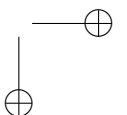
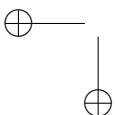
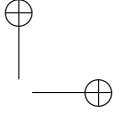
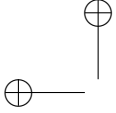


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On the color of transparent substances

Christian Kaernbach¹ & Christian Dörre

Light passing through layers of various thickness of a transparent substance shows a stunning variability not only of brightness and saturation, but also of hue. The color may depending on the thickness of the layer cycle through all possible hues. An example of a hue shift from yellowish green to saturated red is demonstrated for an everyday liquid (pumpkin seed oil). When naming the possible colors of this liquid from memory, participants avoid to name opponent colors. When experimenting with pumpkin seed oil, most participants overcome this reservation and name both reddish and greenish hues. The sometimes surprising hues of transparent substances depending on layer thickness (e.g. saturated red for thick layers of chlorophyll) can be understood on the basis of the interaction of the broadband cone-sensitivity functions with the extinction spectra. The utter variability of the hue of transparent substances runs counter to our intuitions on color as a property of a substance.

Keywords: color perception, hue, transparent substance, color naming

1 Introduction

To the naive observer it appears as if the color of a substance is a physical property of this substance and independent of the observer. Color scientists, however, know the famous citation of Isaac Newton “For the rays to speak properly are not coloured” (Opticks, 1730). More than hundred years earlier, and related to the color of substances, Galileo Galilei states

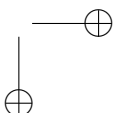
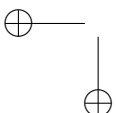
Per lo che vo io pensando che questi sapori, odori, colori, etc., per la parte del soggetto nel quale ci par che riseggano, non sieno altro che puri nomi, ma tengano solamente lor residenza nel corpo sensitivo, sì che rimosso l'animale, sieno levate ed annichilate tutte queste qualità. (Il sagggiatore, 1623)

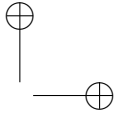
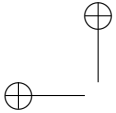
I think, therefore, that these tastes, odors, colors etc., with respect to the object that seems to house them, are mere names; they exist only in the sensitive body, because if life is removed, all of these qualities would be carried off and annihilated.

There are numerous arguments emphasizing the subjective nature of color, based, e.g., on the different genetic dispositions of different observers to perceive color (Sharpe, Stockman, Jägle & Nathans, 1999). Within a single observer, however, the color of opaque objects seems to be a well defined property: in most situations it is time invariant, place invariant, and invariant to illumination changes (see e.g. Lennie & D’Zmura,

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1988; Kraft & Brainard, 1999). Gibson (1973) was the first to emphasize the role of invariants for perception. But is color really that invariant? The present contribution demonstrates that in the case of transparent substances the observed color may within a single observer change drastically in brightness, saturation, and even hue, including the transition to opponent colors.

2 The memory color of pumpkin seed oil

Pumpkin seed oil is a culinary specialty of Styria, Austria. In a glass held against a candle it appears to be of a dark saturated red color, but thin layers or stains are yellowish green. Red and green are considered to be opponent colors (Hering, 1878). How could a liquid at the same time be red and green? The first study aimed at collecting data on the memory color of pumpkin seed oil.

2.1 Method

An online survey was integrated into a course for third-year psychology students at Graz university. Participation was voluntary. No personal data were collected. Therefore, the age range and gender distribution is unknown but should correspond to that of a third-year psychology class at Graz. It may safely be assumed that most of the participants ($N = 56$) were from Styria and well acquainted with pumpkin seed oil.

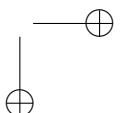
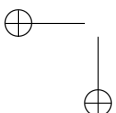
The survey comprised 11 possible color names. These corresponded to the so-called focal colors defined by Eleanor Rosch Heider (1971). Participants were first asked to tick a single color. In a second pass they should tick all colors that would come to their mind in connection with pumpkin seed oil.

2.2 Results

Figure 1a shows the frequency of color naming with a single or multiple choice. When participants were asked to make a single choice, 36 out of 56 participants choose green as the color name for pumpkin seed oil. When given the possibility to name several colors, green is still the color name that comes most often ($n = 50$), but also black ($n = 43$) and brown ($n = 40$) are named very often. Red is named by only four participants in the second condition.

2.3 Discussion

This first experiment demonstrates very clearly that the most prominent memory color for pumpkin seed oil is green. Even if given several response options, red is named very rarely.



