Orange & Teal

Jan Koenderink^{1,2,3,*} and Andrea van Doorn^{1,3}

¹Justus-Liebig University Giessen, FB 06 Psychology and Sports-Sciences,
Otto-Behaghel-Str. 10F, 35394 Giessen, Germany

²Laboratory for Experimental Psychology, KU Leuven, Tiensestr 102, Bus 3711,
3000 Leuven, Belgium

³Department of Experimental Psychology, Utrecht University, Martinus J. Langeveldgebouw,
Heidelberglaan 1, 3584 CS Utrecht, The Netherlands

Received 26 May 2020; accepted 16 November 2020

Abstract

‘Orange & Teal’ has become the preferred ‘look’ of the Hollywood movie industry. Is this craze just another arbitrary fashion? Possibly not, because – apart from the name – this palette has been around for ages in the visual arts. It is variously known as ‘painting in cool and warm,’ drawing *a trois couleurs*, use of a ‘limited palette,’ and so forth. This leaves open the question of whether there might be one or more *fundamental* reasons for the preference for this particular dichromatic pair. Why not yellow–blue, red–turquoise, or green–purple? Reasons might be sought in human anatomy/physiology, physics of surface scattering, or the ecology of the human Umwelt. An in-depth analysis reveals that all these factors cooperate to render the orange & teal complementary palette indeed special. It involves world, body and mind and has to be understood in a proper semiotical (biological) setting.

Keywords

Color, Teal & Orange, Umwelt, cool and warm, limited palette

1. Introduction

As a hands-on introduction to the subject we suggest that the reader enters ‘Orange & Teal’ (see Note 1) in the Google search engine.

* To whom correspondence should be addressed. E-mail: koenderinkjan@gmail.com

First try *image search*. This reveals what the topic is about: a certain look that is applied to any type of scene.

Next try *web search*. This will come up with dozens of sites that address various perspectives. Here are a few:

- Explanation of the term (e.g., Wikipedia ‘Teal’; Note 2).
- Software, lookup-tables and suggestions how to tweak Adobe’s Photoshop. These allow you to implement the *Orange & Teal* look in your own work. It has become a business (just an example: ‘Download 10 completely free orange & teal LUT Collections. orange & teal LUTs – Teal Shadows, Orange Tint, Light Blue and so on’; Note 3).
- Attempts to explain why this look is so attractive (e.g., ‘What is the ‘orange & teal Look’ and Why is it So Popular?’; Note 4).
- Laments that the Hollywood movie industry knows no better than to apply the *Orange & Teal* look to about any movie nowadays (e.g., ‘Into The Abyss: orange & teal – Hollywood, Please Stop . . .’; Note 5).
- Of course, there are quite a few more, although there is a lot of repetition.

Since Internet sources tend to be volatile (the URLs mentioned in the footnotes may not exist anymore tomorrow) it is suggested that the reader attempts a personal search. It will yield results similar to the above. Most likely, there will be some additional perspectives.

Consider the colors figuring in the ‘*Orange & Teal*’ look:

- The color ORANGE is named after the fruit of *Citrus sinensis*, by way of the old French *pomme d’orange* (by a tortuous route from Sanskrit *naranga*). It appeared in the English language in the early sixteenth century. The orange of the *Orange & Teal* look apparently spans a range from yellowish red to reddish yellow. A median display RGB-color would perhaps be #FF7F00 (Note 6). A good orange does hardly scatter any radiation with wavelengths below ca. 530nm and scatters most of it above.
- The color TEAL is a blue–green color. Its name derives from the common teal (*Anas crecca*), a common duck with a teal-colored stripe on its head (see Fig. 1). The word entered English in the early twentieth century (Middle Dutch *teling*, Middle Low German *telink*, by way of Proto-Germanic *tailijaz*). The teal of the *Orange & Teal* look apparently spans a range from greenish blue to bluish green, usually toned down a bit. It is often used for the general range of cyans. A median display RGB-color would be a somewhat attenuated version of #007FFF (‘no red, half green,

Figure 1. The Eurasian teal (*Anas crecca*) from Mangaon, Raigad, Maharashtra, India (photograph by Shantanu Kuveskar). The color teal derives from the blue-green stripe on the male duck's head. Nature has used the orange & teal style on the full head.

full blue'). A good teal hardly scatters radiation with wavelengths above ca. 530 nm and an appreciable amount below.

So much for the colors orange & teal.

Is the 'Orange & Teal' look a millenium novelty? We reckon not, because the warm-cool dichromatic pair – not the name – has been in common use by visual artists for centuries. In informal sketches a drawing in black-gray pencil, ink or chalk would be given a wash of an orange-like pigment (perhaps an earth color, like burned Sienna, display RGB #E97451) and a darkish bluish color (say Paynes gray, a dark blue-gray, display RGB #536878) (see Fig. 2).

It is like a variation on the venerable 'trois crayons' technique of drawing with red and perhaps black and white chalk on teal-colored paper (see Fig. 3).

Such methods offer fast ways to finish sketches and greatly add to the space and atmosphere. It is sometimes referred to as 'painting in cool-and-warm' (Quiller, 1989, p. 40). The colors carry various well known artistically important 'qualities'. For instance, warm colors come forward, cool colors recede.

There is no doubt about the singular artistic usefulness of this particular dichromatic pair. This will be sufficient from a pragmatic perspective. However, the scientist will ask for a *fundamental* reason that this combination is such a universal winner. Such a reason might well be of interest to the artist too.

This is the issue considered in this paper.

Figure 2. John Singer Sargent (1856–1925), *White Ships* (c. 1908). Translucent and opaque watercolor. The painter used a convenient (for travel) limited, orange & teal palette. Brooklyn Museum, New York, USA.

2. Causes of Non-Uniformity and Anisotropy in Colorimetry and Phenomenology

Aesthetic preferences – as for the ‘*Orange & Teal*’ look – may be expected to correlate with physiological, physical and ecological non-uniformities, as well as idiosyncratic – think of cultural differences – phenomenology. We do not speculate on causal factors, but look for correlations. No doubt evolutionary processes play a role. Thus the generic lifestyle of *Homo* will interact with ecological factors (Koenderink, 2019) (Note 7).

