

## ***The Veridicality of Color: A case study of potential human tetrachromacy.<sup>1</sup>***

(This is the pre-publication version of the article, released 1/3/2015. Online version available at <http://glimpsejournal.com/index.php/Glimpse/pages/view/Issue-12-Truth-Veridicality-of-Color>)

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Original oil painting, A Tetrachromat Moon. © and courtesy of Concetta Antico: [www.concettaantico.com](http://www.concettaantico.com)

### **ABSTRACT:**

Color is an inner, highly subjective experience only triggered by properties of light from the external world. Actual color perceptions are inextricably linked to (i) visual processing properties of observers that can vary greatly across individuals, and (ii) minor changes in viewing circumstances. Thus, it can be argued that color is not of this world, or, that color is not a veridical, or even an unbiased index of object properties. To illustrate this assertion we present empirical results on the visual processing of four individuals. All four of these individuals have excellent color perception (as shown by standardized color vision assessment procedures). Two of the individuals are considered standard “normal” trichromat observers, while the other two are “potential tetrachromat” observers – that is, observers with a genetic potential for an extra class of visual pigments used for color vision. By comparing such observers’ color perception performance, and their artistic uses of color, we illustrate how wide the definition of “normal”

human color vision actually is, and how some observers that are typically classified as “normal” might actually experience a world of color beyond what the average color vision normal human experiences. We relate our results showing considerable variation in normal color experience to the question of what portions of reality actually provide the ground-truth for the world's perceived color palette. We also considered how we should conceptualize color meaning when two individuals with different visual processing experiences sit down to discuss the beauty of, for example, a sunset or a field of flowers. Our empirical results strongly support the idea that, above and beyond objective reality, constructive mental processes are the true arbiter of color experience, that color sensations should not be thought of as a true reflection of reality, and that color does not serve as an unbiased indicator of properties in the external world.

#### **KEYWORDS:**

Potential human tetrachromacy, Comparative color experience, Representational painting and non-normative color vision, Color vision genetics

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*"Every act of perception, is to some degree an act of creation ..."*<sup>6</sup>  
- Oliver Sacks

#### ***I'll believe it when I see it ...***

In our casual observations of the world we often take for granted that the visual world we experience is, simply stated, a construction of the complex of the eye-brain-mind of the beholder. For instance, the old adage “seeing is believing” is used to establish truth of a situation based on sensory data, conveying the idea that visual perception is an objective adjudicator of reality. It suggests that *visual confirmation* of something provides a true representation of what exists in the world like an veridical recording of interactions among worldly objects, their physical attributes and features, and as such it implies seeing is a good basis for valid beliefs.

Truth be told, our visual experiences, produced by the collaboration of our eyes-brain-mind, often misleads us.

This we know, of course, as familiar forms of visual trickery a magician's “sleight of hand” effects and visual illusions that misrepresent, or lead us to misinterpret, what truly is.<sup>7</sup>

But beyond these exceptional cases is it generally the case that visually “seeing” something in the world does give a kind of proof of what is real and exists in the world - as a sort of WYSIWYG (*What You See Is What You Get*) reality?

Well, unfortunately, for the case of our sensations of color in the world, reality is not as simple as validating *what we see with our own eyes*.

#### ***What color lies on the surface ...***

Despite what you may believe, color, very simply, is not in the world. Rather, color is a product of the minds of the world's observers.

Most human observers who look out over a field of sunflowers in Provence, France, when asked to report what they see will vary in what they describe. Most likely you'll hear variations on “... I see **yellow** flowers ... **blue** sky ... **dark brown** earth ...” plus a number of other visual qualities of the scene. As it turns out, those highly salient colors perceived and reported by human observers are not actually “out there” to behold. Instead, they reside inside the observer's mind as highly individualized constructions of each observer's visual apparatus and the specific ways it translates visual information received from the world.<sup>8</sup> The view of many perceptual scientists – although it is one that is difficult to assess scientifically – is that the same scene viewed in the same way by two normal observers is likely to evoke different color experiences in the mind's-eye of the two observers.



**Figure 1.** Field of sunflowers by Tambako The Jaguar, on Flickr (<https://www.flickr.com/photos/tambako/11459944395/>)

For this reason one may say that color is not real, or *color is nonveridical*, because color, like many sensations we experience, does not represent an immutable feature of objects in the world. Color is not a genuine, or invariant, code or label that alone objectively identifies the state of the physical world when an observer is unavailable to process it, and color does not “belong” to observed objects. Rather color belongs to transitory states of the observers of objects. Additionally, of course, a given object’s color varies with changes in the spectrum of the illuminating light, the surrounding ambient context that it is viewed in, and subtle changes in the object’s surface texture that alter an object’s reflectance properties.

True, for the most part, even substantial changes in an object’s color are, for practical purposes, discounted by human observers.<sup>9</sup> That is, we realize that color differences experienced for a particular sunflower when viewed in a sunlit field, compared to when that same sunflower is viewed in a vase on the kitchen countertop, should not be occasion for surprise or somehow interpreted as a *different sunflower*. But, nevertheless, the different sensations that arise from two such physical instances of color (that – due to color constancy mechanisms – we cognitively process as “the same”) are purely a product of one’s individual manifestation of human visual processing biology.

Thus, what we sense as “truth in color” is, in fact, our own individual spin on reality. This becomes most obvious when we study other species’ vision. We know, for example, that Honey Bees and Birds, visiting the flower fields we gaze on, see other, very different, salient color features. For example, where we see a mostly uniform yellow and brown color in the face of the sunflower they see shocking displays of pollen on the flowers (what under “bee-vision” we might see as bright neon bands), and where we see uniform blue sky, they detect polarization differences in the content of the sky’s light that, e.g., helps them navigate in the air.<sup>10</sup> Highly personal interpretations of the world’s colors also occur within species and are typically a function of visual processing biology.



**Figure 2.** Simulated Honeybee trichromat vision suggests alternative and highly personal interpretations of a sunflower's colors as a function of visual processing biology. Where a human trichromat with normal color vision sees mostly uniform yellow flower petals and a brown central face of the sunflower, a Honeybee will see a highly salient central display of pollen and spatial target pattern from UV reflectance on flower petals. Such salient markings are most likely a visual processing adaptation evolved due its usefulness to bees and the flowers they pollinate. Images courtesy of Visual News. (<http://www.visualnews.com/2013/04/08/hidden-patterns-how-a-bee-sees-the-world-of-flowers/>)

### **Searching for the ground truth of "normal" human color sensations ...**

We can, however, get a sense of some ground-truth for this suggested range of "normal" human color experience if we examine ways normal human color perception varies as a function of underlying biology and perceptual experience. Thus, rather than focus on how the sensations of a person with normal color vision differ from those experienced by persons with color vision anomalies or deficiencies,<sup>11</sup> we explore how color sensations vary between human observers who have "normal," non-deficient, color vision capabilities, compared to those who might be expected to experience non-deficient but "non-normative" sensations of color vision.

Below we discuss some factors that might lead to non-normative color sensations and their possible use in artistic interpretations of a highly personal sense of color. By examining such factors we hope to move closer to the truth of what color is, and enrich our understanding of how individual differences in normal color sensations originate internally.

Two specific contributors to color's *unrealness* are examined. (1) The biological basis for normal human color perception that is known to vary across individuals, and (2) the idea that color perception may be *trained up* by early developmental experience and perhaps enhanced by prolonged cognitive exposure and cognitive manipulation of color across the lifespan.<sup>12</sup>

### **Color sensations exist because of color vision genes ...**

Jameson describes forms of "normal" color vision in individuals who inherit genetic building blocks for an extra class of retinal photoreceptor compared to normals.<sup>13</sup> Such individuals (who most likely are female) have retinas that contain more than the usual three photosensitive pigment classes, and are referred to as *potential tetrachromats*.<sup>14</sup> Signals generated by these four cone photopigment classes could feed into more than three independent neural channels and impact color perception, and evidence suggests that such women exhibit an enriched color sense compared to a much larger segment of the population who have only three classes of normal cone photopigments.<sup>15</sup>

Genotype and phenotype evidence suggests that females possessing genes for extra photopigment variants actually have tetrachromatic retinas (with four functioning retinal

photopigment classes),<sup>16</sup> and, with the right neural programming, are capable of a dimension of perceptual hue that cannot be experienced by males who have only a single X-chromosome.<sup>17, 18</sup>

While the prospect of human tetrachromacy is controversial and difficult to demonstrate empirically, the expectation is that this kind of X-chromosome-linked difference in color processing adds further variation to the possible phenotypes found in normal color vision individuals, and is thus useful for demonstrating how “normal” color perception is a personal construction that depends on both biology and experience.

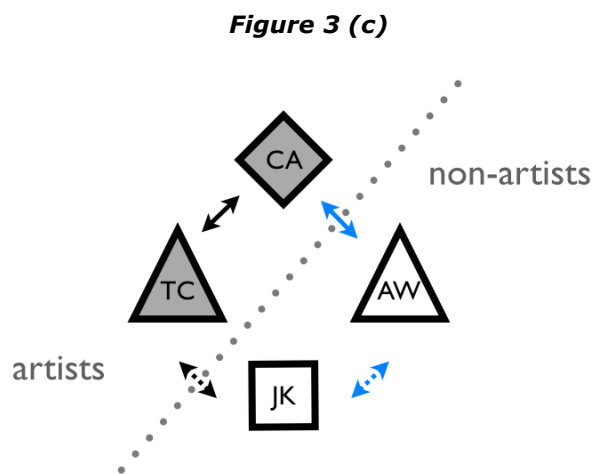
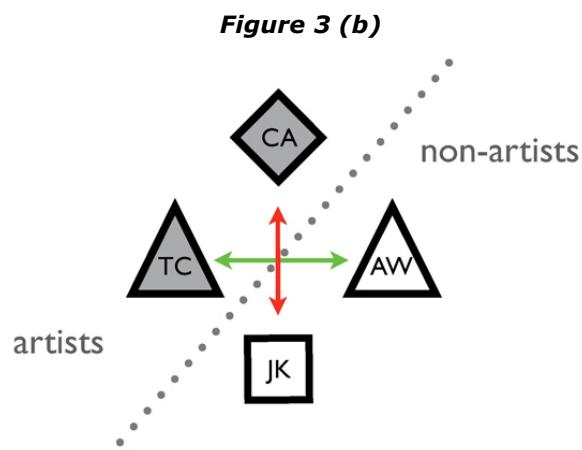
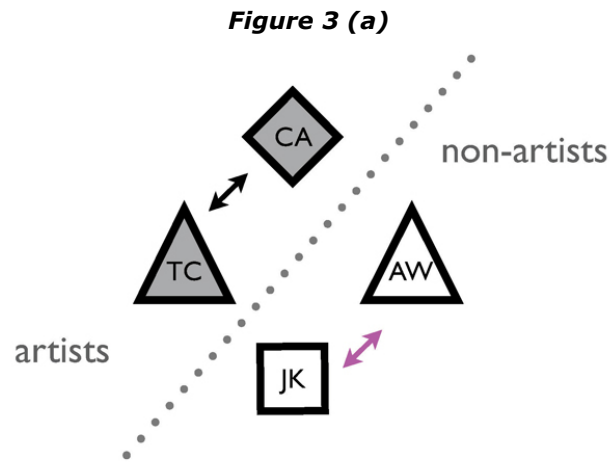
We report a case study of *potential* tetrachromat color perception relative to that of normal trichromat controls.<sup>19</sup> Participants investigated include a female potential tetrachromat,<sup>20</sup> who is also an accomplished professional artist (abbreviated “CA” [www.concettaantico.com](http://www.concettaantico.com)). We compare CA’s data with that of (1) a second accomplished professional female artist (“TC” [www.tuck.communicatingbydesign.com](http://www.tuck.communicatingbydesign.com)) who is color vision normal with no familial color vision anomalies (and presumed to have normal trichromat retinas).<sup>21</sup> With (2) a third color vision “normal” female (“JK”), who is not an artist, has evidence of familial color vision deficiency, and is genetically a potential tetrachromat. And (3) a color vision normal trichromat female (“AW”), with no familial color vision anomalies, and no artistic training or unusual developmental color experience (See Table 1 and Supplement Sections 1 and 3 for additional genotype details. And <http://glimpsejournal.com/index.php/Glimpse/pages/view/2.3-KAJ>).

	Age	Genotyped	Ishihara Plates	FM100	Familial Color Deficiency	Presumed retinal phenotype	Art Training
CA	53	two L-cone gene types, one M-cone gene type	normal	normal	yes	tetrachromat	yes
JK	52	two L-cone gene types, two M-cone gene types	normal	normal	yes	tetrachromat	no
AW	35	N/A	normal	normal	no	trichromat	no
TC	70	N/A	normal	normal	no	trichromat	yes

**Table 1. Participant information.** Four female participant identifiers (col. 1), age at time of testing (col. 2), performance as measured using two standardized color vision diagnostics, Ishihara Pseudoisochromatic Plates and the Farnsworth-Munsell 100 hue test (col.s 3 & 4), reported presence of familial color deficiency (col. 5), presumed retinal phenotype (col. 6) and reported history of art training beginning in early childhood (by an estimated age 7 years). Written informed consent was obtained from all participants after explanation of the nature of the study.

Figure 3 depicts some comparisons that address specific questions about Table 1’s participants. Namely: (a) Can photopigment genotype alone differentiate the perceptual color experience of two observers? (b) Does early exposure to art training alone differentiate observers? (c) Or, is it a combination of photopigment genotype and art training that yields the most significant perceptual variation in our study? Also see Supplement Section 2.