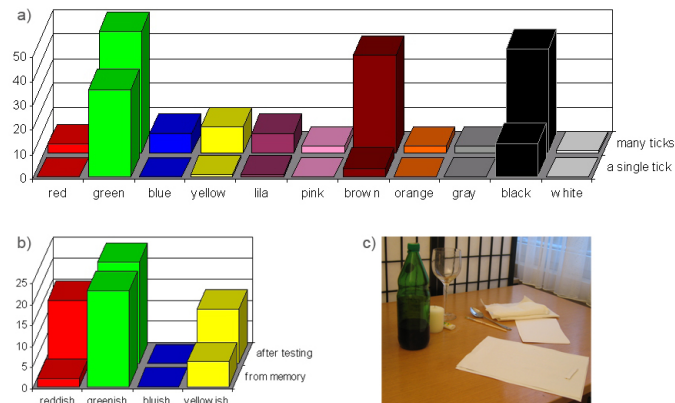


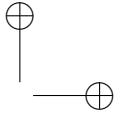
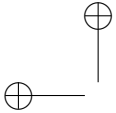
Fig. 1: Frequency of color naming for pumpkin seed oil. a) Single or multiple choice from the focal colors after Rosch Heider (1971). b) Color naming (opponent colors) from memory versus after testing. c) Materials participants could use for testing pumpkin seed oil color.

3 Trying one's hand on the color of pumpkin seed oil

The rare naming of red in the first study may be due to the fact that psychology students in their third year know that green and red are opponent colors and hesitate to attribute those opponent colors to the same substance. Any impression of red that there might have been memorized was probably absorbed by the color brown which may well represent reddish hues without rising associations to opponent colors. The second study tries to overcome this hurdle by reducing the number of choices and by offering the participants the possibility to experiment with pumpkin seed oil before making their ticks.

3.1 Method

In order to focus the query to the opponent color aspect, the second query offered only four response alternatives. The names of the four opponent colors were modified by adding an "ish" to them (reddish, greenish, bluish, yellowish), in order to facilitate the attribution of a certain name to a substance with a non-saturated color. First, this query was presented to the participants ($n = 25$) as a memory task. Participants could tick as many colors as they wanted. Then participants were lead behind a screen where they found a bottle of pumpkin seed oil, white paper, a paint-brush, a spoon, a glass, a candle, and a lighter (see Fig. 1c). They were encouraged to test the color of pumpkin seed oil. No further hints were given. When they were done they were asked to make their color choices again on a second version of the same color questionnaire. In addition, they were asked what they have done in order to determine the color of pumpkin seed oil. The experimenter took note of their report.



3.2 Results

The actions performed by the participants included spreading oil with the paint brush on white paper, filling the spoon, filling a portion of pumpkin seed oil into the glass and holding that glass against the light of the lighter. Figure 1b shows the frequency of color naming from memory and after testing. From memory, participants again name green most frequently ($n = 23$). Red is named only rarely ($n = 2$). After testing, however, red is named by 15 of 25 participants. This increase can not be attributed to social desirability of multiple color naming, as there is no increase for blue ($n = 0$).

3.3 Discussion

In view of their own experiments with this oil, 60% of the participants abandoned their reservations to name pumpkin oil in opponent colors at the same time. Pumpkin seed oil seems to be red and green, for the same observer, and with the same sample of oil. How can this be? The next section treats the physics and physiology of the color of transparent liquids.

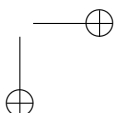
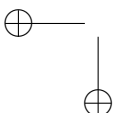
4 The color of transparent substances

We have already mentioned that in most situations the color of opaque objects is time invariant, place invariant, and invariant to illumination changes. For transparent substances such as liquids there is another parameter of importance: transparent substances come in varying thickness. It is evident that this will affect at least two parameters of color perception: brightness and saturation. A very thin layer of a liquid will in general not absorb much light so that the passing light remains bright and of unsaturated color. The thicker the layer, the more light will be absorbed. The remaining light will be less bright and more saturated. It would, however, correspond to our intuition if the remaining parameter of color perception, color hue, would be invariant of layer thickness. In this case the hue of a transparent substance would be a well-defined property of that substance, at least for a specific observer.

As we have seen, this seems not to be the case. Pumpkin seed oil changes its hue drastically, not shrinking away from “illegitimate” transitions between opponent colors. The following sections will treat first simplified and then more realistic models of color vision which show increasing degrees of hue variability for transparent substances.