We assume that object colors are the major factor to take into account when assessing effects on biological fitness. This implies a hunter-gatherer lifestyle based on diurnal foraging. Daylight will be the dominant illuminant and the ‘objects’ will be predominantly surfaces of opaque materials with approximately Lambertian surface scattering properties (Kortüm, 1969).

Object colors occur in the case of spectrally selective reflection factors (Note 8), relative to the scattering of a white object (Koenderink, 2010). That is to say:

Figure 3. Giovanni Battista Tiepolo (1696–1770), *Head of Giulio Contarini* (after a bust by Alessandro Vittoria, 1525–1608; around 1742/1743), red and white chalk on blue paper, 24.5 × 18 cm. It is not uncommon to add a black chalk, but, as evident here, this is not really necessary.

- Object colors result from selectively subtracting chromatic content (via spectral ranges of absorbance) from white (all daylight scattered equally). For instance, a good YELLOW results from a lack of scattering short-wavelength radiation (Koenderink, 2010; Ostwald, 1919). That is ‘subtracting blue from white.’ This is usually represented as a spectral reflectance factor, a material property. The daylight illuminant goes understood.

This sets the object colors apart from the colors of generic colorimetry:

- Beam colors result from adding chromatic, luminous power to darkness. For instance an orangish YELLOW may result from radiant power at 589/590 nm (Note 9). This is represented as a spectrum of radiant power (Newton, 1704). The radiant power is added to darkness (‘nothing’). The representation is æthereal rather than material.

The difference is phenomenologically striking, for phenomenologically the dark–light dichotomy is qualitatively different from the black–white dichotomy. Beam colors appear luminous, whereas object colors appear as less than white (Goethe, 1810: *Schattenhaft*, that is shadowlike). Beam colors are æthereal or aerial, whereas object colors are material, or earthy. This dichotomy has been effectively illustrated in Philipp Otto Runge’s (1777–1810) programmatic painting ‘Der kleine Morgen’ (Note 10).

A striking example is presented in Fig. 4. The full moon, at dusk or nighttime (Fig. 4 right), is perceived as a source, pretty much as the sun is at daytime. It throws shadows, crepuscular rays in the sky and reflection glitter on rippled water. Indeed, photographs in moonlight look like photographs in sunlight if one matches the exposures.

Figure 4. An astronaut on the lunar surface (left) and the full moon in the night sky as seen from the terrestrial environment (right). The astronaut’s suit and the full moon are rendered (near) white in these images, although both are views in the solar irradiated lunar surface. That is because in both cases the photographic exposure was set to best reflect the current situational awareness. Thus the dark dirt fits the environment at left (what is more basic than the ground under your feet) whereas the bright object at right does not properly fit the terrestrial environment but looks like an – albeit welcome – invader (there is no way you might touch it).

Thus the moon apparently sends out a beam, of which we experience the effects. One experiences a beam color. There is no notion that the moon's color might fit on a scale from black to white. It is radiant, has a brightness, but not a gray value. It does not belong to the immediate terrestrial environment.

This is very different when you are actually standing on the lunar surface (Fig. 4 left). The moon is dark gray, this is immediately evident because the white astronaut's suit serves as a reference. There is no notion that the lunar surface is radiant. The surface obviously belongs to the immediate, in this case lunar, environment. One experiences an object color that has a well-defined location on the scale from black to white. In fact, it is darker than the familiar Kodak[®] gray card (Note 11).

This example clearly demonstrates that the experience of beam or object colors is critically dependent on the observer's situational awareness. There has to be sufficient 'anchoring' (Gilchrist, 1999) in order to experience object colors. For instance, a white reference (the astronaut's suit) will work fine. This is crucial for colorimetry. For object colors the anchoring needs to be taken into account, even if the 'proximal stimulus' is a beam of radiant power incident on the cornea in any case. Of course, objects do not physically enter the eye (Note 12), only their scattered beams do. But so do other beams from the environment and this matters.

There are *many* more object colors than there are beam colors. Think of grays, browns, olives, gold, silver, pearl, anthracite, Black is just as important as white. The set of beam colors is really limited. It doesn't even have white and black is 'nothing.' Even the simple object color setting has problems with gold, silver, pearl, or anthracite. However, it easily handles grays, browns, or olives – let alone black or white.

The hunter-gatherer is aware of beam colors in the sky, which are pretty much 'elsewhere,' and object colors in the life world, which is 'here'. The upshot is that object colors do matter for the hunter-gatherer lifestyle, whereas beam colors hardly matter at all. This affects the evolutionary process.

Daylight is rather variable and changes capriciously. In contradistinction, spectral reflectance factors are constant object properties (Byrne and Hilbert, 2003). Adaptation causes objects that are objectively white to appear as such over almost the full range of daylight illuminants (von Kries, 1905). Black objects appear as such too. Thus all gray colors indeed appear gray (because of linearity; Grassmann, 1853) at all times.

This is remarkable. The adaptation (also called 'color constancy' in the context of human perception, or 'automatic white balance' in the case of phone cameras) renders the colors from beams scattered to the eye practically independent of the spectrum of the illuminant. The upshot is that by and large beam colors are correlated with radiant spectra, whereas object colors are

correlated with spectral reflectance factors (or albedos – see subsection 2.1. *Considerations of Colorimetry*)

Colors will vary a bit as daylight varies (Goethe, 1810), although these effects of metamerism and less than perfect adaptation tend to be minor. By and large object colors are object properties. In the hunter-gatherer daily environment ‘roses are red, violets are blue’, always and anywhere. Although imperfect and crucially dependent on ecological statistics (subsection 2.2. *Considerations of Ecology*), this is why color vision offers an evolutionary advantage.

In a nutshell, beam colors mirror light sources, whereas object colors mirror object properties. This is crucial to human perception in a biological context.

Thus the following factors have to be investigated:

- The optical interface, as specified by the color matching functions (Wyszecki and Stiles, 1967; Note 13). This accounts for the anatomy/physiology.
- The set of illuminants. This is limited to variations of daylight. At night, at the camp fire, objects hardly have any colors at all.
- The set of spectral reflectance factors. This involves both physics and ecology.
- The phenomenological structure of ‘color space’. For instance, how well can an object of a certain color be identified in arbitrary settings?