Such questions can help unravel the tangled mystery of where color comes from – primarily because they probe which aspects of color experience are truly due to **nature**, or biology, and which may, in part, be due to **nurture**, or perceptual learning and neural tuning from environmental influences over time.



**Figure 3 (a-c):** Comparisons considered among four participants who vary with respect to the genetic factors underlying their color vision, and their perceptual learning due to early exposure to color through art training. Square symbols denote participants with a genetic potential for Tetrachromacy. Triangles are participants with trichromat color vision and are presumed to possess trichromat genotypes. Shaded symbols depict individuals with a lifelong exposure to working with color through art training. Unshaded symbols are individuals with no formal art training or explicit early color training experiences. As explained in the text, three empirical questions that can be considered as suggested by solid or dotted double-arrows shown:

Namely, **(a.)** Does photopigment genotype alone differentiate the color perceptions of two observers? **(b.)** Is early exposure to art training sufficient to differentiate observers? **(c.)** Does a combination of photopigment genotype and art training yield the most significant differences in our study? For details of this discussion see Supplement Section 2. © Kimberly A. Jameson. Courtesy of Kimberly A. Jameson.

### ***In art and life, the true color of real-world objects depends on chromatic contrast ...***

"I told my dentist my teeth are going yellow. He told me to wear a brown tie." <sup>22</sup>  
- Rodney Dangerfield

If color genes weren't complicated enough, empirical complications from viewing color in context must also be considered. That is, juxtaposed colors in natural scenes are widely recognized to alter color appearance, producing induced color effects on foreground objects, and this is known by scientists, people who work with color everyday, and artists who routinely use color induction effects in art work.<sup>23</sup>

In empirical tests of potential human tetrachromacy, chromatic contrast is typically under-appreciated as an important (some might say "necessary") viewing requirement for capturing the subtle effects tetrachromacy might allow.<sup>24</sup>

Chromatic contrast bears on our discussion of color veridicality for two reasons. First, if color-processing differences exist across normal trichromats and potential tetrachromats, then such variation evolved while evaluating color in contextually-rich viewing circumstances (presumably to correctly identify desirable color targets embedded in environmental context). Second, compared to de-contextualized singleton stimuli often used in experiments, color in context is dimensionally more complex. Together these imply that, at the very least, experiments need to use some form of viewing context to optimize discovery of differences between tetrachromat and trichromat processing. To address this, experiments presented in the sections below incorporate a chromatic content specifically designed for our empirical task (see Supplement Section 3).

### **Sussing out the veridical correlates of color in a complicated empirical landscape ...**

So, real-world color is subjective, **and** depends on genetics **and** viewing circumstances. What's more, existing methods of standardized color vision assessment are woefully inadequate for detecting human tetrachromacy phenomena.<sup>25</sup> For all these reasons we chose an alternative empirical approach that assessed participants' color experience correlates. That is, instead of using a task that relied on subjective judgments of color, we chose a task that depended on luminance (or brightness) perception.<sup>26</sup> The task used is known to tap into early visual processing differences, and depends on photoreceptor signals that pose an early constraint on color experience. The task is an indirect, albeit highly reliable, way to measure photoreceptor response for stimuli that vary in spectral frequency.<sup>27</sup> It involves "Minimum Motion Isoluminance" phenomena in which subjective judgments of motion direction convey perceived brightness underlying illusory motion for color stimuli.<sup>28</sup>

To enrich viewing circumstances our experiments used two contexts: (1) a neutral gray background<sup>29</sup> and (2) a novel color background designed to maximally engage the fourth photoreceptor class that potential tetrachromat artist CA was presumed to phenotypically express.<sup>30</sup> All Table 1 participants completed seven experiments varying visual adaptation levels and chromatic context.<sup>31</sup> For CA we hypothesized that minimal-motion stimuli presented in this constructed background would impact illusory motion in distinctive ways for her compared to individuals with phenotypes arising from the other, different, genotypes we tested. See Supplement Section 3 for details.<sup>32</sup>

Our analyses ask only if participants' measured isoluminant settings reveal differences in perceived brightness for 20 color conditions we tested, and whether any associations were found

between those differences and color vision genotype or evidence of art and color training across the lifespan.

**Result synopsis:** Our preliminary experimental study consisted of comparing CA with 3 female participants (Table 1). TC is a trichromat artist, AW is a trichromat non-artist, JK is a potential tetrachromat non-artist possessing a combination of retinal photopigment genes that differ from CA's. We designed the MM-isoluminance task to involve an adaptation background color that is spectrally dominant near the peak response of CA's presumed extra photopigment class, while differing from the presumed photopigment peaks suggested for potential tetrachromat JK by her genotype. Thus, the experiment is designed to test for (1) whether CA is more sensitive to subtle differences in a range of colors compared to control participants. And, if so, (2) whether CA's difference is due to (a) being an artist or (b) being a potential tetrachromat, or (c) necessarily being both (a) and (b).

Results found for tests (a) – (c) reveal that compared to control participants tested: (1) CA's differences were highly significant, but varied across conditions tested in all experiments; and (2) CA's potential tetrachromat differences were found most apparent in data from (i) chromatic context (e.g., color background) experiments, (ii) experiments using lower background luminance levels, and (iii) for stimulus conditions dominant in "reddish" regions of color space.

Results unambiguously support conjecture (c) stated earlier: CA's differences are necessarily due to being both (a) an artist and (b) a potential tetrachromat.

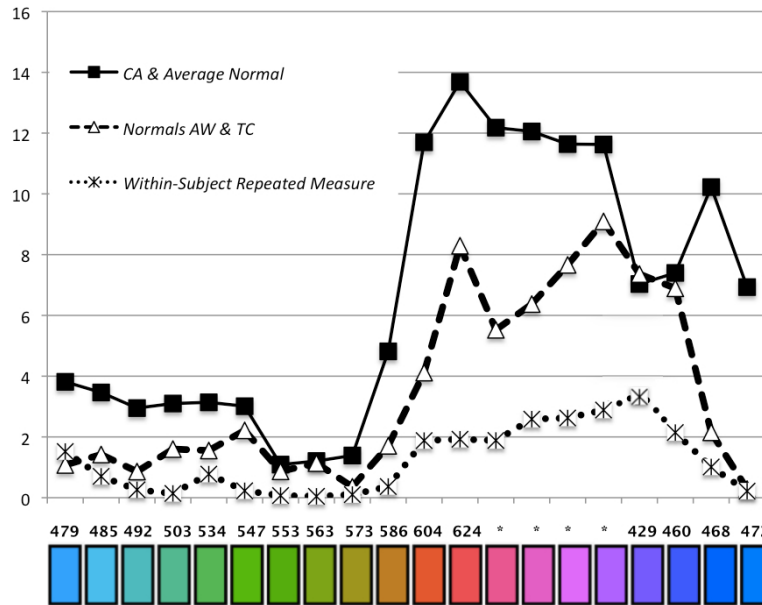
**Results detail:** We quantify CA's potential tetrachromat effects by comparing CA's perceptions to that of control subjects tested. Thus, our analyses only report ***potential tetrachromat performance differences relative to control performance*** (see Supplement Section 3 detail).

Figures 4 and 5 plot a single condition tested where large individual differences in settings seen are indicative of results trends. Figure 4, top curve, shows participant CA differs most from an average trichromat control for settings involving "reddish" stimuli; the middle curve shows significantly less variation when comparing two normal trichromat controls (AW & TC); and the bottom curve shows minor baseline variation seen in one individual's (TC) repeated measure performance. Figure 4 curves comparing participants' stimulus settings (in nonparametric digital display RGB primary values) show areas of large, atypical, differences and suggest that for some color regions, potential tetrachromat CA performs very differently from the other participants tested.

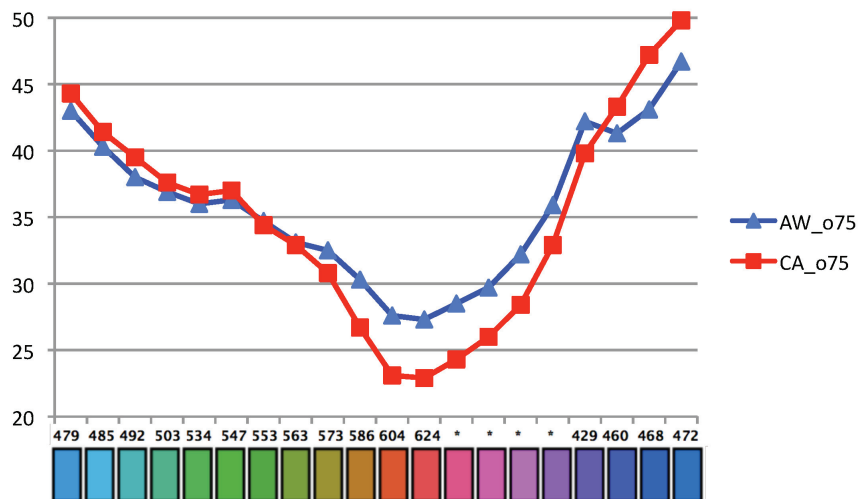
Figure 5 illustrates how spectroradiometric measures convey observed differences between CA and AW (the non-artist normal trichromat tested), showing differences in the two participant's settings in terms of measured luminance information present in color stimuli.

In Figure 5, CA's important differences compared to trichromat AW are: Spectral regions showing (1) significantly different isoluminance settings, and (2) different patterns of observed isoluminance settings. Detail in Supplement Section 2. Additional results suggest these differences are due to luminance processing, and imply that CA's extra photopigment class plays a crucial role in her MM-isoluminance settings for the color space regions tested.





**Figure 4.** Three curves show observed differences in RGB display primary units found for the Minimum Motion Isoluminance settings compared across participants assessed. The vertical scale gives the magnitude (in RGB Euclidean distances) of the difference between two participants' observed MM-isoluminance settings. The horizontal axis shows pseudo-colored approximations of 20 stimulus conditions used and their dominant wavelength measurements in nanometers (conditions with two dominant wavelength peaks are denoted with an "\*" value). Note, if **no differences** existed between two participants' compared settings for the 20 color stimulus conditions tested, then the corresponding graph would resemble a flat horizontal line with a vertical value equal to zero. Curves shown here deviate from the zero-difference scenario, and illustrate the regions of color space where variation in participants' responses was found, and the magnitude of those variations relative to the idea of a zero-difference baseline, or even an average 1.2 repeated-measure difference found for an individual (shown in the bottom curve). The authors acknowledge T. Satalich and A. K. Romney for helpful advice on the graphic display of these data. © Kimberly A. Jameson. Courtesy of Kimberly A. Jameson.



**Figure 5.** Luminance measurements of Minimum Motion Isoluminance settings for CA compared to those of normal trichromat AW. The vertical axis shows measurements in  $\text{cd}/\text{m}^2$ . The horizontal axis depicts a pseudo-color gradient of the 20 stimulus conditions used and their measured dominant wavelength in nanometers (conditions with two dominant wavelength peaks are asterisked, rather than a dominant peak value). © Kimberly A. Jameson. Courtesy of Kimberly A. Jameson.

Based on CA's summary results relative to normal trichromat control participants, we tentatively conclude:

(1) Potential tetrachromat CA's exhibits (i) non-deficient color perception (E.g., excellent performance on standardized color vision tests), and (ii) MM-isoluminance settings that markedly differed in some regions of color space compared to normal trichromat controls.

(2) CA seems to have an extra cone class population (presumably a long-wavelength sensitive cone class variant) contributing to cues used in the MM-isoluminance task, in addition to the usual signal contributions arising from M-, L- and S-cones that normal trichromats possess.

These results suggest that potential tetrachromat CA:

- Has color perception that is both non-deficient and non-normative.
- Establishes minimum motion for some color stimuli at luminance levels that are outside the range of isoluminant settings found for normal trichromat controls to which she has been compared.
- Exhibits settings for isoluminant, or equally bright, stimuli that show her greatest deviations from normal include stimuli with substantial mid- to long-wavelength, or "reddish", spectral components – a result consistent with the idea that she expresses a fourth cone class which is the basis for her setting differences compared to those of trichromatic controls.
- Exhibits enriched color experience in dim light conditions (low daylight, or low photopic, vision) such as in shadows and for low ambient levels (also seen in CA's artwork: Figures 6-9. Supplement Section 4 discusses consequences for CA's art).



**Figure 6.** Original oil painting "A Tetrachromat Moon." © Concetta Antico. Courtesy of Concetta Antico. [www.concettaantico.com](http://www.concettaantico.com).



**Figure 7.** Original oil painting "Coastal Caves." © Concetta Antico. Courtesy of Concetta Antico. [www.concettaantico.com](http://www.concettaantico.com).



**Figure 8.** Original oil painting "Last Light La Jolla." © Concetta Antico. Courtesy of Concetta Antico. [www.concettaantico.com](http://www.concettaantico.com).

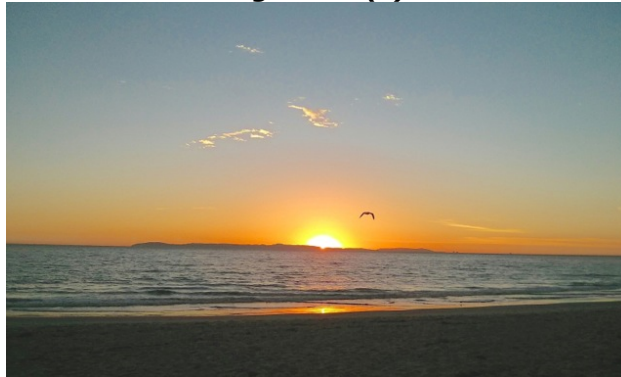


**Figure 9.** Original oil painting "The Eye Of Heaven." © Concetta Antico. Courtesy of Concetta Antico. [www.concettaantico.com](http://www.concettaantico.com).