4.1 Two monochromatic receptors

Imagine a color system that depends on two monochromatic receptors, one being sensitive to light with the wavelength λ_1 , and the second type being sensitive to wavelength λ_2 . The intensity of the light passing through 1 mm of that substance will be damped by a factor of $\alpha < 1$ at wavelength λ_1 , and by a factor of β at wavelength λ_2 . The intensity I_{λ_1} of the light at wavelength λ_1 is a power function of the layer



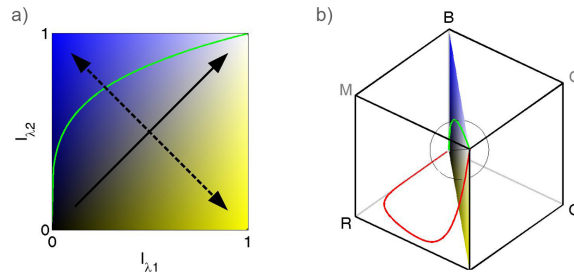
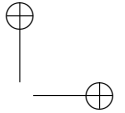
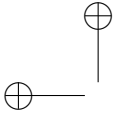


Fig. 2: The color of a transparent substance of varying thickness in monochromatic color models. a) Two-dimensional monochromatic model. Color is described as point in a square. For infinitesimal thin layers, the color of the liquid is white (top right-hand corner). With increasing thickness, brightness (solid single-headed arrow) decreases and saturation (dotted double-headed arrow) increases. b) Three-dimensional monochromatic model. Color is described as point in a cube. The two-dimensional model is included as plane within that cube. For infinitesimal thin layers, the color of the liquid is white (corner pointing to the reader). With increasing thickness, brightness decreases and saturation increases. The hue (a cyclical variable, thin circle) may change slightly without crossing the borders defined by primary and secondary colors.

thickness ρ : $I_{\lambda_1} \propto \alpha^\rho$. For the other wavelength we get $I_{\lambda_2} \propto \beta^\rho$. We can then relate the two intensities to each other. The relation between them is again a power law: $I_{\lambda_2} \propto I_{\lambda_1}^{(\ln \beta / \ln \alpha)}$.

Figure 2a shows an example of the course of the light intensity at the two wavelengths with increasing layer thickness—assuming equal intensity at the two wavelengths for the unfiltered light. At the top right-hand corner, the light is not attenuated at all, as with an infinitesimally thin layer. With increasing thickness, I_{λ_1} is reduced faster than I_{λ_2} . The brightness (solid arrow) decreases, and the saturation (dotted double arrow) increases. If saturation is defined as nearness to the outer axes, it increases continually with increasing thickness, until maximally saturated but very dark light remains for thick layers (lower left-hand corner). The hue is in this model a dichotomic parameter, taking two values: above or below the diagonal. For reasons of simplicity let's refer to these two values as blue and yellow. The hue does not change as a function of layer thickness. Either the entire curve is above the diagonal ($\alpha < \beta$, blue hue), or it is below the diagonal ($\alpha > \beta$, yellow hue). Starting with colorless (“white”) illumination, there is no way how the curve could ever cross the boundary between the two hues (defined as the diagonal, i.e. the line of equal illumination of the two receptors). In a color system of this type, substance hue would be a well-behaving property of a substance.



4.2 Three monochromatic receptors

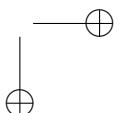
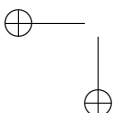
The situation changes slightly if taking into account a third receptor, sensitive for wavelength λ_3 . Again, the intensities are power functions of the thickness, and of each other. The hue is now no longer a dichotomic variable. It is a cyclical variable, rotating around the brightness axis within a three-dimensional color cube. Given three different attenuation coefficients, the hue is no longer constant as a function of layer thickness. Figure 2b shows an example. With the color labels attached to the corners of the three-dimensional color cube, we can describe the course of the hue as a function of layer thickness as follows: It starts in the $(1, 1, 1)$ corner (white, pointing towards the reader). It then approaches yellow, because apparently the blue receptor is damped more strongly than the other two. For medium thick and very thick layers there is no longer any blue light in the light passing through the substance. The rest of the curve is nearly within the bottom face of the cube. Here the curve approaches the red corner, because the green absorption is stronger than the red absorption. Once nearly all green is absorbed, the color approaches the $(0, 0, 0)$ corner (black) nearly within the red axis.