Humans are able to keep about a thousand colors apart (Note 14; Koenderink *et al.*, 2018a), may remember (in long-term memory) a few dozen at best and can name up to a dozen (Griffin and Mylonas, 2019; Note 15). This cannot be due to physiology, for just noticeable differences (JND) data (MacAdam, 1942) suggest that there are about forty million colors that can be mutually discriminated (Wyszecki and Stiles, 1967). The pragmatic resolution is very much less than what straight psychophysics suggests – effectively ruling out anatomical/physiological constraints as a relevant factor.

We proceed to consider the various factors in some (intentionally minor) detail. This involves considerations of ecological optics, physics of material properties, colorimetry and experimental phenomenology.

2.1. *Considerations of Colorimetry*

2.1.1. *RGB-Color Space*

Consider a mosaic of Lambertian papers under standard day-light (CIE D65 illumination, say). This is roughly the setting of an artist’s studio of the old times (Note 16).

Figure 5. At left the daylight spectrum (95% limits) partitioned into blue, green and red (spectral compositions) parts. These parts really *appear* blue, green and red (qualia), a phenomenological fact that is outside science’s power to explain. The location 528 nm (dashed vertical line) is at ‘spectral green’. Cut at this wavelength one has a Schopenhauer-style bipartition of white that looks orange & teal (Fig. 6). At right the color matching functions obtained when one uses the three parts of white as fundamentals.

We make sure that a white and a black surface are present in the scene so as to “anchor the gamut” (Gilchrist, 1999). All colors are ‘shadows of white’, that is to say they scatter less than the white object at any wavelength. Formally all such colors can be obtained as convex combinations of three “parts of white” (Koenderink, 2010; Schopenhauer, 1816), namely blue, green and red.

There is a unique optimum way to define such parts (Note 17), that is by cutting the spectrum at 483 nm and 565 nm (Note 18). It yields the largest color gamut available for this setting. This spectral tripartition has a long history, by way of Goethe (1810), Schopenhauer (1816), Ostwald (1917, 1919) and Schrödinger (1920). See Fig. 5 and Bouma (1946) for formal and historical details).

The dominant wavelength of the blue part is 458 nm, of the green part 528 nm and of the red part 594 nm. The luminances (CIE, 1932) are in the (approximate) ratio blue:green:red = 7:55:38 and thus are mutually very different. However, phenomenologically the three parts are on a par. In terms of compositional weight the parts appear of similar importance (Koenderink et al., 2018b, 2018c).

Presented as equiluminant the parts look very unequal indeed. For instance, it is impossible to present a true yellow because no other hue can match its luminance. Equiluminance can indeed be achieved for beam colors, but not for object colors. Thus it fails to apply to images of natural objects or scenes.

In the case of object colors the notion of ‘luminance’ is best avoided. Luminance has no fundamental meaning in colorimetry proper anyway. Historically, it was introduced by the CIE as a definition for use in business and industry and has never had a solid scientific meaning (Note 19). In the context of object colors it is not even obvious how to apply the concept in a meaningful way.

Figure 6. Bipartition of white with cut locus at the dominant wavelength of the green part. This location coincides with the location of maximum chromatic power (the color content) of the parts. The two gradients are Goethe's 'Kantenspektren' (edge spectra), which are simply the cumulative radiant power of daylight starting from either end of the spectrum. This enables one to spot other interesting bipartitions, like yellow–blue and red–cyan.

By expressing any color as the additive combination of a fraction R of the red part, G of the green part and B of the blue part (all fractions being represented as numbers on the unit interval $\mathbf{I}$), one maps any color in the RGB-unit cube ($\mathbf{I}^3$).

This cube exhausts about two-thirds (63%) of the theoretical object color gamut, but the number of colors that do not find a place inside the cube is actually very small because such colors are extremely rare. Moreover, even colors that lie outside the cube still remain very close to it (Notes 20, 21).

Thus the RGB-cube is really a remarkably good approximation to the color solid gamut. All object colors of hunter-gatherer interest can be effectively represented. For designers and digital artists the RGB-cube simply represents color space *per se*. It fully exhausts the gamut they can work with.

For generic databases of object spectral reflectance factors we find that the RGB-cube amply contains the bulk of the colors (Note 22). The reason is that the spectra that cause such outliers are extremely unlikely to occur in nature (Note 23). Actual spectral reflectance functions are quite smooth and unlike the Schrödinger optimal colors (Note 24). Such outliers as appear in reality are completely irrelevant. Databases of spectral reflectance factors of 'natural' materials fit into the RGB-cube with (much) room to spare.

A simple non-linear transformation (Note 25) yields RGB-display colors (similar to sRGB; Note 26) such as populate many electronic displays. We use it in our illustrations.

Since RGB-colors are designed to represent object colors, it is really awkward to describe them in colorimetric terms that were designed for beam colors. Thus, the Ostwald coordinates color, white and black content are natural for object colors (Smith and Lyons, 1996), but cannot even be defined in straight colorimetric terms. Reasons are that black is ‘nothing’ (zero radiant power) and white depends upon context. Ostwald’s color, black and white contents make sense in a context where colors are ‘shadows of white,’ in the Goethean sense. That object colors imply situational awareness places them outside the realm of colorimetry proper.

Luminance is irrelevant to RGB. It applies to display technology and so forth. Luminance has nothing to do with object colors *per se*. It has no upper limit whereas the RGB-coordinates are constrained to a finite interval. Of course, one may notice one display to be brighter than another, but that does not seriously affect the colors one sees. Observers only notice it when the display units are presented side by side. That is an unnatural context in which the anchoring on black and white is lost (Notes 27, 28).

2.1.2. Chromatic Adaptation

Daylight is rarely CIE D65, for it may vary quite a bit over minutes, time of day and season. Fortunately, the white object stubbornly tends to look white. Anytime. This remarkable phenomenon is known as ‘chromatic adaptation’. Formally, it is described by a linear adaptive scaling, a generalization of von Kries’s Coefficient Law (von Kries, 1905).

Due to such ‘auto white balance’ (AWB, a term from camera technology) the RGB-coordinates of white are invariably $\{1, 1, 1\}$. The same holds for the black object with RGB-coordinates which are invariably $\{0, 0, 0\}$. For arbitrary objects the RGB-coordinates vary as the daylight varies. The good news is that this variation is minor (Note 29).

The assumption that the RGB-coordinates of all objects are invariant with respect to variations of daylight is formally incorrect, but happens to be ‘good enough for hunter-gatherer existence’ (Note 30). The reasons are ecological and physical.