***If object color is uncertain, what does a potential tetrachromat see as different?***

**Simulating CA's potential variation:** Based on empirical data, Figure 10 simulates how potential tetrachromat CA may perceive color in real-world scenes differently from normal trichromat control participant AW.

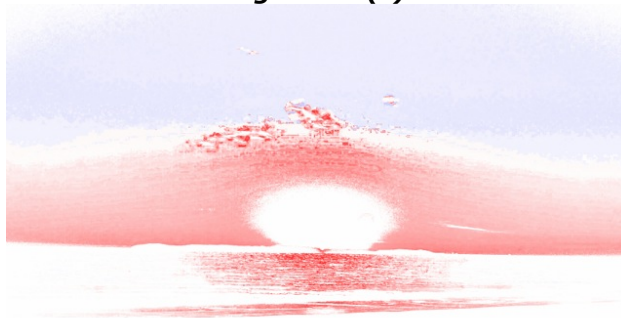
**Figure 10 (a)**



**Figure 10 (b)**



**Figure 10 (c)**



**Figures 10 (a-c).** Simulated image conversions based on measured luminance settings for CA relative to those of normal trichromat control AW. Panel (a.) an original digital image. Panel (b.) shows a conversion of the original that tags all the pixels that are perceived as different by the potential tetrachromat with black, and tags pixels perceived the same with white. Panel (c.) shows the same pixels identified in panel (b.), but additionally colorized with a heatmap color code that captures quantitatively the observed differences for CA relative to AW. The legend at the bottom of Panel (c.) shows the heatmap color scale used. In the heatmap color code, image pixels are colorized heavy red where the potential tetrachromat's perception is different in

a more sensitive way than what a normal would perceive – where “more sensitive” connotes needing less wavelength-specific luminance energy to establish isoluminance relative to an adaptation field standard. Image pixels that are colorized as the heaviest blue are different by being less sensitive than what a normal observer would see (i.e., pixels needing more wavelength-specific luminance energy to establish isoluminance). White heatmap color values denote pixels where perception is the same for potential tetrachromat observer CA and normal trichromat observer AW. The total percentage of pixels where CA and AW differ in the processing of the image shown is 66% of image pixels. See Supplement Section 5 for more detailed analyses using simulated converted images. Original photo: Newport Beach Sunset, Jan. 06, 2014. © Kimberly A. Jameson. Courtesy of Kimberly A. Jameson.

While Figure 10 is only a simulated approximation of CA’s scene processing, it strongly suggests that color in visual scenes, for this potential tetrachromat, is substantially different from that experienced by normal trichromat control AW, even if these two observers were seated side-by-side viewing the same amazing sunset.<sup>33</sup>

### **Where does color live?**

In everyday visual processing observers enlist and synthesize a variety of different visual processing mechanisms to achieve a coherent interpretation of information in a visual scene. Examples of visual processing information that can require creative mental interpretations are features of scenes such as object location and shape identification, texture, color information, and movement cues.

Most observers assume that color exists purely in the physical properties of light reflecting off real-world objects.<sup>34</sup> The truth is color’s origins are much more complex. Color is a product of our visual systems – eyes, brain, and mind. It is something that, of course, needs the physical properties of reflected light to exist, but which is not veridically linked to those properties, in part, because to manifest color sensations that map to specific physical spectra one needs added human constructions – such as specification of an observer-specific photoreceptor response model, or a chromatic contrast transformation matrix – and these exist strictly in the retinas and heads of observers, and not in the same domain that spectral light inhabits. What’s more, this and other research, suggest that color awareness, or expertise, can be *tuned-up* through exposure and training that provides a refined neural signal, which, at a minimum, gives rise to measureable differences in detectable color, and at a maximum may make available a dimension of perceptual hue that cannot be experienced by “normal” observers.

So, while color may provide a reliable “normal” individual code for interactions with environmental stimuli, the truth-value of that code is to a degree idiosyncratic, or multi-valued, and these investigations suggest it can be enriched beyond what is considered “normal” by both (1) increasing genotype complexity and (2) unusual exposure to color manipulation, which includes cognitive experience with color, over the lifespan of an observer.

### **Color and Truth and Art.**

Color is an inner, highly subjective, experience triggered by properties of light out in the external world. Truth is about a correspondence of propositions in a language with reality. For color, we can take this language to be color names. For example, what does the term for the concept “red” mean to two different human observers? Both use the term to describe their subjective impressions of a particular stimulus, say a particular rose. But what does “truth” mean in this context? Some research has viewed this question pragmatically by focusing on *Shared Truth*.<sup>35</sup> Thus, for the rose example, when one person asks another to bring a red rose from among a variety of differently colored roses, she may return with a rose that both agree to be “red” though that red may vary for the individuals and in this way the meanings of colors, and their veridicality, are shared in a way that makes them internally consistent across different observers with varying sensations.

## Conclusions.

To illustrate the subjectivity of color perception we presented results from individual observers known as “potential tetrachromats,” and suggest how such observers might experience a world of color beyond what the average human experiences, and how that relates to the question of what a ground-truth might be for appreciating the world's color palette. We also considered how we should conceptualize color meaning when two individuals with different visual processing potentials sit down to discuss the beauty of a field of flowers.

The above-mentioned quote from Oliver Sacks concerning the constructive nature of perception exactly captures the highly human-dependent construction of real-world color. This is not to suggest that color has no physical basis whatsoever. Instead, what empirical results imply is that color does not reside in the external world because even for a single observer its physical measurement does provide a one-to-one mapping with sensation. Thus, the laws of physics are not enough to tell us what color an observer will see with her mind's eye. To estimate that, we need to add several additional things to the physical measures of spectra – influences from viewing context, a construction or theoretical formalization (i.e., an assumption about visual processing signals) or some empirically-derived information about what specific receptor-types an observer possesses (be they standard normal human trichromat, or four distinct classes of cones, or those of a trichromat honey bee with a different set of 3 cone classes).

However, if we suppose that the human ability to perceive color in the world is not merely a fanciful accoutrement, and it has an important purpose, then we are forced to ask what that purpose might be. While its human purpose remains debatable, we believe that each individual's personal color experiences are probably reliable across the lifespan; and when these are cognitively coded as concepts and in language, they can serve as a shared truth among groups of observers with varying color perceptions and who reside in pragmatically similar environments and societies.

Still, color sensations are not a true reflection of what is out there. They do not serve as unbiased indicators of properties in the external world. No matter how counter-intuitive the idea that color is purely a construction of our human interaction with the world – and despite the certainty of our feelings for the true blue of clear sky, the honest greens of foliage, and the reliable tones of red earth in truth, the bad news is color is only in your mind, but the good news is color is all in your mind, and you talk about it with others.

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## ENDNOTES

<sup>1</sup> Acknowledgements: The authors gratefully acknowledge T. Satalich and A. K. Romney for insightful suggestions on data representation, and the members of the Color Cognition Group at UC Irvine for helpful comments on this research – especially L. E. Narens. We greatly appreciate advice and resources provided for these empirical investigations by C. F. Chubb, UC Irvine. We also thank Jon Lomberg ([www.jonlomberg.com](http://www.jonlomberg.com)) for his insights on the artistic uses of color in painting the representation of terrestrial light. The views and opinions expressed in this work are those of the authors and do not necessarily reflect the official policy or position of any agency of the University of California, the University of Nevada, or The National Science Foundation. This work is licensed to the authors under Creative Commons Attribution-Noncommercial-NoDerivatives Works 4.0 International License. August 1, 2014.

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<sup>5</sup> Blackthorn Media. Santa Monica, CA. <http://blackthorn-media.com>.

<sup>6</sup> Sacks, O. (2009). *Musicophilia: la musique, le cerveau et nous*. Éd. du Seuil.

<sup>7</sup> See [http://www.ted.com/talks/beau\\_lotto\\_optical\\_illusions\\_show\\_how\\_we\\_see](http://www.ted.com/talks/beau_lotto_optical_illusions_show_how_we_see).

<sup>8</sup> The opposite view – that physical spectra are enough to convey what colors will be experienced – is what is referred to as the “physicalist trap” by psychophysicists (see Mausfeld, R. (2002). *The Physicalistic Trap in Perception Theory*. In: D. Heyer & R. Mausfeld (eds.). *Perception and the Physical World*. Chichester: Wiley).

<sup>9</sup> Perhaps the most important feature of color experience (a feature that most certainly facilitates development and use of short-term and long-term memory) referred to by psychophysics experts as “color constancy.”

<sup>10</sup> Backhaus, W. (1993). Color vision and the color choice behavior of the honey bee. Issue: Neurobiology of the honey bee. *Apidologie*, 24(3), 309-331.

<sup>11</sup> As is the case in individuals possessing forms of color vision “dichromacy,” often referred to as “color weakness” or “color vision deficiencies” (see Birch, J. (2001). *Diagnosis of Defective Colour Vision*. (London: Butterworth-Heinemann).

<sup>12</sup> While the focus here is on cases where color processing variation occurs across individuals presumably due to underlying color vision biology there is also ample scientific evidence that color behaviors and color concepts vary substantially across societies of individuals due to pragmatic factors. Anthropologists have argued that not every group pays as much attention to color as is done in Western, technologically-developed, groups. For example, Conklin’s description of the Hanunóo show preferences to use distinctions of light vs. dark, desiccation vs. freshness, and deep vs. pale appearances over anything that resembles the Western uses of color or hue, saturation and brightness (Conklin, H.C. (1955). Hanunóo color categories. *Southwestern Journal of Anthropology* 11: 339-344). Also note, Kuschel and Monberg’s discussion of research on communities that talk little about color (Kuschel, R. and Monberg, T. (1974). We Don’t Talk Much About Colour Here: A Study of Colour Semantics on Bellona Island. *Man, New Series*, Vol. 9, No. 2, pp. 213-242. ). Cross-cultural variations in color appreciation, while clearly important and interesting, are not examined in the present article.

<sup>13</sup> See Jameson, K. A. (2009a). Human Potential for Tetrachromacy. *Glimpse: The Art + Science of Seeing*, 2.3, Autumn Issue on Color, 82-91. And,

Jameson, K. A. (2009b). Human Potential for Tetrachromacy - Online Supplementary Material. Published online only as a supplemental resource in *Glimpse: The Art + Science of Seeing*, 2.3.

<http://www.glimpsejournal.com/2.3-KAJ.html>.

<sup>14</sup> The term Tetrachromat implies four, or “tetra-”, color, or “chromat.”

<sup>15</sup> Evidence of color processing differences correlated with possession of extra photopigment opsin genes is discussed in: Jordan, G. and Mollon, J. D. (1993). A study of women heterozygous for colour deficiencies. *Vision Research*, 33, 1495-1508.

Jameson, K. A., S. Highnote and L. Wasserman. (1998a). Understanding color appearance: Can variation in photopigment opsin genes give rise to individuals with perceptual tetrachromacy? Published Poster Abstract. *European Conference on Visual Perception*. Oxford, England.

Jameson, K. A., S. Highnote and L. Wasserman. (1998b). Photopigment opsin genes and color perception. Published Poster Abstract. *Annual Meeting of the Optical Society of America*. Baltimore, Maryland.

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Bimler, D. Kirkland, J. and Jameson, K. A. (2004). Quantifying Variations in Personal Color Spaces: Are there Sex Differences in Color Vision? *COLOR Research & Application*, 29(2), 128-134.

Jameson, K. A. (2005). Culture and Cognition: What is Universal about the Representation of Color Experience? *The Journal of Cognition & Culture*, 5, (3-4), 293-347.

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Jameson, K. A. (2009). Tetrachromatic Color Vision. Invited contribution to *The Oxford Companion to Consciousness*. Wilken, P., Bayne, T. & Cleeremans, A. (Ed.s). Pp. 155-158. Oxford University Press: Oxford.

Bimler, D., and Kirkland, J., (2009). Colour-space distortion in women who are heterozygous for colour deficiency, *Vision Research*, 49(5), 536-543.

Jordan, G., Deeb, S. S., Bosten, J. M., Mollon, J. D. (2010). The dimensionality of color vision in carriers of anomalous trichromacy. *Journal of vision*, 10 (8), 12.

[http://scholar.google.com/citations?view\\_op=view\\_citation&hl=en&user=NEkBSWMAAAAJ&citation\\_for\\_view=NEkBSWMAAAAJ:u-x6o8ySG0sC](http://scholar.google.com/citations?view_op=view_citation&hl=en&user=NEkBSWMAAAAJ&citation_for_view=NEkBSWMAAAAJ:u-x6o8ySG0sC)

<sup>16</sup> Direct examination of all forms of these different retinal classes in the living human retina is not yet medically possible (due to adaptive optics measurement constraints) but it is presumed such individuals



have, sufficiently represented, three normal cone pigments plus, one additional photopigment corresponding to a genetic variant they carry.

<sup>17</sup> Mollon, J.D. (1992). Worlds of Difference. *Nature* 356, 378-379.

<sup>18</sup> First suggested in 1948 by Dutch scientist H.L. de Vries, in a study of color-blind men (De Vries, H. L. (1948). The Fundamental Response Curves of Normal and Abnormal Dichromatic and Trichromatic Eyes. *Physica*, XIV(6), 367-380).

