color terms are more closely associated than previous research on Hering's theory has suggested. This close association raises serious questions about the viability of Hering's theory as a universal model of the mental representation color appearance.

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Note

1. Throughout, color terms (in the original language or in translation) appear in italics, colors appear in plain type, and a color lexicon and the people using it are capitalized. Thus, a Somali-speaking observer who uses the Green–Blue (GB) color naming motif is a Somali GB speaker, and generally calls the blue samples *buluug* (*blue*), which is the Somali term for blue.

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Supplemental Materials.