2.1.3. Bipartition of White

Take some wavelength in the visual range and split the daylight spectrum at that wavelength into two parts. The parts will generally be colored and by construction mutually complementary, because they trivially add to white. The color content (Note 31) of the parts is the same, again, by construction. The

color content assumes a unique maximum at 528 nm (see Fig. 6), which happens to be the location of the dominant wavelength of the green part.

This unique bipartition yields the colors $R = 1.05$, $G = 0.5$, $B = -0.13$ and $R = -0.05$, $G = 0.5$, $B = 1.13$. Notice the under and overshoots! These colors lie on the boundary of the color solid gamut, thus (just) outside the RGB-cube. After clipping one has $R = 1$, $G = 0.5$, $B = 0$ and $R = 0$, $G = 0.5$, $B = 1$. Dominant wavelengths are 576 nm and 476 nm, that is, *orange & teal*.

Thus, the orange & teal bipartition of white is the most colorful bipartition available in the generic object colors context. The cut locus is at the green spectral location. Orange & teal are the major chromatic ‘parts of white.’ This renders this complementary pair colorimetrically unique.

2.2. Considerations of Ecology

2.2.1. Daylight

Daylight derives from the sun, even if the sky is heavily overcast. Daylight is sunlight filtered by the atmosphere augmented from scattered radiation from the terrestrial environment and from the sky. Thus, there are numerous factors that determine the spectral composition of daylight at any moment and place.

On a global view the ecologically relevant sources of radiation are thermal. They can be characterized by the temperature of the source, using basic statistical arguments (Note 32). The ecologically relevant temperatures range from just below 1000°K (glowing embers, Roman oil lamps running on tallow) to (much) less than the melting point of tungsten (3695°K). Spectra for even higher temperatures are based on ‘color temperature’, which is not a regular temperature, but rather a parameter in Planck’s formula. Examples are blue skies with color temperatures of 10,000°K and more (clear blue poleward sky up to 27,000°K). The thermal radiation varies from red, over white to cyan.

Figure 7 shows the beam colors as a function of the temperature, either the actual temperature of a source (Roman oil lamps 1500°K, incandescent light bulbs typically 2700°K up to 3200°K), or the (virtual) color temperature. On the hot end they do not get bluer than cyan, on the cool end they are really red.

Figure 7. The colors of thermal radiation as a function of (color-)temperature. At the cool side the color tends to red (glowing embers), at the hot side (even in the limit to infinite temperature) they tend to teal. This by-and-large covers the range of natural illuminations. Most variations of daylight in hunter-gatherer time are limited to a much narrower range centered on about 5500°K.

At about 5400° K the radiant power spectrum is almost flat. From a phenomenological perspective it is interesting that there is no contribution in the purple–green dimension.

On a more detailed view daylight is as unpredictable and capricious as the weather. Even worse so, it is affected by local factors, mainly the scattering from environmental objects.

In order to capture this one uses statistical models. A sufficient model has stochastic spectral slope and curvature. For random Gaussian processes the slope and curvature are mutually statistically uncorrelated (Born and Wolf, 1999). There is no need to add intricate jaggedness; these articulations average out due to the spectral widths of the human cone pigments.

Generating radiant spectra in the log-radiant power domain avoids non-physical effects, such as negative radiant power. This allows for very simple models (see Fig. 8.)

2.2.2. Spectral Reflectance Factors

The spectral region over which human vision works is really narrow. Of the chromatic power 99% is contained in the interval 398–682 nm, with the median at 505 nm (Note 33). That is about three-quarters of an octave.

This implies that the physics does not vary in kind over the visual range (Feynman *et al.*, 1964). The physics is due to chemical configuration changes. These are of major biological relevance. Atomic electronic transitions occur in the ultraviolet and molecular mechanics rules in the infrared. As a consequence, the statistics of spectral reflectance factors is translationally invariant along the physical spectrum. This allows for simple statistical models with excellent (statistical) predictive power. All we need to do is estimate the spectral correlation

Figure 8. A dozen random samples obtained with a simple variety of daylight generators. On our laptop we generate tens of thousands of samples a second.

Figure 9. A dozen spectral reflectance factors generated by a simple statistical model. On our laptop we generate thousands of samples a second.

length. It can be obtained from statistical study of object color gamuts, or even from images (Koenderink and van Doorn, 2017; Note 34).

Generating random reflectance functions is best done in terms of the ‘spectral signature’ from the scattering theory of turbid layers (Kortüm, 1969; Note 35). This avoids non-physical effects such as reflection factors outside the range $[0, 1]$. One transforms to the reflection factor domain using the Kubelka–Munk function (Kubelka and Munk, 1931; Note 36. See Figs 9–12).

The correlation length is of the order of the spectral width of the visual band. Thus, spectral articulations are heavily damped, minimizing effects of metamerism. This is what makes vision useful to the hunter-gatherer, since it implies that object colors are approximately object properties.

Blood is always red, bananas are always yellow, ripe blueberries are always blue. Such is the human condition (Note 37). This is very unlike the colors of the sky, which vary greatly with time of day and meteorological factors. From a biological perspective that is not problematic because these do not belong to the relevant environment.

2.2.3. *Metamerism*

Pick a fiducial point in the RGB-cube. Under standard daylight this color can be due to infinite, mutually different spectral reflectance factors. Pick one of these and illuminate it by all possible daylights. One obtains an infinity of mutually different RGB-coordinates. Putting this all together we find a volume surrounding the fiducial point. Any point in the volume is compromised in that there are circumstances in which it might be confused with the fiducial. This is known as ‘metamerism’ (Koenderink, 2010; Wyszecki and Stiles, 1967).

Figure 10. Random daylight colors (top row) and random object colors (bottom row). The daylight colors have been rendered maximally light (one of the coordinates equals one). The object colors are shown as illuminated by CIE D65 standard daylight. We show one mosaic in random order (left column) and one in sorted order (right column). (Because a three-dimensional cloud cannot be sorted in a two-dimensional order, the sorting is not perfect. Here we sorted first overall by hue, then per row by saturation.)