<sup>19</sup> See also: Jameson, K. A. and Winkler, A. D. (2014a). Preliminary research report on the results of Concetta Antico's psychophysical color vision testing and its relation to her photopigment opsin genotype. July 15, 2014. URL: <http://aris.ss.uci.edu/~kjameson/JamesonWinkler2014.pdf>.

Jameson, K. A. & Winkler, A. (2014b). New results on color appearance space and the potential for human tetrachromacy. Conference presentation at the Annual Cognitive Sciences Association for Interdisciplinary Learning (CSAIL). Hood River Valley, Oregon. August 2014. Published abstract: Program for CSAIL, July 31, 2014. URL: [http://www.reed.edu/csail/accepted%20abstracts/CSAIL\\_2014\\_Program\\_v3.pdf](http://www.reed.edu/csail/accepted%20abstracts/CSAIL_2014_Program_v3.pdf). Video URL: <https://www.youtube.com/watch?v=CgAUg6PFTbs>. And,

Jameson, K. A. and Winkler, A. D. (2014c). Concetta Antico's potential tetrachromacy. Invited presentation at Art Opening "Super Vision Soiree." August 15, 2014. The Abbey on 5th Avenue. San Diego, California. Video URL: <http://www.youtube.com/watch?v=9JnyL9t4U8s&feature=youtu.be>.

<sup>20</sup> That is, a female with the genetic potential for retinal tetrachromacy. Genotype details are described in Supplement Section 1 and were provided by C. Antico (Antico, C. (2014). Scientific detail of Concetta Antico's genetic potential for tetrachromatic color vision. June 13, 2014. URL: <http://conchettaantico.com/scientific-details/>).

<sup>21</sup> A family history of color deficiency is a marker for potential tetrachromacy in females (see Note 13's references for Jameson 2009a and 2009b for details).

<sup>22</sup> Dangerfield's subtly insightful joke relies on the nerdy color theory fact that a brown neck-tie should induce a pale blue tint on the wearers smile, and that blue induced color contrast might help cancel a yellowed appearance, producing a bright white smile. Source: [www.brainyquote.com/quotes/quotes/r/rodneydang167295.html](http://www.brainyquote.com/quotes/quotes/r/rodneydang167295.html)

<sup>23</sup> On the importance of chromatic contrast see: Plantier, J., Aubry, J.-P., Vienot, F., Ossard, G., Roumes, C. (2007). Chromatic contrast-sensitivity functions. *Perception*, 36, ECVF Abstract Supplement ([www.perceptionweb.com/abstract.cgi?id=v070290](http://www.perceptionweb.com/abstract.cgi?id=v070290)) and [www.vision.psychol.cam.ac.uk/jdmollon/papers/WebsterMollon94.pdf](http://www.vision.psychol.cam.ac.uk/jdmollon/papers/WebsterMollon94.pdf) (Webster, M.A. and Mollon, J.D. (1994). The influence of contrast adaptation on color appearance. *Vision Research*, 34, 1993-2020). Also several impressive demonstrations due to Dale Purves and colleagues can be found at: [www.purveslab.net/seeforyourself/](http://www.purveslab.net/seeforyourself/).

<sup>24</sup> See Note 15 above, Jameson et al. (2001) reference for a discussion.

<sup>25</sup> See Jameson (2009, 2009a, 2009b) cited earlier for methodological details on the problems of finding human tetrachromacy using existing standardized color vision assessment tools.

<sup>26</sup> Because the measure considered here is one of overall luminance (rather than a hue measure), limitations encountered when evaluating a potential tetrachromat color difference while using a 3-primary (RGB) display color space are avoided.

<sup>27</sup> Introduced by Anstis and Cavanagh (Anstis, S.M. and P. Cavanagh. (1983). A minimum motion technique for judging equiluminance. In: J. Mollon and L.T. Sharpe, Editors, *Color vision: physiology and psychophysics*, Academic Press, London) and later optimized by Lu and Sperling (Lu, Z.-L. & Sperling, G. (2001). Sensitive calibration and measurement procedures based on the amplification principle in motion perception. *Vision Research*, 41(18), 2355-74).

<sup>28</sup> For an example, see a motion illusion demonstration film at <http://www.tenthousandthings.info/#!videos-&-demos>.

Empirical methods used in the present investigations are due to:

Herrera C., Sun P., Groulx K., Wright C., Chubb C., Sperling G. (2013) How do the S-, M-and L-cones contribute to motion luminance assessed using minimum motion? *Journal of Vision* 13:1021-1021;

Winkler, A. D. (2010). *Dissociating neural mechanisms underlying visual processes*. Dissertation. Gradworks.umi.com. <http://gradworks.umi.com/33/97/3397322.html>;

Winkler, A. D., C.F. Chubb, & C.E. Wright. (2009). Individual Differences in the Effects of Color and Spatial Frequency on Perceived Equiluminance. [Abstract] Annual meeting of the Cognitive Neuroscience Society; and

Winkler, A., Wright, C. E., & Chubb, C. (2005). Dissociating the functions of visual pathways using equispatial stimuli [Abstract]. *Journal of Vision*, 5(8):362.

<sup>29</sup> Neutral mid-level gray is the most common background adaptation configuration in MM-isoluminance studies (e.g., Anstis and Cavanagh, 1983; Lu and Sperling, 2001; Herrera et al., 2013; Winkler, 2010; Winkler et al., 2005, 2009).

<sup>30</sup> The sensitivity of the extra photoreceptor that CA is thought to possess can be inferred reliably from her

opsin genotype. Note, however, that we have not medically confirmed the expression, or the size of the expressed population of this extra photoreceptor type in her retinas. This kind of verification is not yet medically possible, but may be in the near future with advances in technology. As discussed in the online supplement, we believed our chosen chromatic context may optimize detection of a tetrachromat difference in the data of CA.

<sup>31</sup> Details of the seven experiments are shown in Table S1 of the Supplement.

<sup>32</sup> For a narrated slide deck of preliminary results see: [www.tenthousandthings.info/#!videos-&-demos](http://www.tenthousandthings.info/#!videos-&-demos).

<sup>33</sup> Additional examples and further implications of the above findings for the veridicality of normal color perception in real-world settings are discussed in Supplement, Section 5.

<sup>34</sup> Scientists of perception with philosophical leanings have referred to this a “Physicalist Trap” of color sensation theory (Mausfeld, 2002, cited earlier).

<sup>35</sup> See: Komarova, N. L., Jameson, K. A. and Narens, L. (2007). Evolutionary Models of Color Categorization based on Discrimination. *Journal of Mathematical Psychology*, 51, 359-382.

Komarova, N. L. and Jameson, K. A. (2008). Population Heterogeneity and Color Stimulus Heterogeneity in Agent-based Color Categorization. *Journal of Theoretical Biology*, 253, 680-700.

Jameson, K. A. and Komarova, N. L. (2009a). Evolutionary models of color categorization. I. Population categorization systems based on normal and dichromat observers. *Journal of the Optical Society of America, A*, Vol. 26(6), pp. 1414-1423. Reprinted in *The Virtual Journal of Biomedical Optics*, 4(8).

Jameson, K. A. and Komarova, N. L. (2009b). Evolutionary models of color categorization. II. Realistic observer models and population heterogeneity. *Journal of the Optical Society of America, A*, Vol. 26(6), pp. 1424-1436. Reprinted in *The Virtual Journal of Biomedical Optics*, 4(8).

Narens, L., Jameson, K. A., Komarova, N. L. and Tauber, S. (2012). Language, Categorization, and Convention. *Advances in Complex Systems*, Invited contribution to special issue. vol. 15, issue 03, pages 1150022-1-1150022-21.

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## Article Supplement

### Section 1. Photopigment Opsin Genotypes for Two Potential Tetrachromats:

As previously detailed by Jameson<sup>1, 2, 3</sup> molecular genetics research has determined that genotypes involving more than the three normal photopigment opsin variants are not uncommon, and that mechanisms governing the expression of such photopigment opsin genes does not rule out the possibility of an individual expressing more than three classes of retinal photopigments. The aim of much of the research into potential human tetrachromacy is to discover (a) how the possession of extra photopigment opsin genes may alter perceptual processing of color, and (b) what the X-chromosome linked features of the L-cone and M-cone opsin genes implies for potential human tetrachromacy and gender-linked color vision processing differences. For additional detail see the research articles and information available at The Human Tetrachromacy Research Collaborative website ([www.tenthousandthings.info](http://www.tenthousandthings.info)).

**Genetic testing:** Participant CA was color vision genotype assessed in 2012 by an independent research laboratory which stated CA has the genes for retinal tetrachromacy. Specifically, CA’s gene sequence for long-wavelength (L-) sensitive type cells shows an Exon 3 codon 180 polymorphism in the nucleotide sequence of her L-cone opsin gene electropherogram (personal communication from Concetta Antico, May 28, 2014). CA’s genotype results are at <http://concettaantico.com/scientific-details/>. CA was featured in a Fuji Television Documentary entitled “Science Mysteries” that aired in June 2013 (see <http://www.youtube.com/watch?v=D9Eamc4JV9A>). Future genetic analyses will confirm or qualify these results, and explore additional photopigment opsin allelic variations CA may possess.

Figure S1 (a)

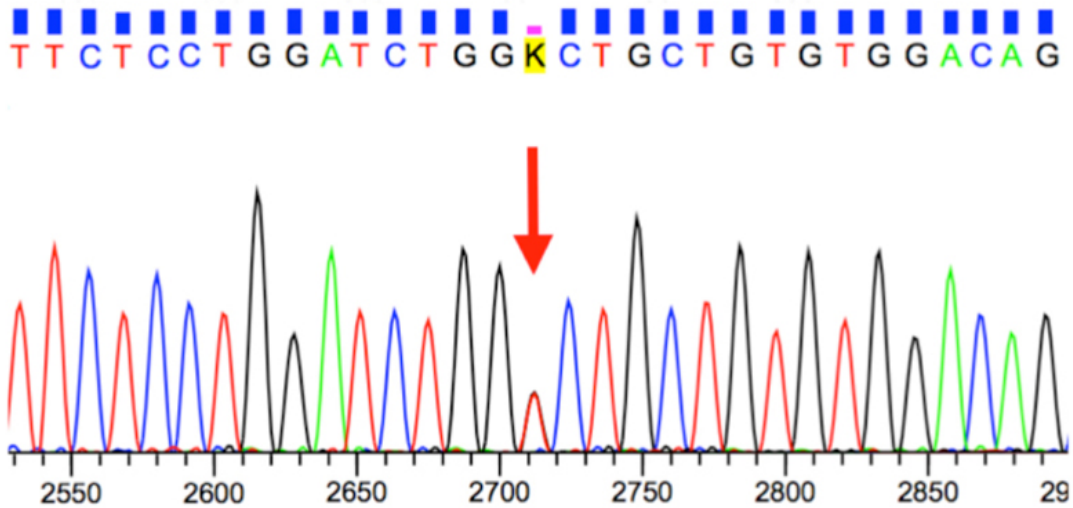
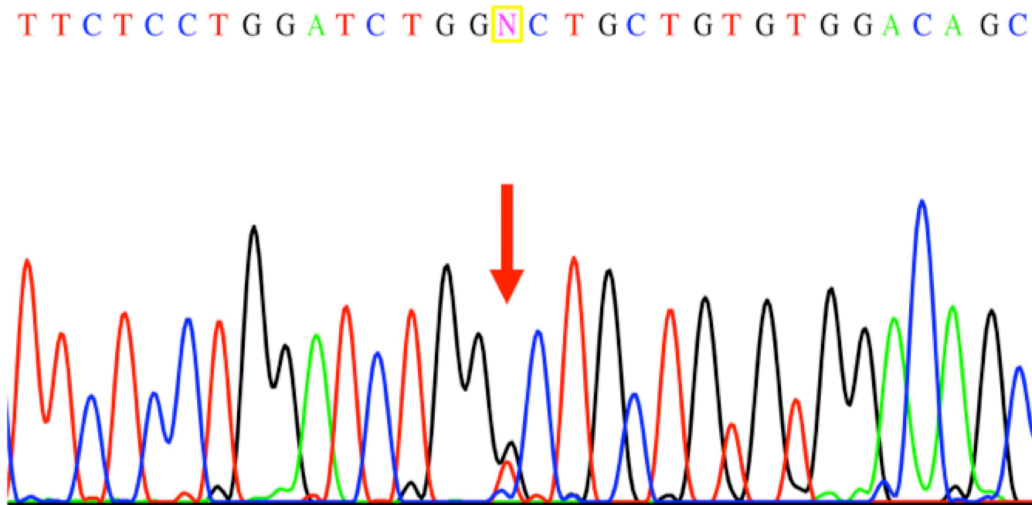


Figure S1 (b)



**Figure S1 (a-b). Electropherogram images of genetic sequence excerpts from two participants with different potential tetrachromat genotypes.** Panel (a) shows Participant CA with an L-opsin gene codon 180 polymorphism (top) and panel (b) shows participant JK with an L-opsin gene codon 180 polymorphism. Note that JK was additionally found to possess an M-opsin gene polymorphism (not shown). Curved peaks depict the intensity of the nucleotides (ddNTPs) observed in the DNA. Alphabet characters printed across the top of the peaks represent regional gene sequences observe. Central red arrows are added to emphasize the serine and alanine polymorphism is present on this L-opsin gene at position 180 on Exon 3. At indicated locations in both panels two similarly intense nucleotide traces are drawn as a black curve and a

red curve. Such traces are high quality mixed bases as shown by the tagged signals in the alpha-character sequence. Panel (a) was provided for use in this article by participant CA.<sup>4</sup> © Concetta Antico. Courtesy of Concetta Antico. [www.concettaantico.com](http://www.concettaantico.com). Panel (b) is adapted from results reported by Jameson & Wasserman (2002)<sup>5</sup> with permission from the authors. © Kimberly A. Jameson. Courtesy of Kimberly A. Jameson.