Brightness is again on the axis between black and white. Saturation can again be defined as nearness to the external surface of the cube. Both parameters change the same way they did in the two-receptor model: with increasing thickness brightness goes down and saturation increases. Hue, however, is no longer constant. It can be considered as a cyclical variable (indicated by a light gray circle in Fig. 2b). The value of this variable changes as the layer thickness increases. There are however limits to the changes that can be produced by such a monochromatic three-receptor model. Starting with white illumination at zero thickness, the hue will always stay within one sextant of the hue circle. It will never cross a boundary as defined by the planes where two receptors are equally illuminated. In a color system of this type, substance hue would be a medium-well-behaving property of a substance.

Pumpkin seed oil seems to show by far more hue variability than predicted by the three-dimensional monochromatic model. The color phenomena observed with this liquid require a more sophisticated model.

4.3 Three broadband receptors

The receptors of the human color system are not only sensitive to a single wavelength, but to a broad scope of wavelengths (see Fig. 3a, sensitivity data from Stockman, MacLEod & Johnson, 1993). They are even overlapping for huge parts of their sensitivity regions. For the present problem, however, the overlap is not important. The important point is the integration of light over a certain range of the spectrum. If such a broadband detector is activated by light passing through an inhomogeneous filter, i.e.



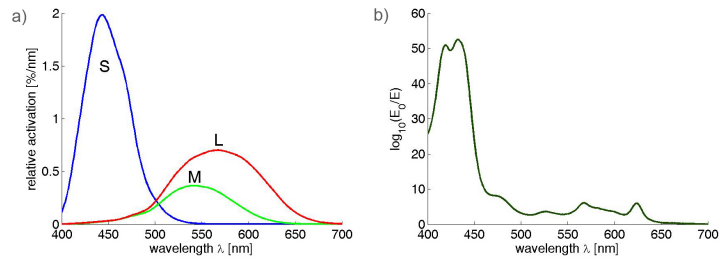


Fig. 3: Broadband sensitivity and extinction spectra. a) Cone sensitivity for S, L, and M cones. b) Extinction spectrum of pumpkin seed oil.

a filter that treats light of different waveforms differently, the power law of receptor activity as a function of layer thickness of this filter is invalidated.¹

Figure 3b shows the extinction spectrum of a sample of pumpkin seed oil. We recorded this spectrum at Graz university. It was the same pumpkin seed oil that was used in study 2. The relevant observation is that in a region where the L receptor is still sensitive ($\lambda > 650\text{nm}$) pumpkin seed oil does not absorb anything. This “window” is responsible for the red shift of thick layers of pumpkinseed oil as here light will pass through even for thick layers of this liquid that do not let pass light of other wavelengths.

The exact course of the hue of a transparent substance as a function of its thickness can be depicted in the isoluminant *l-s* color plane (MacLeod & Boynton, 1979). Figure 4a shows this color plane in linear coordinates. The area of available colors is circumscribed by the line given by monochromatic excitation, i.e. by maximally saturated light. This line is then complemented to the total area of possible colors (white area) by building the so-called convex hull, i.e. all colors that could be built by mixing colors from the monochromatic border. The point of zero saturation (“white point”) is in this representation very close to the bottom axis of the diagram. It is connected to the so-called unique hues by straight lines. These unique hues vary slightly between observers and depending on the method used to measure them (Kuehni, 2004), but the variability is small as compared to the effects observed for transparent colors (see below). The unique hue curves plotted in Fig. 4 were calculated taking the medians of the studies cited in Kuehni (2004) for the respective colors.

¹ Only under very special constraints for extinction spectra and photoreceptor sensitivity (Gaussian idealization) would broadband receptors follow the power law (MacLeod & Golz, 2003). Apparently, this idealization fails to describe real world absorption and receptors.

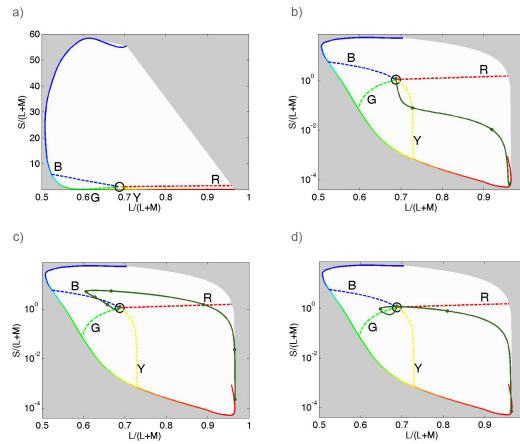


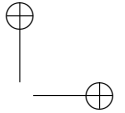
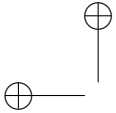
Fig. 4: Two-dimensional isoluminant $l-s$ color plane. a) Linear coordinates. Four dotted lines connect the white point (circle) to four unique hues. b) The s -axis scaled logarithmically. Formerly straight lines are now curved. The color of layers of pumpkin seed oil of varying thickness is indicated by the solid line starting at the white point. The nodes on this line indicate orders of magnitude in brightness (compare Table 1). c) and d) The color course of chlorophyll A and B.