Fortunately for the hunter-gatherer, these volumes are smallish—though much larger than the JNDs (Note 38). See Fig. 13. The order of colors (Note 39) that can be mutually discriminated can be disarranged under a change of daylight. This implies that the psychophysical JNDs are irrelevant to the hunter-gatherer lifestyle. Distinct colors are colors that appear in the same order under arbitrary changes of daylight. Colors that are not ‘distinct’ in this sense but can be discriminated are useless as identifying tags.

Figure 11. A thousand computer-simulated random object colors. They approximately cluster about the orange & teal-plane.

Of course, such mutually different (at least in the actual setting), but technically not ‘distinct’ colors may well aid in spatial discrimination and so forth. However, that has nothing to do with colors as qualities (identifying tags).

We find that there remain somewhat over a thousand colors that can be mutually distinguished throughout the hunter-gatherer ecology. The regions of most confusion are near the green and purple vertices of the RGB-cube in the purple–green plane. Best distinctions are near the orange & teal plane.

Figure 12. Histogram of hue angles for a thousand random colors. Notice the pronounced peaks at teal (cyan–blue range) and orange (red–yellow range). (The hue- scale is partly redundant in order to present the periodic structure more clearly.)

2.3. Psychophysics and Phenomenology

Psychophysics does not yield much of a handle on the present issue, but experimental phenomenology does. In a study involving a group of Italian, naive subjects (Albertazzi *et al.*, 2015), we found that the basic cool–warm dichotomy appears prominently and in various ways when participants rate colors on scales of affective factors.

Results from culturally-dependent color naming are less clear (Lindsey *et al.*, 2015). One certainty is that color categories fail to be explained by the psychophysical JNDs. It appears that finer distinctions are made in the warm than in the cool, which is supposed to reflect the fact that relevant objects tend to be warm-colored, whereas backgrounds tend to be cool-colored (Gibson *et al.*, 2017).

Experiments on confusions in sorting color circles show that most confusions occur in the green-magenta dimension (Koenderink *et al.*, 2019). In a recent experiment on confusions in color successive reproduction (involving short-time color memory; Koenderink *et al.*, 2018a) we find that the linear size of confusion regions is as much as twenty times larger than the psychophysical JNDs suggest.

Figure 13. Confusion ellipsoids (95% level, three times enlarged for better visibility) due to metamerism of both spectral reflectance factors and daylight illuminants. We used a sample size of 10,000. For each sample we generate a fresh random reflectance and a fresh random daylight. We compute the color that derives from these. We also compute the color of the reflectance illuminated with the standard illuminant CIE D65. We define the difference of those two colors as a sample of the metameric difference at the location of the second color. We end up with a field of 10,000 such differences at random points in the RGB-cube. In the final analysis we compute the covariance ellipsoids at a number of locations in a regular body-centered cubic (BCC) lattice (91 possible locations). In order to do this we collect sample points in a small region around the point. Each ellipsoid is based on at least 100 samples, if the number of points in the small region is less, we omit that point. The spatial resolution (the region in which we look for at least a hundred points) is about the spacing of the BCC lattice points.

The teal–orange and green–magenta planes are evidently important features of the symmetry of RGB-space, but there is no clear empirical indication that resolution in the teal–orange dimension might be superior. The confusions in the warm region are much less than those in the cool region.

2.4. Preliminary Conclusions

We draw conclusions that pertain to the orange & teal issue. For these conclusions we need to take account of colorimetry (thus anatomy/physiology), physics and ecology, as discussed in the previous paragraphs. The main conclusions are:

- **The orange & teal dimension is the most colorful bipartition of white.** Figure 6 documents this remarkable optimum. The cut locus is the mid-point of the spectrum, the wavelength of ‘spectral green’ (Note 40).
- **The orange & teal dimension is abundantly populated.** More than three-quarters of all ‘natural’ object colors falls in the orange & teal category. The non-uniformity is very striking if one plots a histogram of hue angles (Fig. 12) and in the distribution over the RGB-cube (Fig. 11). This is predominantly due to the physics of spectral reflectance factors.

Figure 14. Distribution of hues in the foreground pixels (lower one-third of the image) of photographic images of ‘open landscapes’. We used 410 images from an open-source database. Notice the peaks at teal and (especially) orange. The ratio of teal–oranges to purple–greens is 2.65.

Similar results are found in databases of photographs of the natural environment. As an example we used a database of 410 ‘open landscape’ photographs (Note 41).

We used only the lower one-third of each image, thus the statistics is on data from the foreground. There is a pronounced dominance of orange & teal hues, with a strong emphasis on the oranges (Fig. 14). There can be little doubt that orange & teal (after black and white, of course!) dominates the natural environment.

The frequency of the RGB-coordinates in the database is $r:g:b = 100:95:70$. The counts of the teal–orange and green–purple instances are in the ratio 2.65:1. Thus the teal–orange articulations are almost three times as abundant as the green–purple articulations.

From the perspective of basic physics the dominance of teal–orange over purple–green is due to the correlation length of the articulation of the spectral reflectance factors. The empirical ecological statistics fit the predictions from the generic facts that the visual range is very narrow whereas the spectral correlation length exceeds its width. The teal–orange then dominates because it reflects spectral slope, whereas the purple–green reflects spectral curvature (Note 42).

This implies that the orange & teal fashion is due to a very basic property of human color vision on the intersection of physics (the world), the

physiology (the body) and qualia (the mind). Neither of these realms is able to deal with the issue without taking account of the others.

- **The orange & teal dimension is especially well resolved.** Metamerism is less of a problem in the orange & teal dimension than it is in other dimensions. Hunter-gatherers may have a good sense of animal (inside and outside), plant and earth colors. Metamerism hardly hurts.
- **The orange & teal dimension appears prominently in results from questionnaires focussing on affective factors** (Albertazzi *et al.*, 2015). It coincides with the conventional cool–warm dimension of the visual arts. The orange & teal and orthogonal green–purple dimensions appear prominently in confusions for color reproduction from short-term memory.

These observations apply to the generic cases. It is certainly possible to find singular outliers, although these are rare. A well-known instance from the hunter-gatherer lifeworld is the structural colors of many insects. A *Morpho* wing is not a well-defined ‘visual object’ (an invariant with respect to viewing conditions) but has a Dr. Jekyll and Mr. Hyde nature. Careful psychophysical experiments will detect minor deviations in perfect chromatic adaptation and so forth, especially near the limits of the generic parameter ranges. Formal models come up with cases in which metamerism causes confusion between roses (commonly thought of as ‘red’) and violets (commonly thought of as ‘blue’). Many more instances could be cited (Koenderink *et al.*, 2020).