Participant JK was reported in previous empirical studies as possessing codon 180 polymorphisms on both L-opsin and M-opsin genes (Jameson et al., 2001, Jameson et al. 2006). Genetic expression mechanisms may rule out the expression of more than one M-cone class by JK, thus, given theoretical assumptions, CA and JK are both considered Exon 3 codon 180 L- opsin gene heterozygotes (although further genetic testing is needed to confirm these results). JK has familial evidence of color deficiency (maternal grandfather).<sup>6</sup>

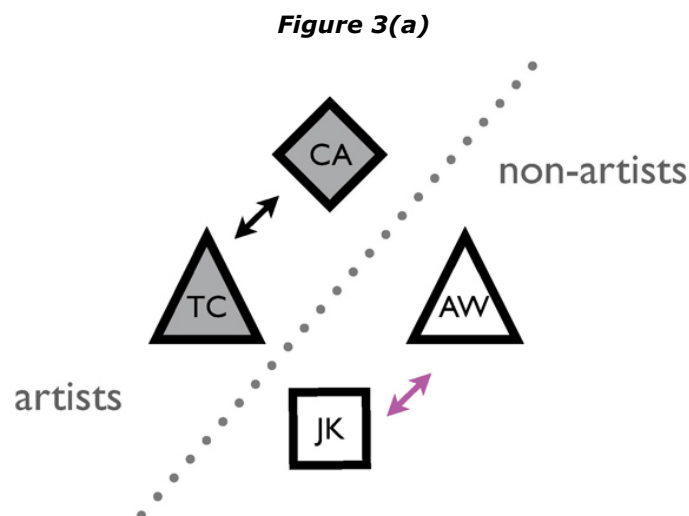
Figure S1 provides electropherogram images of genetic sequence excerpts for these potential tetrachromat participants, demonstrating that CA and JK have two different genetic sequences providing a basis for human tetrachromacy.

## Section 2. Empirical questions and preliminary results detail:

Across participants a good deal of individual variation was seen when comparing individuals' Minimum Motion (or "MM") isoluminance settings. Three empirical questions posed earlier used criteria that evaluated observed variation **beyond a level of difference we expected given the normal individual variation typically observed**. Specifically, we employed a "greater than 2 standard deviations" difference criterion for potential tetrachromat variation relative to what we typically observed between two individuals (see Supplement Section 3). We now elaborate on these three empirical questions.

**Figure 3(a)'s Empirical Question:** In comparisons across individuals who have essentially the same level and duration of art training, it is the case that photopigment genotype predicts differences found in the settings of two observers in our MM isoluminance task?

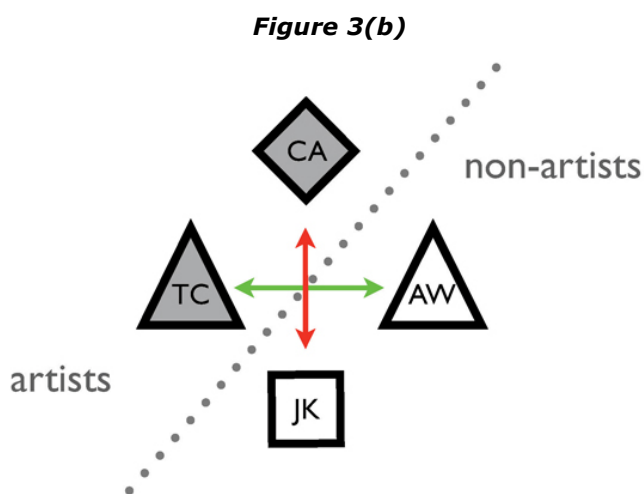
The answer to this Figure 3(a) question would be "Yes" if both black and pink arrows shown depicted statistically significant differences observed for empirical settings of compared participants.



**Figure 3(a) Result:** Experimental data show that both black and pink comparisons were observed as significantly different - especially for "reddish" color stimulus conditions (detailed below).

**Figure 3(b)'s Empirical Question:** If we consider participants with the same genotype/phenotype (that is, we compare our two potential tetrachromats – CA and JK – and compare our two trichromats – AW and TC) do we find participant's exposure to art training at an early age, and across the lifespan, is a factor that differentiates their performance in the MM isoluminance task?

The answer to this second empirical question would be "Yes" if in Figure 3(b) both red and green arrows were found to be statistically significant differences for empirical settings of compared participants.



**Figure 3(b) Result:** Experimental data revealed that observed differences varied across the two genotypes tested.

That is, the green arrow comparison, between AW and TC, was not different (by the abovementioned 2 SD criterion). Thus, for this pair of trichromats, the answer to Figure 3(b)'s question is either *"Early exposure to art training is not sufficient to differentiate the behavior of these two trichromats in this particular task"* or *"It does not appear that art training alone is sufficient to differentiate the behavior of these two trichromats"* (under the assumption that another, more sensitive test may be needed).

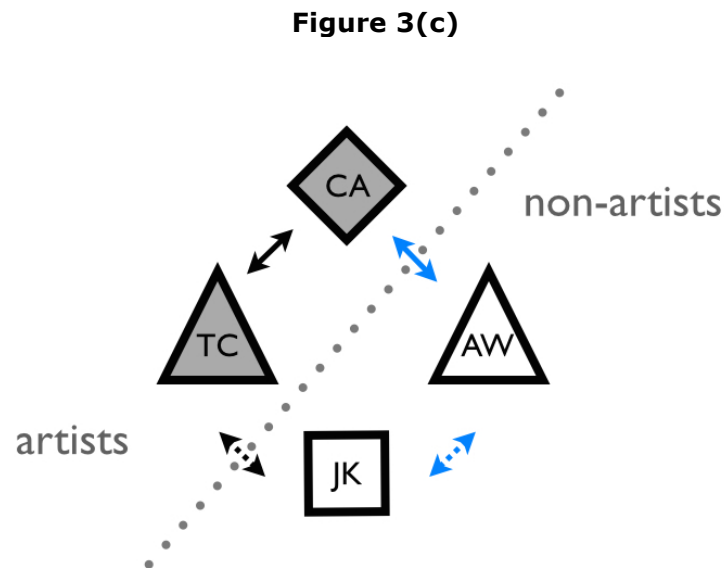
By comparison, the red arrow comparison for tetrachromat genotypes, between CA and JK, was different (by a 2 SD criterion). Thus, for this pair of putative tetrachromats the answer to the Figure 3(b) question is *"Yes, early exposure to art training seems to differentiate the behavior of these two participants."* Note, however, this result is tentative because our empirical task was designed to optimize use of presumed sensitivities of CA's personal photopigments, and, as a result, the task is more likely to detect CA's specific form of tetrachromatic potential than it is to detect that of participant JK who possesses an alternative potential tetrachromat genotype.

Accordingly, the answer to Figure 3(b)'s question is *"Yes, for these two potential tetrachromat participants, exposure to art training at an early age and across the lifespan is a factor that differentiates observers' performance in our MM isoluminance task."*

**Figure 3(c)'s Empirical Question:** Finally, we asked, what happens when both factors are varied? Do results suggest that *photopigment genotype/phenotype* and *early art training* appear to synergize? And do our results suggest that these two factors can contribute in an additive way to the variation found in the comparisons of participants' settings?

The answer to this third empirical question would be "Yes" if in Figure 3(c) the solid arrow

comparisons (blue or black) were found to differ by either a similar amount or a greater amount (but not a lesser amount) than the similarly colored dotted-arrow comparisons shown.



**Figure 3(c) Result:** Both blue and black solid arrow comparisons were different by a greater amount from the respective dotted arrow comparisons.

That is, the Figure 3(c) result suggests that *photopigment genotype/phenotype* and *early art training* factors appear to synergize, in the sense that they contribute in an additive fashion to the degree of variation found between participants' MM isoluminance settings.

### Figure 3 Results Summary:

For all three empirical questions, observed differences described were substantial but were not uniform across all conditions or experiments. Specifically, difference trends were most pronounced in (1) experiments involving a chromatic context (e.g., color background), (2) experiments using lower background luminance levels (i.e., 30-40  $cd/m^2$  adaptation levels) and (3) for color stimuli with substantial energy components in spectral regions normally associated with "reddish" appearances.

Results for Figure 3's questions are also supported by findings depicted earlier in Figures 4 and 5. Figures 4 and 5 show where the greatest variations are observed for some participants. Figure 4 shows how potential tetrachromat CA differs most from an average trichromat control for conditions involving "reddish" stimuli. Figure 5 illustrates setting differences between CA and normal trichromat AW are linked to luminance variation.

These preliminary findings establish that CA exhibits important differences from the trichromat controls in this task, namely: CA exhibits (1) non-normative levels of MM isoluminance settings, and (2) non-normative patterns of MM isoluminance settings. Our results suggest that, at minimum, CA exhibits luminance processing differences in this task, implying her extra photopigment class is playing an important role in the MM isoluminance settings she established across color conditions tested. Moreover, the results unambiguously support Figure 3(c)'s conjecture that *genotype/phenotype* and *early art training* factors synergize. Thus, CA's non-

normative perception appears to be due to her being both an artist and a potential tetrachromat.

### **Section 3. Empirical Tests and Minimum Motion Isoluminance Methods Used:**

#### **Rationale for using a new empirical approach.**

Difficulty showing effects of potential tetrachromacy on human color perception can, in part, be attributed to limitations inherent in standardized color vision assessment methods. For this reason, we chose to explore a new empirical route for isolating some perceptual consequences of potential tetrachromacy, using a task that employed interactions between brightness, color, and perceived motion while also employing a minimally complex viewing circumstance. The empirical method we used employs a task referred to as “minimum motion isoluminance”.

Minimum motion phenomena are analogous to effects used in the motion picture industry: In the movie industry a series of successively flickered static-image frames produce seamless perception of a scene in motion. Perceived motion from these still images seems real but is illusory. Minimum motion is a dramatic form of illusory motion that is perceived when a series of still off-set image stimuli of *different subjective brightnesses* are rapidly presented, or flickered successively, across time. By comparison, when flickered stimuli are instead *subjectively equal in brightness* (in the stimulus format just described), the illusory motion is instead “ambiguous” and reported with essentially equal frequency as moving in one direction or the other. Physical luminance settings of stimuli that maximize uncertainty regarding the direction of illusory motion are known to reliably coincide with observer’s personal settings of subjective isoluminance (See demonstration available at <http://www.tenthousandthings.info/#!videos-&-demos>). Such “M M isoluminance settings” vary greatly across individuals and are not expected to be uniform across color space. Comparing such settings of isoluminance across a given observer’s perceptual color space informs us about the contributions made by that individual’s different photoreceptor classes, and we suggest that comparing settings of isoluminance *across individuals* may further tell us something about the ways settings may vary due to signal processing arising from retinas with three versus four photoreceptor classes.

Potential tetrachromat individuals may express multiple long- (L) or medium- (M) wavelength-sensitive cone types and skewed proportions of one cone type relative to another. In general, isoluminance estimates obtained using hue and spatial frequency variation are likely to be depend on variation in the relative number of L:M cones expressed on an individual’s retina, peak photopigment sensitivities, and/or number of distinct cone types.

Indeed, normal color vision observers may be expected to have different M M isoluminant settings compared to observers who have the potential for tetrachromacy. This is the empirical approach and question we used to evaluate CA’s tetrachromatic potential.

The use of the MM paradigm here is exploratory, and it has not previously been used to investigate color processing among opsin genotype variants. It is used here because: (a) none of the existing color vision assessment methods are designed to reliably detect color vision differences that might arise from retinal tetrachromacy.<sup>7</sup> And, (b) humans evolved color sensations via real-world viewing circumstances – that is, in complex visual contexts, as a composite of moving dynamic scenes, contextualized by foliage, figure and background, under illumination changes, and, rarely as isolated color patches.

For this reason we additionally used manipulations of viewing complexity that might help differentiate potential tetrachromat CA from a trichromat observer. We did this because color

processing depends greatly on the surrounding environment in which a stimulus is viewed, and overly simple, non-naturalistic, viewing circumstances may not be complex enough to enlist some nuanced contributions to color processing contributed by an extra class of photoreceptors that a tetrachromat possesses. Thus, we tested CA using a variety of contexts – e.g., personally constructed luminance and chromatic variations of adaptation state – with the aim of increasing the chance of detecting a tetrachromat processing difference that might exist.<sup>8</sup>

**Methods.** We used a well-established, highly reliable “Minimum Motion” (MM) paradigm developed by Anstis and Cavanagh (1983) and later optimized by Lu and Sperling (2001).<sup>9</sup> Experimental apparatus, stimuli and procedures used are based on the accumulated work of Herrera, Winkler, Chubb, Sperling and colleagues.<sup>10</sup> The paradigm was recently used to behaviorally classify individual differences in retinal physiology underlying perceptual variability among observers due to a double dissociation between wavelength and spatial frequency of stimuli used (Winkler 2010, Winkler, Chubb & Wright 2009). Herrera et al. (2013) expanded the color conditions explored from the minimally-saturated red and green (used by Winkler and colleagues) to twenty color conditions consisting of maximally-saturated hues from a color space isoluminant plane. The results reported here used the design of Herrera (2013). We use this paradigm to obtain participants’ personal settings of subjectively equivalent “brightness” in a MM task for 20 color conditions. Such settings are 20 highly reliable points where individual’s isoluminance adjustments establish a minimum illusory motion percept attributable to subjective brightness differences between constant gray patches and 20 separately defined color patches.