Table 1

Layer thickness for pumpkin seed oil and solutions of chlorophyll (1mg/l) that lead to certain brightness reductions (cf. also Fig. 4b-d).

Brightness	Layer thickness for		
	Pumpkin seed oil	Chlorophyll A	Chlorophyll B
10^{-1}	0.3 mm	1.5 m	1.5 m
10^{-2}	0.9 mm	3.2 m	4.7 m
10^{-3}	3.5 mm	5.2 m	46.0 m
10^{-4}	10.0 mm	7.8 m	
10^{-5}		12.0 m	
10^{-6}		20.0 m	
10^{-7}		29.0 m	

In order to have a better representation of the perceived colors in this isoluminant $l-s$ plane it is common practice to plot the s -axis logarithmically (Fig. 4b-d). Please note that in this representation formerly straight lines (e.g. the lines of unique hues, or the right border of the convex hull) are now curved. Figure 4b shows the course of the hue of pumpkin seed oil of varying thickness in the isoluminant $l-\log(s)$ plane. This course was calculated using the sensitivity data of the three types of cones (Fig. 3a) and the extinction data for pumpkin seed oil (Fig. 3b). The nodes in the hue curve correspond to orders of magnitude in the brightness. The hue curve starts for thin layers in the sector between unique green and unique yellow, which corresponds



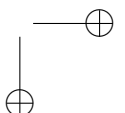
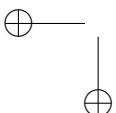
to the olive green type of hue so characteristic for pumpkin seed oil stains. It passes the border defined by the unique yellow curve at a total extinction of 90 % (first node of hue curve), and ends far in the red region (extinctions of 99 % and 99.9 %). Table 1 shows the thickness of the layers for the nodes of the hue curve. Layers of about 1 mm show a deeply saturated red hue. Stains must obviously have less than 0.3 mm equivalent thickness in order to have a greenish appearance.

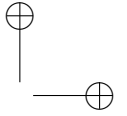
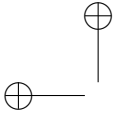
This drastic change of hues is not specific for pumpkin seed oil. Figure 4c and 4d show the course of the hues for different thicknesses of layers of a solution (1mg/l) of Chlorophyll A and B. Chlorophyll A is known as the bluish chlorophyll, and indeed does the hue pass from green to blue (e.g. node 2, thickness 3 m) but goes then on to red (node 5, 12 m). Except for yellow, no unique hue is left out during this stroll through color space. Chlorophyll B is also named the yellowish chlorophyll, with its hue passing from yellowish green to slightly bluish green (node 1, 1.5 m), passing the zero-saturation point, and ending again in the deeply saturated red region (node 2, 5 m). It is astounding to learn that the world's most frequent green dye can be blue, red, and yellow, depending on the thickness of the layer. The hypothetical solution density (1mg/l) corresponds approximately to that of green tea, so plunging into a deep pool of green tea would be revealing.

5 Discussion

The human color vision system has evolved in contact with mostly opaque objects. It is therefore not surprising to find that it fails to extract invariant hue from transparent substances. This failure tells us that color is not a property of objects or substances but a low-dimensional construct we make of those high-dimensional spectra, in a way that is appropriate to get some reliable information on opaque objects. It is astounding in how far our intuition on such basic percepts as color can err: Intuitively we would erroneously assume that the hue of a liquid is a good descriptor of this substance.

It would be worthwhile to consider the role of action in color perception. The big increase in opponent color naming of pumpkin seed oil (see Fig. 1b) was due to the possibility to play with the liquid. The more we experience the various aspects of a colored substance, including its gloss, iridescence, opalescence, and its aspects in various thicknesses, the more we get a complete view on the color properties of this substance, leading to a construct which is by far more complex than the classical three-dimensional color construct. Our knowledge on the "coloricity" of a substance would thus strongly depend on what we have done to or with the substance. We might finally consider classical three-dimensional color as a small facet of a knowledge database on "light behavior" of a substance that would depend strongly on the personal experience of the observer.





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