Important and interesting as such cases are for the scientist, in no way do they affect the generic forces that drive the hunter-gatherer evolution. They do not hurt the biological fitness of the hunter-gatherer, because they are either of minor influence or of exceedingly rare occurrence.

Focusing on singular cases and small deviations from the rule is common (and frequently useful) in scientific research, but that should not blind one to the overall picture. We submit that the overall picture is pretty much what we presented here. Of course, there will be endless arguing about marginal cases. Our selection of the relevant and marginal facts was focused on the ecology of hunter-gatherer existence in savanna and tundra environments. Major differences are to be expected for different lifestyles and Umwelts – think of insects, birds or fishes. The issue is not physics, it is semiotical biology.

3. Orange & Teal in Pictorial Rendering

3.1. Painting

Painting is somewhat complicated in that it deals not just with color, but also with physico-chemical properties and interactions of pigments, binders and

substrates. For instance, it is very different for watercolor versus oil media. This tends to constrain the choice of colors, which is already limited to the commercially available pigments anyway.

We simply go on what we learn from artist-friends in the studio and what we glean from treatises on artists' methods.

In watercolors, Indigo (ca. #3FFF00), Burned Sienna (ca. #623034) and White Gouache are all one needs. It is amazing what can be achieved with so little. Of course, this is really an orange & teal palette.

In oils, popular limited palettes use white, black and orange & teal, although black is often obtained through a mixture of complementaries and a very deep blue may be obtained with Ivory Black. The orange might be Cadmium Orange (ca. #ED872D) or (more commonly) Burned Sienna, with Ultramarine Blue (ca. #120A8F) as complementary. Notice that greens may actually be mixed too, so such limited palettes are broader than might be expected at first blush.

The famous Zorn palette (after Anders Leonard Zorn, 1860–1920) has Yellow Ochre, Vermilion Red or Cadmium Red Deep, Ivory Black and Flake White. Sometimes Cobalt Blue would be added. It is really all one needs (Fig. 15). It has been emulated many times over. This is essentially an orange & teal palette too.

3.2. Image Processing

Given an arbitrary RGB-image (Foley *et al.*, 2005), how to convert it to a 'limited palette?' The most direct way is by way of the Ostwald system (as multiple times reinvented in computer graphics). One splits the image in a color content, a white content and a black content image (Bouma, 1946; Koenderink, 2010; Note 43). The 'color' is specified as a hue angle (Note 44; see Figs 16 through 18).

The hue angle can be 'summarized' in terms of just two complementary hues. One takes orange & teal. Then an RGB-image is synthesized using color and white content with the summarized hues. One obtains a dichromatic image

that contains the same results by setting $\{R, G, B\} \rightarrow \left\{ R, \frac{1}{2}(R+B), B \right\}$. This

effectively silences the green–purple channel. However, the method discussed here has more general applications. It is really remarkable that this works as well as it does (Note 45). One really needs to study the image intently in order to notice that all hues except two (!) are missing.

The result perhaps reminds one of Land's famous demonstrations from the nineteenfifties (Land, 1959). Most 'explanations' from that time apply to the present case too. Human vision apparently synthesizes a somewhat crippled color circle from only two, mutually complementary hues.

Figure 15. Anders Zorn (1860–1920), *The First Time* (1888). Finnish National Gallery. This is a good example of the use of Zorn's limited palette.

It is easy enough to do soft, or fuzzy, summarizing. Thus the orange & teal look can be attenuated or amplified arbitrarily. No problem to program this for smartphone applications. Indeed, one finds 'filters' (Note 46) galore for sale on the Internet. Orange & teal means business.

3.3. Monochrome 'Duo-Toning'

A very different case is that of the orange & teal *duotone*. Duotones (or tritones, quadtones, ...) are really monochrome images. One assigns colors to gray levels. For instance, one renders light tones orangish and dark tones teal-ish; see Fig. 19.

This actually works to 'colorize' monochrome images to some extent and has gained a certain popularity. It has been used as an artistic device in

Figure 16. A hue histogram of the image shown in Fig. 18 top. This is a Kodak[®] test image, supposed to show ‘all colors.’ In fact, orange & teal strongly dominate, with a heavy accent on orange. This is typical of the bulk of generic images (say family holiday snapshots).

old-fashioned analog and chemical photography since the late nineteenth century as so called ‘split-toning’ (Note 47).

4. Conclusions

The scientific investigation of the ‘Orange & Teal’ look yields a number of striking facts at the interfaces of physics, physiology, biology, ecology and phenomenology. The tight interlocking of facts of mutually distinct ontologies correlates with the biological evolution of *Homo*. Since we only enjoy a momentary glance of evolutionary history, we formally have to remain

Figure 17. For the original image see Fig. 18 top. At left the color content. This is just the image in which we switched all hues to red. Thus, higher color content is indicated by more red. At right the white content. More white is indicated by lighter graytone.

with the facts and treat the striking correlations between disjunct domains as accidental.

The ‘*Orange & Teal*’ look is indeed special. It is not that just any complementary pair (say red–turquoise or yellow–blue) would work out in a similar fashion. Thus we need not be surprised at the current Hollywood craze (Note 48). It is simply a continuation of familiar methods from art history by other means – intentionally, or by accident. Modern technology, especially in image processing (even ‘in camera’) is certainly a game changer (Note 49).

In our analysis we wield tools that focus on the human Umwelt and life-world. This is rare in mainstream colorimetry and psychophysics. It is for this reason that we needed to draw on ideas from the dark ages of color science (Runge, 1810; Goethe, 1810; Schopenhauer, 1816; Maxwell, 1855; von Helmholtz, 1855, 1867; Ostwald, 1917, 1919; Hering, 1905–1911; and Schrödinger, 1920) that are rarely referenced, let alone used, in current work, except as a display of erudition or in historical reviews.

Many of these authors were genuinely interested in object colors as seen under natural daylight. These are most relevant to the life-world. Perhaps unfortunately, such a focus does not naturally fit the current colorimetric frameworks very well. However, the latter formalism can certainly be applied, albeit in an unconventional manner. At least, that is how it would appear to the mainstream. The reluctance derives from the common rejection of phenomenological facts by the sciences.