**Participants.** Four females with normal or corrected visual acuity volunteered for participation. Two participants CA and JK possess the genetic potential for tetrachromacy (although they have different genotypes), and two AW and TC are normal trichromats. All investigations were performed with participants’ informed written consent. Procedures adhered to protocols based upon the world medical association declaration of Helsinki ethical principles for research involving human subjects, and were approved by the ethical review board of the University of California, Irvine.

#### **Details of Apparatus, Stimuli and Procedure.**

Subjects participated in two components: *Phase 1* involved 1-2 hour phase of testing to assess color vision using standardized methods, and *Phase 2* involved testing, over several sessions, seven minimum motion isoluminance experiments (~40-50 minute duration). Total approximate duration of experimental participation is estimated at between 5.5 and 7.5 hours, distributed across several days.

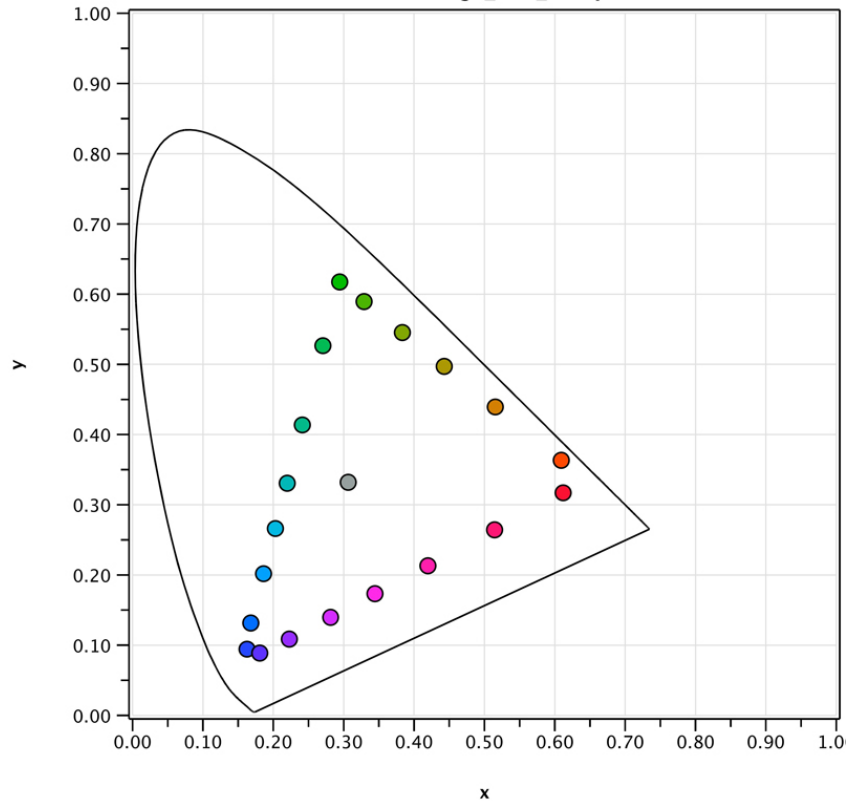
**Phase 1:** Participants were assessed using standardized procedures and some novel analysis approaches.<sup>11</sup> Diagnostics for color deficiency used were Ishihara Pseudo-isochromatic Plates, the Farnsworth-Munsell 100-hue Test, the O.S.C.A.R. flicker photometric test, and the Neitz anomaloscope matching task.<sup>12</sup> The four female participants scored as color vision normal on all four tests.

**Phase 2:** Participants tested in seven MM experiments. Subjects sat with restricted head movement to view a computer screen (~22 inches distant) and responded to MM stimulus by key-press indicating direction (left or right) of perceived stimulus motion. Stimuli subtended 2.1 degrees of central visual angle, as a small spinning disk. Otherwise the screen was chromatically uniform, at some specific luminance level, for a constant observer adaptation state. Figure S2 lists CIE coordinates of 20 color conditions tested, approximating one observer’s final settings. Over seven experiments a subject provided ~7000 isoluminance judgments (plus practice and initiation trials). Table S1 lists trials per experiment. Results from two experiments only are reported here (highlighted in yellow in Table S1).



<i>Adaptation Luminance Level</i>	<i>Uniform Neutral Gray Background</i>	<i>Uniform Color Background</i>
Lowest	20 color points; 50 trials each	20 color points; 50 trials each
Low-middle	20 color points; 50 trials each	20 color points; 50 trials each
High-middle	20 color points; 50 trials each	20 color points; 50 trials each
Highest	20 color points; 50 trials each	not assessed

**TABLE S1.** Design of minimum motion isoluminance condition experiments. Table © Kimberly A. Jameson. Courtesy of Kimberly A. Jameson.



**Figure S2.** Measured chromaticities of twenty color stimuli (plus a measured neutral gray adaptation stimulus) displayed as CIE(x,y) coordinates. Colors were evaluated by subjects, in each of the seven experiments, to establish isoluminance with a reference neutral gray. Color appearances are approximate. Original image. © Kimberly A. Jameson. Courtesy of Kimberly A. Jameson.

**Quantifying normal individual variation in MM isoluminance settings for purposes of evaluating variation due to potential tetrachromacy.**

Before quantifying potential tetrachromat effects we first quantified the degree of *normal difference* seen between two color vision normal subjects. There is considerable known variation in individual subjective isoluminance even among individuals with normal color vision. We compared two normal trichromat control females (AW with TC). Due to the steepness of individuals' corresponding psychometric functions in our minimum motion task (indicating even small physical changes in stimuli produced perceivable brightness differences) many of our paired comparisons between AW and TC are highly significant. In order to determine an appropriate baseline for further comparisons, we first calculated the mean unsigned T-value derived from paired t-tests between AW and TC across all twenty color conditions, and for each background tested. The mean degree of significance for the lowest-luminance gray condition (Mean = 6.86, SD = 7.9) was

comparable to that of the lowest-luminance chromatic condition (Mean = 7.97, SD = 8.5). In order to meet our more conservative criterion, subsequent t-values were required to be greater in degree than our normal trichromat mean deviation plus one standard deviation (e.g. +/-14.76 in the gray condition and 16.43 in the chromatic condition). Since this more conservative criterion renders observed AW-versus-TC differences insignificant, results from all other comparisons between other participants were compared to an average normal trichromat (e.g., "Average Normal" in Figure 4 main article) defined by aggregating the data of two normal trichromats, AW and TC. This result, in conjunction with the earlier findings of Herrera et al. (2013) provides a benchmark for evaluating what would be expected as normal or insignificant variation among the remaining participants assessed in the present study. Further details of the empirical task are in Jameson and Winkler 2014a and 2014b.<sup>13</sup>

#### **Section 4. Art and Potential Tetrachromacy:**

Many factors contribute to an observer's color sensations. Some are external to the observer (e.g., object illumination and ambient lighting, composition of natural scenes, surrounding surfaces and textures) others are internal factors (e.g., visual processing system structural biology, an observer's internal mental state – i.e., levels of adaptation, awareness, chemistry, and visual processing experience). One question addressed here is whether **visual processing experience** plays a prominent role in color perception.<sup>14</sup>

Recall that our results showed that normal color-vision trichromat artist TC exhibited MM isoluminance results that were similar (within individual variation) to those of **non-artist** trichromat control AW. And, by comparison, potential tetrachromat CA was shown to dramatically differ from the both trichromats tested (TC and AW).<sup>15</sup> These results have more value if we demonstrate that CA (potential tetrachromat artist) and TC (trichromat artist) are both color experts and exceptional painters: Figures S3 – S7 provide that demonstration.

**Figure S3 (a)**



**Figure S3 (b)**



**Figure S3.** A Canyon Cameo, Mission Hills. San Diego. October, 2011 16" by 20" Oval. Example of (a) a

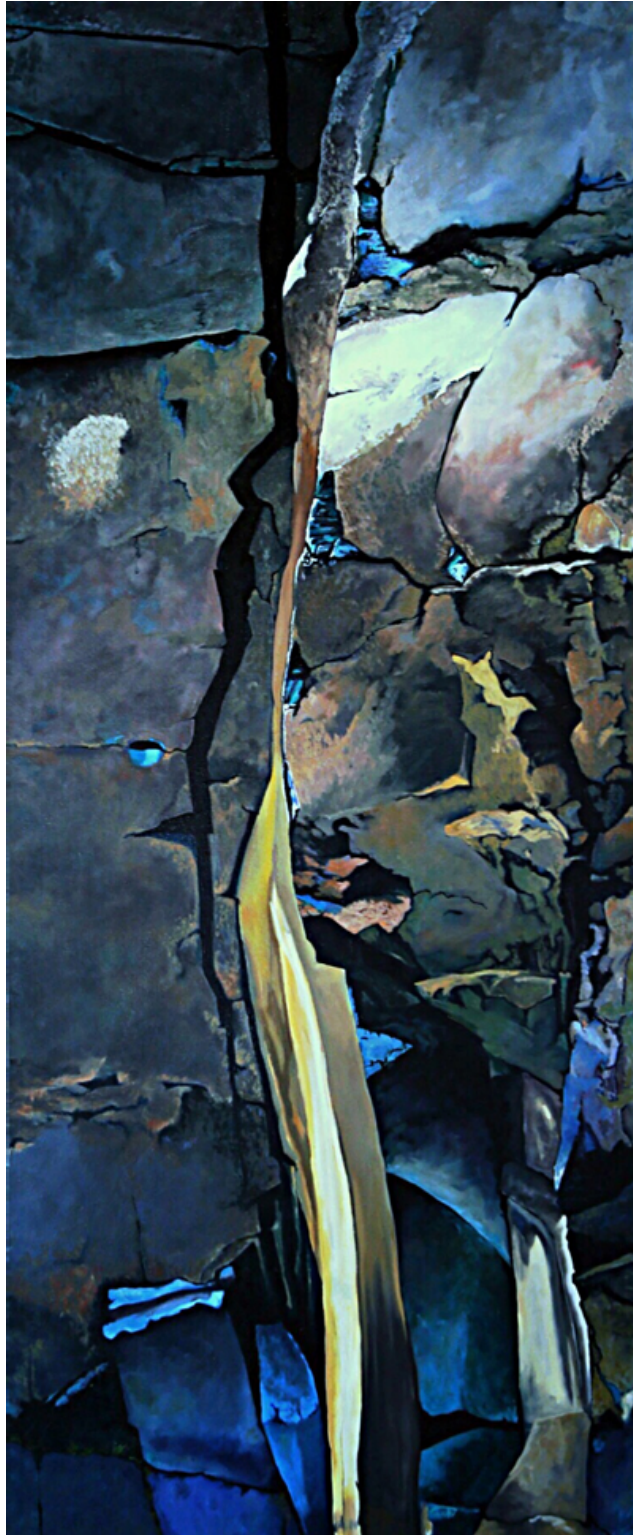
photo depicting a painting and the subject of the painting, and (b) a palette of color appearances (identified through completely separate analyses of independent empirical data), that is clearly observable in the painting in (a). Methods for empirically identifying this "palette" are detailed in Section 3 and graphics in Figure S8. Panel (a) photographed image © Concetta Antico. Courtesy of Concetta Antico. [www.concettaantico.com](http://www.concettaantico.com). Panel (b) original image. Kimberly A. Jameson. Courtesy of Kimberly A. Jameson.



**Figure S4.** Poplar Pathway, Julian, California. 18" by 24", September, 2012. Photo depicting a painting and the subject. Study first the portion of the photo with the scene before considering the painting. At this stage there is a chance you don't see pink in the shadows. Next study the painting, and carefully look at the shadows next to the poplars. You not only see pink in the shadow of the photo, but perhaps you even begin to see more pink everywhere because she has called to your attention to it (is this the beginning training of color expertise?). It appears in the sky, in shadow. She seems to be painting her impression of the ambient light and its interplay with the scene. © Concetta Antico. Courtesy of Concetta Antico. [www.concettaantico.com](http://www.concettaantico.com).



**Figure S5.** Pastures of Provence, France. 12" by 24", May, 2010. Photo depicting a painting and the subject. Clearly the cloud cover increased during the course of painting this scene, but still the presence of blue in the shadows of the painting, the spread of warm and rose tinted blossoms bordering the hedgerows, the orange emphasis of flowers near the wood stumps, the variegated green-blues of foliage in the distant trees and shrubs – these all seem derivative of a palette that is consistent with empirical differences inherent in the data (incl. their positioning and placement in shadowed and low luminance areas), and compatible with the suggestion that she is highlighting for her audience what and where she is perceiving deviation relative to the trichromat viewing audience she is so accustomed to communicating with and teaching. © Concetta Antico. Courtesy of Concetta Antico. [www.concettaantico.com](http://www.concettaantico.com).



**Figure S6.** Forces of Nature. Waterfall Rock Outcropping, Eastern Gorge, The Dalles, Oregon. *Original Oil.* 72" by 34". Artist: Tuck Contreras. Owned by and exhibited in Mariza, Resturant, New Orleans, LA. © Tuck Contreras, August 2006. Image Courtesy of Tuck Contreras. [www.tuck.communicatingbydesign.com](http://www.tuck.communicatingbydesign.com).



**Figure S7.** Memento. Original Oil. 34" by 43". Artist: Tuck Contreras. © Tuck Contreras, August, 2014. Privately owned by Carolyn Acuff. Image Courtesy of Carolyn Acuff.

Two important observations can be made via Figures S3 through S7. **First**, they show how potential tetrachromat artist CA uses color in her paintings in ways that seem consistent with her empirical results. And **second**, they demonstrate that TC's art also suggests a very high level of learned color expertise (making her an appropriate artist control participant), but CA's uses of color in her paintings appear to differ from TC's uses of color.

Regarding (1): Consider Figure S3's photo of painting and scene. First simply examine the natural scene portions of the photo (ignoring the painted canvas) and carefully note the colors in the photographed natural scene. Now, study the photographed painting. Note the additional use of color on the canvas that is not present in the photographed scene. There may seem to be a good deal of additional color in the painting compared to the physical scene – but careful consideration suggests the extra color is not random -- CA is not simply adding extra color, of every sort, everywhere.<sup>16</sup> Close examination suggests the additional color CA paints systematically align with colors that empirical data suggest CA has better access to at lower light-levels compared to a normal observer. That is, CA is primarily adding color to the scene, especially in shadowed portions, from regions of color space that were independently found to *stand-out* as conditions for which CA differed substantially from normal control participants.<sup>17</sup>

For this reason we believe that CA may be painting the extra sensations she actually sees in reflected light. Extra color in her paintings is not simply a stylistic interpretation that she adds on for the benefit of her trichromat viewers, it is her rendering of what she experiences when viewing a natural scene, emphasizing the color she realizes normal trichromats may not be able to pick-up.

This conjecture can be further examined using CA's other works, and permits preliminary evaluation of where our MM isoluminance data suggests she differs from a trichromat in natural

scene interpretation. One might venture to say in Figures S4 and S5 it appears she is communicating to her trichromat audience: "Look, I see this color and tone in these shadows, I see a range of tints in this sky, I see color contrast and veiling in the spaces adjacent to these surfaces."<sup>18</sup> In other words, CA seems to be painting the effects of light in nature, using added color and color relationships, to capture and convey her specific experiences of light in the landscape.

Regarding point (2) mentioned: We can compare Figures S3 – S5 with the color use of trichromat control artist TC in Figures S6 and S7. For example, depiction of rock formations in Figures S6 and S7 show strong, astute use of color, emphases of color variation in surfaces, and more. The examples clearly show that TC is no slouch with respect to uses of color in representing surface reflectances. However, compared to artist CA, TC seems to use color in different, possibly stylistic ways that specifically accord with the palette of a color-vision normal viewing audience, as her painted shadows are deeper achromatic shades and deeper blues, highlights are contrasting yellows and higher lightness values, the result is beautiful, highly skilled, and engages the viewer in prolonged interpretation, but the *kinds of color* used -- the palette and the emphases -- seem to be trichromatic emphases, and there is little or none of the lavender, rose, orange and gold tinges that one finds in CA's shadow work. Thus, while trichromat artist TC shows very adept and complex color use in her painting, the uses do not seem to signal "*I see more, or different, color here ...*" and, instead, color seems to be used for emphasis of an edge, or contour, and contrasting color for dramatic or emotional effect, or to embolden a line or object. Such uses of color may follow more from a conceptual or dramatic technical contrast, rather than from an impressionistic rendering of observations of a scene as seems to be occurring in the examples by CA.

Figure S3 – S7's preliminary comparisons help convey how CA's artwork is very likely capturing signaling impacts that arise from an extra photopigment class on her color perception.<sup>19</sup> These works of art demonstrate that CA and TC are both color experts and exceptional painters. This fact coupled with the highly significant differences seen when comparing CA's and TC's empirical data suggest that art training is not the sole basis for CA's observed deviations from normal. CA's genetic potential has likely been trained up by her many years of extensive art practice, and these two factors seem to synergize and contribute to the unique color perception underlying her observed empirical differences.

## **Section 5. Simulating natural scene processing based on MM isoluminance empirical data**

As a technical matter, it is essentially impossible to devise a way to allow a normal color vision observer to "see" a natural scene the way a human tetrachromat might uniquely experience it since a trichromat may not have access to some scene variation arising from an extra pigment class possessed by a tetrachromat. Thus, while it's natural to wonder how natural scene perception may differ for a potential tetrachromat, it's difficult to directly demonstrate. Despite this difficulty, one approach for understanding color sensations variation across individuals is to analytically simulate observer perception using models of photopigment processing. This is commonly done for color deficient observers (e.g., see <http://asada0.tumblr.com/post/11517603099/the-day-i-saw-van-goghs-genius-in-a-new-light>) and involves converting reflectance data from naturalistic images using known photoreceptor response information from observers with non-normative color vision.<sup>20</sup>

Figure 10 in the main article provides one such demonstration for potential tetrachromat artist CA relative to trichromat participant AW. Briefly, the method we designed for such conversions analyzes each pixel of an original photographed image (a) and uses CA's empirically observed comparison to AW to determine which portions of the original image CA would experience differently from AW. Then in (b) we convert each image pixel that would appear different in some

quantifiable way to CA to a black pixel, and convert pixels that will not look different to white pixels. The proportion of changed pixels varies from image to image (depending on properties of the original scene), but for this particular sunset image a large number (~66%) of pixels are estimated to look different to CA compared to normal trichromat control AW. Also, for any image converted, not all pixels are affected equally. Figure 10's image conversion can be broken down as a function that gives an impression of the magnitude and distribution of the estimated perceptual differences. Thus, pixels altered by an amount between 0 - 5% are 43.90% of the image pixels. Pixels altered by 5 - 10% are 11.20%. Pixels altered by > 10% are 10.93%. Total pixels changed are 66.03%.

Figure 10(c) takes our simulation one step further by refining the image's information using a meaningful heatmap color code (Figure 10(d) shows the heatmap scale used). In panel (c) all image pixels that were coded as black in (b) are changed to some color in the range shown in (d), which continuously varies from a strong red, through white, to a strong blue. The extremes of the heatmap continuum indicate the greatest differences between CA and AW. Values at the red extreme of the scale indicate CA's data reflect an increment difference. The blue extreme values code for change by a decrement difference. Thus, in panel (c) pixels coded heavy red, can be understood as pixels that are seen differently by CA as being more "powerful" than what a color vision normal observer would perceive, whereas pixels coded as the heaviest blue are experienced by CA as less powerful, or less intense, compared to what our normal observer sees.<sup>21</sup>

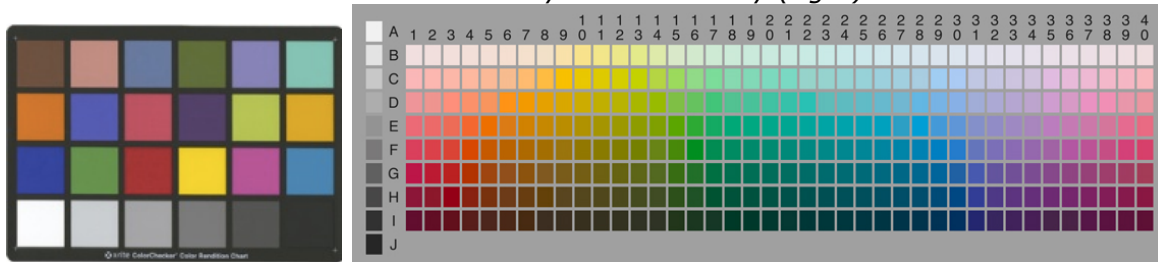
**Standardized images converted using potential tetrachromat results**

Figure S8 shows our conversion algorithm applied to two standardized images used in color reproduction science and industry: The Munsell Color Checker and the World Color Survey stimulus array. Two valuable observations are made apparent in Figure S8's image conversions.

First, based on our relative comparison of experimental data from CA with that of AW, we find that the modeled potential tetrachromat psychophysical transformation has the following properties:

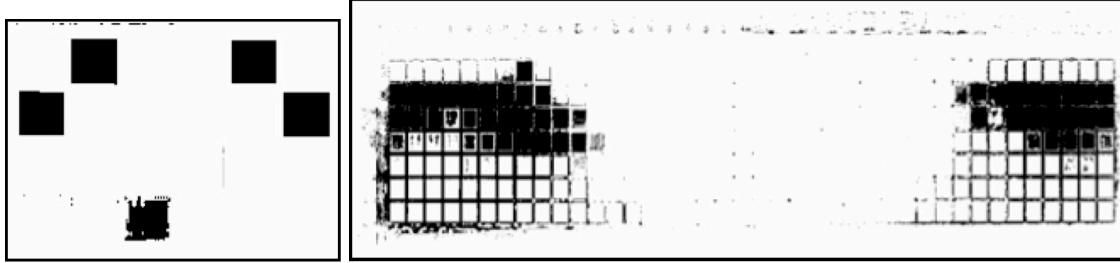
- (i.) It does not exhibit uniform variation from normal across all spectral frequencies -- that is, some frequencies are impacted more than others. For example, spectra of color tiles numbered (1) to (5) in Figure S8(c) are perceived differently by CA, whereas the other color tiles in the original image (a) are not.
- (ii.) Its deviations from normal do not represent changes in a uniform direction -- that is, sensitivities for some color spectra are increased, whereas sensitivities at other spectral frequencies are decreased. And,
- (iii.) It does not always deviate from normal -- that is, for some spectral frequencies the tetrachromat psychophysical function processes stimuli in a manner that is statistically indistinguishable from normal processing.

**Figure S8 (a)** Original images: Munsell Color Checker (left).  
World Color Survey Stimulus Array (right).

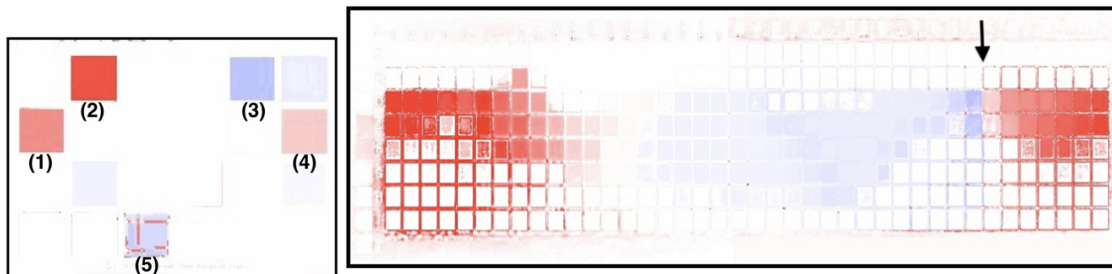




**Figure S8 (b)** Images algorithmically converted in which black pixels tag areas of perceived difference:



**Figure S8 (c)** Images converted using a warm-to-cool heatmap color code:



**Figure S8 (d)**



**Figure S8.** Simulated image conversions of the Munsell Color Checker (left) and the World Color Survey Munsell Color Array (right). Panel (a) shows a digital image "originals". Panel (b) shows conversions of originals in (a) that tag pixels perceived as different by the potential tetrachromat with black, and pixels perceived as not different with white. Panel (c) shows panel (b)'s pixels additionally colorized with a meaningful "heat map" color code that captures the empirically observed MM isoluminance differences for CA relative to those of AW. Panel (d) shows a heatmap color scale used. In the heatmap color code, image pixels are colorized heavy red where the potential tetrachromat's perception is different in a more sensitive way than what a normal would perceive – (where "more sensitive" connotes needing less wavelength-specific luminance energy to establish isoluminance with a adaptation field standard). Image pixels that are colorized as the heaviest blue are different by being less sensitive than what a normal observer would see (or, pixels needing more wavelength-specific luminance energy to establish isoluminance with a adaptation field standard). White codes pixels where perception is the same for potential tetrachromat observer CA and normal trichromat observer AW.

The right-most "hot" end of the color scale codes relative differences where CA was more sensitive to luminance than AW, and the left-most "cool" end of the color scale codes where CA was less sensitive to luminance than AW. Between these extremes the color scale varies as a log function of %-boost experienced by CA relative to AW (where boost is a parameter given by a psychophysical function derived from spectral measures for hue and luminance (CIELhc) given pixel RGB values, and is therefore based entirely on the observed comparison of CA's empirical data with that of AW). Panel (d) scale is based only on the first-order motion, MM isoluminance task, comparisons between the potential tetrachromat CA and the normal female control AW. If we were to consider additional influences from higher-order scene processing for CA and AW, or additional data from a different potential tetrachromat type and a different color normal control, then this heatmap color scale would be expected to vary in both color-coded range and numeric values. Image credits: Panel (a), left side. Munsell Color Checker image available online (<http://www.poynton.com/notes/color/GretagMacbeth-ColorChecker.html>). Munsell Color Checker image used here is an optically-scanned image of an actual color checker. Courtesy of Kimberly A. Jameson. Panel (a), right side. The World Color Survey Stimulus Array (<http://www1.icsi.berkeley.edu/wcs/images/jrus-20100531/wcs-chart-4x.png>) publically available online. Images used in Panels (b), (c) and (d) are original images. © Kimberly A. Jameson. Courtesy of Kimberly A. Jameson.

These data suggest that while some processing differences may be very significant they are not global, and they do not always involve a heightening of perceptual processing. To our knowledge such subtleties have not been systematically described in previous empirical reports investigating the psychophysical functions underlying potential human tetrachromacy phenomena.