This focus is particularly relevant to the visual arts, past and present. The warm–cool dichotomy is fundamental in the visual arts. Colorimetry as such is unable to single out such a dimension in a principled way. As expected, the warm–cool dimension frequently pops up as special in the phenomenology of object colors. We submit that a biological focus on colorimetry in the context of the hominin Umwelt and lifestyle – that is roughly where evolution left our

Figure 18. Top original image, Kodak® Test Image 28. At bottom an orange & teal rendering. This is a true dichromatic image, no other hues but orange & teal. You have to compare details in order to appreciate the difference. At first blush the images look very similar.

Figure 19. An orange & teal duotone. For the original image see Fig. 18 top. Here we use a monochrome version of the original. Light parts are tinted orangish, dark parts tealish, the precise tint gradually changing with tone. Near the endpoints of the scale hardly any hue is added, thus white remains white, black remains black. Most tinting is done in the mid-tones. At left for each graytone on the horizontal axis the color, white and black components have been indicated in the vertical direction. At right the orange & teal gradient was inserted in the color component. There is not more information than in the black & white original, but the image looks colored.

visual systems – should be assumed in studies on color in the visual arts. Such a focus also properly applies to experimental phenomenology.

The bottom line is that Hollywood’s apparently superficial orange & teal craze happens to reveal – from a proper biological perspective – an intricate tangle involving:

- **world**, the articulations of generic radiant and reflectance factor spectra
 - **body**, as represented by basic colorimetry
 - **mind**, the awareness of the chromatic qualities of things
- as a holistic, inextricable trinity.

Acknowledgements

The work was started at the Department of Psychology, Justus Liebig University, Giessen, Germany. We are grateful to Karl R. Gegenfurtner for providing a congenial environment. Jan Koenderink was supported by the Alexander von Humboldt Foundation and gratefully acknowledges the support of the Miller Institute at the University of California at Berkeley. The work was supported by the program by the Flemish Government (METH/14/02), awarded to Professor Johan Wagemans.

Notes

1. Both the & sign and the sequence are ignored by the Google search algorithm.
2. <https://en.wikipedia.org/wiki/Teal>.
3. <https://fixthephoto.com/orange-~\&~teal-lut>.
4. <https://petapixel.com/2017/02/23/orange-teal-look-popular-hollywood/>.
5. <https://theabyssgazes.blogspot.com/2010/03/orange-~\&~teal-hollywood-please-stop.html>.
6. The conventional designation is hexadecimal, with RGB-coordinates running from #0 to #FF. Thus #FF7F00 is understood as {#FF, #7F, #00}, or (decimal) {255, 127, 0}. Since 0 (or 00) is supposed to be nothing and 255 everything, we may finally read #FF7F00 as ‘full red, half green, no blue.’ Why the hassle? Because #FF7F00 is the format typed into code and widely used on the Internet to identify colors. For modern designers and digital artists it is the bridge between color in intuition and as computer description.
7. Throughout the paper we use terms like ‘biological perspective’ to indicate what might be called ‘hominin ethology’. It is semiotics rather than anatomy/physiology (von Uexküll, 2010).
8. Another common term for ‘reflection factor’ is ‘albedo,’ literally ‘whiteness’. We use reflection factor, although the optical process is diffuse scattering, rather than specular reflection.
9. That is the sodium D-doublet, i.e., the radiation emitted by the sodium vapor lamps used in urban environments for economic reasons.
10. There exist two versions of this programmatic painting. Runge planned four large oil paintings for a major project (on the *Tageszeiten*). The project never materialized, as Runge died in 1810. *Der kleine Morgen* (1809/1810) is at the Hamburg Kunsthalle. We consider the painting to be a major station in the history of color science.
11. The gray card reflects 18% of the incident light, the lunar surface has an average albedo of only 12%.
12. As the eidolons in the Lucretius *Rerum Natura* (Zucca, 2020).
13. Introduced in subsection 2.1. *Considerations of Colorimetry*.
14. In the sense that they can be reproduced from short-term memory. This makes biological sense, whereas the psychophysical just noticeable differences (MacAdam, 1942) do not.
15. This is about ‘basic color terms’ (Berlin and Kay, 1969). Note that words like ‘orange’ (an object), ‘dark green’ (a variety of green) or ‘lusty galant’ (name for a pale shade of red in the late 1500s in England) do not count as basic color terms. If one were less strict one would end up with the dictionaries of color names that run up into the many thousands. At

<https://codepen.io/meodai/full/VMpNdQ/> you find a convenient dictionary of 25,810 color names. For each it has the hex code. It is by no means ‘complete’, for we could not even find ‘lusty gallant’. But we did not know that ‘Lily of the Nile’ is #9191BB. And so forth.

16. In our part of the world an artist’s studio would be a spacious room with large window facing the North sky, the walls washed white or yellowish (to beat the blue cast of the North sky).
17. The gamut of object colors is contained in Schrödinger’s color solid, a centrally symmetric, convex volume. The optimum RGB-cube is the inscribed parallelepiped of maximum volume (Koenderink *et al.*, 2020).
18. As computed for the CIE D65 illuminant (Koenderink *et al.*, 2020).
19. The Commission Internationale d’Eclairage (CIE) adopted the standard photopic observer in 1924.
20. The blue coordinate may theoretically over- or undershoot by 0.07, the green coordinate by 0.19 and the red coordinate by 0.17. The worst deviations occur for strong tints and shades. For the red, green and blue ‘parts of white’, the most colorful RGB-colors, the under- and overshoots are – by construction – zero. That is because they lie on the surface of the object color solid. For the ‘full colors’ (or ‘semichromes’), the object colors with the maximum chromatic power, the under- and overshoots are limited to 0.059 in the blue, 0.13 in the green and 0.14 in the red.
21. The lack of fully saturated reds can – with very careful observation – be visually noticed. This observation has been used in the past as an argument against the Ostwald system (Bouma, 1946). In practice the fully saturated reds are not available as physical object colors, so the comparison is with spectrally very selective beam colors.
22. Typically under- or overshoots up to about 0.05 for less than about 3% of the colors.
23. They are Schrödinger optimal colors (Bouma, 1946; Schrödinger, 1920) with spectral reflectance either zero or one and no more than two transitions between these levels.
24. The Schrödinger ‘optimal colors’ are colors on the boundary of the color solid gamut. That implies that they are of maximum brightness as an object color.
25. Clipping to the unit interval and a ‘gamma correction’.
26. The official specification of sRGB is IEC 61966-2-1:1999. The fourth working draft can be downloaded at www2.units.it.
27. Conventional colorimetric methods (Centore, 2017) start from spectral radiances, thus are keyed on beam colors. The generic example is CIE XYZ (Schanda, 2007; Smith and Guild, 1931–1932). Methods keyed to object colors start from spectral reflectance factors. The best-known example is the Ostwald system (Ostwald, 1917).