Second, qualitatively, the color stimuli in Figure S8 (a) that end up transformed by the algorithm are of interest. Concentrating first on the Munsell Color Checker stimulus, two orange-ish samples (i.e., corresponding to (1) and (4) in panel (c)) are stimuli closest to the peak wavelength area of CA's extra photopigment class, and are found to differ in a positive "boost" direction, which is consistent with the idea that her extra photopigment class is contributing to an isoluminance signal. The rose colored tile (labeled (2) in panel (c)) is tagged for the greatest "boost" difference, and that stimulus is reddish-blue, and is a bit of a puzzler from a the standpoint of our current modeling perspective – however, the present model is admittedly only a first-order approximation of possible scene processing differences. Last, there is the lavender (labeled (3)) and gray (labeled (5)) stimuli in panel (c) that change the greatest in the scale's "anti-boost" direction.<sup>22</sup> Thus, two bluish-reds (a rose with blue tint (i.e., (2)) and a lavender blue with some red in it (i.e., (3))) are the extremum coded by the heatmap scale.

If we consider the finer sampled stimulus of Panel (a) on the right – the highly recognizable Munsell Color Array used in the well-known line of color categorization research started by Berlin & Kay (1969)<sup>23</sup> – we note an obvious pattern in the heatmap conversion in (c.). Namely, "hot" and "cold" codes are mostly assigned in a continuous gradient across the array, but there is an apparent discontinuity at column 34 of the array where an arrow points to a strong "anti-boost" blue value adjacent to a midlevel red "boost" value in column 35. This singularity is interesting, and it seems to correspond to the two bluish-red curiosities noted earlier (stimuli (2) and (3)) in the heatmap conversions done for the Color Checker stimulus. The result that reddish-bluish combinations should catch both ends of our heatmap scale is somewhat surprising -- especially when they are nearest neighbors in an array that represents an empirically robust, smooth, trichromat perceptual ordering -- but the explanation for this particular discontinuity we leave as a puzzler left for future research, and welcome the reader to ponder the possible underlying mechanisms for this lavender/rose curiosity that may spring to mind!

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## Supplement Endnotes and References

<sup>1</sup> Jameson, K. A. (2009). Tetrachromatic Color Vision. Invited contribution to *The Oxford Companion to Consciousness*. Wilken, P., Bayne, T. & Cleeremans, A. (Ed.s). Pp. 155-158. Oxford University Press: Oxford.

<sup>2</sup> Jameson, K. A. (2009a). Human Potential for Tetrachromacy. *Glimpse: The Art + Science of Seeing*, 2.3, Issue on Color, 82-91.

<sup>3</sup> Jameson, K. A. (2009b). Human Potential for Tetrachromacy - Online Supplementary Material. Published online only as a supplemental resource in *Glimpse: The Art + Science of Seeing*, 2.3.

<http://www.glimpsejournal.com/2.3-KAJ.html>.

<sup>4</sup> Antico, C. (2014). Scientific details of Concetta Antico's genetic potential for tetrachromatic color vision. Licensed to Concetta Antico under Creative Commons Attribution- Noncommercial-NoDerivatives Works 4.0 International License. June 13, 2014. Available at <http://concettaantico.com/scientific-details/>.

<sup>5</sup> Jameson, K. A. & Wasserman, L. M. (2002). Color Appearance Variations associated with Photopigment Opsin Genotypes. *Perception*, 31, supplement, 15b.

<sup>6</sup> Wasserman, L. M., Szeszel, M. K. & Jameson, K. A. (2009). Long-Range Polymerase Chain Reaction Analysis for Specifying Photopigment Opsin Gene Polymorphisms. *Technical Report Series # MBS 09-07*. Institute for Mathematical Behavioral Sciences University of California at Irvine. Irvine, CA, USA. Available at [http://www.imbs.uci.edu/files/imbs/docs/technical/2009/mbs\\_09-07.pdf](http://www.imbs.uci.edu/files/imbs/docs/technical/2009/mbs_09-07.pdf)

<sup>7</sup> There are several reasons existing tests are not good at detecting potential tetrachromacy, including (1) the tests are based on 3-dimensional color space assumptions (a true functional tetrachromat might need more than 3 color space dimensions), (2) by design tests concentrate on color relationships that are characteristic of forms of color vision deficiency that involve color within gamut compressions or reductions (a functional tetrachromat might exhibit gamut complexifications or extensions), (3) only a portion of the tests involve context dependent binocular viewing (i.e., color sorting tasks like the FM100, and pseudoisochromatic tests like the Ishihara plates) or conditions that could optimize detection of tetrachromat differences.

<sup>8</sup> Based upon pilot results from CA's "odd-one-out" triad task choices of surface color samples, a distinct "singularity" region of CA's color space was noted that suggested a non-normative ordering of color stimuli – a finding implying a need for an extra dimension of color space mapping in CA's color space similarity relations.

<sup>9</sup> Anstis, S.M. and P. Cavanagh. (1983). A minimum motion technique for judging isoluminance. In: J. Mollon and L.T. Sharpe, Editors, *Color vision: physiology and psychophysics*, Academic Press, London. And, Lu, Z.-L. & Sperling, G. (2001). Sensitive calibration and measurement procedures based on the amplification principle in motion perception. *Vision Research*, 41(18), 2355-74.

<sup>10</sup> Herrera C., Sun P., Groulx K., Wright C., Chubb C., Sperling G. (2013) How do the S-, M-and L-cones contribute to motion luminance assessed using minimum motion? *Journal of Vision* 13:1021-1021;

Winkler, A. D. (2010). Dissociating neural mechanisms underlying visual processes. Dissertation.

Gradworks.umi.com. <http://gradworks.umi.com/33/97/3397322.html>;

Winkler, A. D., C.F. Chubb, & C.E. Wright. (2009). Individual Differences in the Effects of Color and Spatial Frequency on Perceived Equiluminance. [Abstract] Annual meeting of the Cognitive Neuroscience Society; and Winkler, A., Wright, C. E., & Chubb, C. (2005). Dissociating the functions of visual pathways using equisalient stimuli [Abstract]. *Journal of Vision*, 5(8):362.

<sup>11</sup> For example, Jameson, Bimler, & Wasserman (2006) explored novel analyses of standard assessment data from color-deficiency test to identify carriers of color-deficiency.

<sup>12</sup> Birch, J. (2001). *Diagnosis of Defective Colour Vision*. (London: Butterworth-Heinemann).

<sup>13</sup> A narrated slide show of the summary results is available at: <http://www.tenthousandthings.info/#!videos-&-demos>

<sup>14</sup> Color vision appearance modeling has historically focused on understanding aspects of color processing directly attributable to signals arising from retinal photopigment classes, leaving investigations of perceptual learning and the possible training of color vision expertise, for other investigators. Here we address this perceptual learning question directly by investigating a potential tetrachromat who is an accomplished artist, who has had intimate access to extensive color training and use across her lifespan, and who thus presents an opportunity to investigate the possible interplay between photopigment opsin signal variations and the training and use of such signal processing to impact color sensation. Questions posed earlier in the main article emphasize this as an opportunity to investigate which portions of color sensation experience are due to **nature** and which are due to **nuture**.

<sup>15</sup> For four out of seven experiments CA differed from the normal controls by more than 2 standard deviations, on several color conditions tested.

<sup>16</sup> We thank artist Jon Lomberg ([www.jonlomberg.com](http://www.jonlomberg.com)) for pointing out the subtle correspondences between CA's empirical data and the palette of additional color found in some of CA's paintings.

<sup>17</sup> One is reminded of "The El Greco Fallacy" (<http://www.ncbi.nlm.nih.gov/pubmed/24577418>) with the examples given where a photo of a painting and the subject are shown (taken with same RGB filters/film) because the artist while making the painting must gaze both on the scene and on the painting and, presumably, reproduce as closely as possible, the scene as painted pigments. Still, the photo composite of both the painting and the original subject demonstrates the artist made the painting more colorful, which raises the ghost of the El Greco fallacy. Despite this possibility, we cannot rule out that the potential tetrachromat artist paints onto the canvas *exactly what she sees*, and, possibly, the RGB film better registers the extra color when it is artistically rendered in pigments on canvas, but less so (due to photographic filters) when it is present as reflected daylight in the scene itself. Another possibility is that perhaps the actual differences perceived by the tetrachromat are interpreted on the canvas, using a perceptually-learned added color emphasis. Although this latter possibility requires some implicitly acquired meta-knowledge concerning what normals actually cannot see (such meta-knowledge could be easily acquired across the lifespan of a potential tetrachromat). The painted emphases would then be signals of emphasis from the tetrachromat artist, saying, "look I see extra colorful light here ... and here ... and here"... This rationale for extra color would be consistent with French Impressionist style of painting, or with a style of painting light reflected off objects (as oppose to the objects themselves).

<sup>18</sup> Figure S4 and S5 captions provide some details in line with this preliminary conjecture.

<sup>19</sup> One can examine similar color differences shifts and emphases as those found here in the original scenes photographed compared to CA's painted depictions through simulations of other painter's approximated shifts in tonal and light emphases. See Asada's Memorandum (<http://asada0.tumblr.com/post/11517603099/the-day-i-saw-van-goghs-genius-in-a-new-light>), for example, with simulations of Van Gogh's *The Sunflower* [see "Sunflowers" (F456) Original [http://media.tumblr.com/tumblr\\_lswv15YZrp1qa3fjk.jpg](http://media.tumblr.com/tumblr_lswv15YZrp1qa3fjk.jpg) versus the Protanomalous simulation (60%) [http://media.tumblr.com/tumblr\\_lswv1eZh7K1qa3fjk.jpg](http://media.tumblr.com/tumblr_lswv1eZh7K1qa3fjk.jpg)]

<sup>20</sup> Webster M.A., Juricevic I., & McDermott K.C. (2010). Simulations of adaptation and color appearance in observers with varying spectral sensitivity. *Ophthalmic Physiol Opt*; 30(5): 602-10.

<sup>21</sup> Details of the algorithm designed to convert these images are provided in an in-progress technical report by Jameson & Goldfarb.

<sup>22</sup> Note, mid-level gray stimulus (5) in panel (c) shows signs of a multivalued artifact – blue conversion code with red code aliasing – because the hue and luminance levels of the original gray stimulus straddle a tipping point in the algorithm.

<sup>23</sup> Berlin, B. and Kay, P. (1969). *Basic Color Terms*. University of California Press, Berkeley and Los Angeles.

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## About the Authors

### **Kimberly A. Jameson**

Kimberly A. Jameson is a cognitive scientist conducting research at the Institute for Mathematical Behavioral Sciences at the University of California, Irvine (<http://www.imbs.uci.edu/~kjameson/kjameson.html>). Color plays a prominent role in her empirical and theoretical work, which includes research on the mathematical modeling of color category evolution among communicating artificial agents; individual variation and universals in human color cognition and perception; and comparative investigations of the ways the world's cultures name and conceptualize environmental color. She is founder and director of the Human Tetrachromacy Research Collaborative (<http://tenthousandthings.info/>) a multidisciplinary group of researchers investigating the molecular genetic, perceptual, behavioral and applied aspects of potential human tetrachromacy – and is the lead researcher responsible for the preservation, transcription, and digitalization of the Robert E. MacLaury cross-cultural color categorization archive. On issues concerning naturalistic color processing, she frequently investigates the interactions between environmental camouflage and upland fowl plumage with her hunting companion Beausoleil. (<http://www.imbs.uci.edu/~kjameson/Beausoleil.html>).

### **Alissa D. Winkler**

Ali Winkler's research focuses on modeling the function of neural mechanisms that contribute to individual perceptual differences using psychophysical and neuroimaging methods. Winkler's involvement studying the links between visual processing, potential tetrachromacy and art (described in this issue) is especially exciting because it permits an opportunity to demonstrate first – that the brain has the capacity to make use of sensory input from a fourth photoreceptor class, and second – how the brain incorporates this additional sensory input into a personal cognitive architecture that supports a shared conceptual meaning system. Winkler currently works as a cognitive neuroscientist, researching perceptual adaptation of color and form in the Visual and Perception Lab at University of Nevada, Reno ([www.linkedin.com/pub/alissa-winkler/26/680/747](http://www.linkedin.com/pub/alissa-winkler/26/680/747)).

### **Christian Herrera**

Christian Herrera is a cognitive neuroscientist currently working in the Chubb-Wright Lab in the Department of Cognitive Sciences at University of California, Irvine. Using psychophysics and Bayesian statistical modeling he investigates properties of human visual processing. Recently, he's working on how to isolate color from other visual input and how to model other properties of the color signal, like saturation and brightness, and how motion and color are related. (<http://www.cogsci.uci.edu/~cherrer2/>).

### **Keith Goldfarb**

Keith Goldfarb is a software artist and co-founder of Rhythm and Hues Studios (<http://www.rhythm.com/home/>), the pioneering visual effects company honored with dozens of awards, including multiple Oscars, Baftas and Clios for outstanding visual effects and technical achievement. As Chief Software Architect and anointed "Color Guru" at Rhythm, for 26 years Keith directed R&D on multiple fronts, from the basics of compiling core image and geometry libraries to managing project workflow of enormous production environments for blockbuster films. Keith's innovations uniformly received high praise and were imitated by Rhythm's competitors. In 2014 Keith transitioned to Blackthorn Media (<http://blackthorn-media.com>) where he currently works on the creation of original properties. He also dabbles in the area of "transmedia" no doubt anticipating the myriad of ways a future viewing-public might couple with next-generation entertainment interfaces. Other creative pursuits include crafting salmon-roe gelato for his cats, and reciting, in original language, Byzantine liturgical poetry.