28. The CIELAB system (in common use) derives from the beam color perspective but arbitrarily sets an upper limit to luminance. Yet it is not keyed for object colors because it ignores the object color solid. The CIELAB system is purportedly ‘perceptually uniform’. This uniformity is largely derived from the Munsell system (Munsell, 1905), which is originally a phenomenological metric, not based on object color optics, nor on psychophysics. This scaling renders the system strongly nonlinear, so it is essentially unfit for generic colorimetric purposes.
29. Both the color solid and the RGB-cube depend upon the illuminant spectrum. It is very unlikely that the physiological implementation would somehow follow that. Much more likely is that the RGB-system is fixed, like in a phone camera. There is indeed no evolutionary pressure to do otherwise, because automatic white balance makes that the ‘ideal’ color solid is for all practical purposes not different from the one for CIE D65 daylight, at least for a range of color temperatures from 2500°K to (virtual) infinity.
30. Here the measure is the practical power of color discrimination as evident from the accuracy in reproduction from short-term memory.
31. The ‘color content’ of the color $\{R, G, B\}$ is defined as $\text{Max}[R, G, B] - \text{Min}[R, G, B]$. The ‘supplementary’ (thus also ‘complementary’) color is $\{1 - R, 1 - G, 1 - B\}$, which is easily seen to have the same color content.
32. That is Planck’s treatment of the photon gas in thermodynamic equilibrium.
33. Half of the chromatic power is contained within 456–578 nm, a relative bandwidth of only 0.24. That amounts to a third of an octave. Such numbers derive from considering the white content of the RGB-colors of (connected) spectrum regions.
34. We use the autocorrelation function.

$$R(x, \tau) = \frac{e^{-\frac{|x|}{\tau}}}{\tau} (|x| + \tau),$$

which derives from the superposition of pulses from a renewal process on the wavelength axis with Laplacean pulse shape

$$\frac{e^{-\frac{|x|}{\tau}}}{\tau}.$$

The correlation halfwidth is approximately 1.68τ .

35. Technically K/S , that is the ratio of the absorption and scattering cross-sections.

36. One has that

$$\frac{K}{S} = \frac{(1-R)^2}{2R},$$

where R is the reflectance factor of an optically thick layer.

37. When no holds are barred – no ecological constraints – it is formally possible to create conditions under which an invisible change in the natural ‘white light’ would not affect the white of a daisy, but would swap the red and blue of the rose and violet (Koenderink *et al.*, 2020). It is the reason why many philosophers assert that colors are not object properties (Block, 2003; Byrne and Hilbert, 2003). But biologically speaking, they are.
38. In this simulation the median major axis of the ellipsoids is 0.04. There is room for about a thousand to two thousand distinct colors.
39. Technically, four colors can be said to get ‘out of order’ if the volume subtended by them changes orientation. Intuitively this implies being ‘pulled inside-out’ in RGB-color space.
40. ‘Spectral green’ is 528 nm, the dominant wavelength of the green part and in the range of reported ‘unique green’.
41. Available from an MIT site (Torralba and Oliva, 2002).
42. The covariance matrix for the RGB-coordinates, as found in photographs of the natural environment, is approximately modeled by

$$\begin{pmatrix} 1 & \rho & \rho^2 \\ \rho & 1 & \rho \\ \rho^2 & \rho & 1 \end{pmatrix},$$

where $\rho = 1 - \varepsilon$ with $0 < \varepsilon \ll 1$ (Koenderink and van Doorn, 2017). A typical value is $\varepsilon \approx 0.1$. This captures the effect of the long correlation length in the simplest manner. To the lowest relevant order the ratio of the eigenvalues is

$$1 - \frac{8\varepsilon}{9} : \frac{2\varepsilon}{3} : \frac{2\varepsilon}{9}.$$

The corresponding dimensions are $\{1, 1, 1\}$ (black–white), $\{1, 0, -1\}$ (teal–orange) and $\{1, -2, 1\}$ (purple–green). For $\varepsilon = 0.1$ the eigenvalues are in the ratio 0.9:0.075:0.025. Thus the teal–orange dimension has three times more power than the purple–green dimension, whereas the black–white dimension dominates: only 10% of the power is chromatic. This is perhaps the simplest model that explains the ecological statistics, at least in an approximate sense (Koenderink and van Doorn, 2017).

43. One of these is superfluous, because these images add to uniform white. For display purposes it tends to be most convenient to ignore the black content (black is for free, even if the display is off), although the printer

- will rather ignore the white content (the white of the paper comes for free) – it makes no formal difference.
44. Here ‘angle’ refers to the color circle, that is the phase along the red–yellow–green–cyan–blue–magenta polygonal loop on the RGB-cube, of total length six. To use a number modulo six is preferable given the structure of RGB-space, but 2π is less than 5% different from six, so in practice there is hardly a difference.
 45. Of course, this image is already ‘keyed’ to orange & teal (as evident from Fig. 16). But that is true of almost any generic image (this is a Kodak[®] test image, displaying all colors!).
 46. Mainly aimed at the tyro photographer who desires a Hollywood look.
 47. The selenium toning used by Ansel Adams (1902–1984) became famous (see Adams, 1948, 1950). It was originally a by-product of improving the archival quality of his prints.
 48. It apparently started with *Oh Brother, Where Art Thou?* (2000), directors Joel & Ethan Coen (‘the Coen brothers’) and cinematographer Roger Deakins. From an artistic and color vision perspective this movie is a must-see.
 49. In the case of the aforementioned Coen brothers movie the complete film was converted digitally (‘DI,’ that is Digital Intermediary) into the orange & teal look. CINESITE used a chroma-key algorithm (Sang and Vinh, 2013) to turn the Mississippi summer green into a light golden brown, caucasian skin turning orange.

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