Article

PERCEPTION

Perception
2015, Vol. 44(10) 1153–1178
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DOI: 10.1177/0301006615594700
pec.sagepub.com
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Chromatic Dimensions Earthy, Watery, Airy, and Fiery

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Abstract

In our study, for a small number of antonyms, we investigate whether they are cross-modally or ideaesthetically related to the space of colors. We analyze the affinities of seven antonyms (*cold–hot*, *dull–radiant*, *dead–vivid*, *soft–hard*, *transparent–chalky*, *dry–wet*, and *acid–treacly*) and their intermediate connotations (*cool–warm*, *matt–shiny*, *numb–lively*, *mellow–firm*, *semi-transparent–opaque*, *semi-dry–moist*, and *sour–sweet*) as a function of color. We find that some antonyms relate to chromatic dimensions, others to achromatic ones. The *cold–hot* antonym proves to be the most salient dimension. The *dry–wet* dimension coincides with the *cold–hot* dimension, with dry corresponding to hot and wet to cold. The *acid–treacly* dimension proves to be transversal to the *cold–hot* dimension; hence, the pairs mutually span the chromatic domain. The *cold–hot* and *acid–treacly* antonyms perhaps recall Hering's opponent color system. The *dull–radiant*, *transparent–chalky*, and *dead–vivid* pairs depend little upon chromaticity. Of all seven antonyms, only the *soft–hard* one turns out to be independent of the chromatic structure.

Keywords

Chromatic dimensions, antonyms, cross-modality, ecological factors, experimental phenomenology

It has been reported that persons in *delirium tremens* occasionally perceive pink elephants and blue mice (London, 2009, Chapter 2), and the weirdness of the experience is heightened by the fact that the animals are felt to have the *wrong colors*. At least, an informal inquiry suggests that many people like mice to be pink and elephants to be blue. Why might such feelings arise?

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One explanation may be that it is an ecological fact that small things are fast, light, and emit high sounds, whereas large things are slow, heavy, and emit low sounds. Pink is lighter than blue, which is appropriate to mice, whereas blue suits elephants. These experiences are reminiscent of the Aristotelian idea of a science of the sensible qualities based on couples of contraries such as warm and cold, and dry and wet (Aristotle, 1906, pp. 420a25–420b). Perhaps, it is not entirely fortuitous that in sound, *the minor falls* and *the major rises*; that in the general population, shapes are mapped on hues (Albertazzi, Canal, Malfatti, & Micciolo, 2015; Albertazzi et al., 2013) and perceived as harmonious or disharmonious (Albertazzi, Canal, Dadam, & Micciolo, 2014); or that even abstract concepts such as *impartiality* turn to be Blue–Green (Albertazzi, Canal, Micciolo, & Malfatti, 2013). In principle, then, logic might prove to be white (London, 2009), this being a matter worth testing experimentally. Culture may play a role in the choice of the antonyms for these dimensions: For example, Western music construes pitch according to an up-down spatial relationship, that is, *high* and *low* (Pratt, 1930), while in Bali and Java, pitches are *small* and *large*, and among the Suyá of the Amazon basin, they are *young* and *old* (Seeger, 1987). These facts raise questions such as the following: What kinds of dimensions are mapped by the scales of antonyms? What similarities do patterns such as high/low, small/large, young/old share? Why do several couples of antonyms map cross-modal and emotional dimensions as well? (Albertazzi, Canal, & Micciolo, 2015; Palmer & Schloss, 2010, 2011). One explanation may be the tendency in the general population for a sensory feature in one modality to be matched with a sensory feature in another modality (Deroy, Crisinel, and Spence, 2013; Deroy and Spence, 2013; Martino & Marks, 2000; Maurer & Mondloch, 2005; Parise & Spence, 2009; Sagiv & Ward, 2006; Spector & Maurer, 2008, 2011). To explain the associations, Spence has distinguished among structural correspondences (due to neural correlates, hence potentially universal), statistical correspondences (due to learning, hence potentially influenced by different environments), and semantic correspondences (due to language influence, hence potentially different among cultures) (Spence, 2011, 2015). More recently, and specifically with regard to inducers that take the form of concepts, such as the days of the week or the months, cross-modal associations have been explained in semantic (ideasthetic) more than sensory terms (Mroczko-Wasowicz & Nikolić, 2014; Nikolić, 2009; Simner, 2012; Ward, 2013; Ward and Mattingley, 2008; Ward et al., 2007). A perceptual feature which proves to play an important role in cross-modal associations is color. In fact, it has been associated with olfaction (Demattè, Sanabria, & Spence, 2006; Hanson-Vaux, Crisinel, & Spence, 2013; Kemp & Gilbert, 1997; Levitan et al., 2014), acoustics (Ward, Huckstep, & Tsakanikos, 2006; Moos, Simmons, Simner, & Smith, 2013; Moos, Smith, Miller, & Simmons, 2014; Simner et al., 2005), and touch (Ludwig & Simner, 2013; Martino & Marks, 2000).

The existence of such ecological facts (Parise, Knorre, & Ernst, 2014)—of which there are many and in many modalities—suggests that there may be an evolutionary basis for these aesthetic/ideaesthetic associations in perceptual awareness. Mapping them is a task of experimental phenomenology (Albertazzi, 2013; Koenderink, 2013). In our study, for a small number of antonyms, we investigate whether they are cross-modally or ideaesthetically related to the space of colors. In other words, whether there exist sets of antonyms that show a cross-modal relation to chromatic qualities, which would confirm the role of color in sensory and ideasthetic cross-modal associations.

Dimensions of Perceptual Awareness

If one refers to *dimensions* of perceptual awareness, *dimension* is not used in the formal sense of linear algebra. Physical dimensions concerning *quantity* are nonnegative numbers multiplied by some physical "unit." In classical physics, the units are essentially conventional (a yardstick for length, a stone for weight, etc.). In awareness, the *units* are *qualitative* and *volatile*.

The proper Bayesian prior for a nonnegative quantity is hyperbolic (Jaynes, 2003). This prior implies scale independence and thus applies to physical measures of quantity like weight or size. This is reflected in the ubiquitous Weber–Fechner Law of psychophysics (Fechner, 1860/1966). Such measures have a natural origin (zero on the scale) but lack a natural unit (*one* on the scale). Taking the logarithm (as the Bayesian prior or the Weber–Fechner Law suggest) yields a scale from minus to plus infinity with an arbitrary *midpoint*. In this representation, the midpoint represents the arbitrary unit.

The qualities of perceptual awareness are typically unlike this representation in that they lack a natural origin and have finite limits. Commonly, qualitative dimensions are structured in terms of *opponent pairs* such as occur in color perception (Hering, 1920/1964). The opponent pairs, for example, hot/cold or dry/wet, usually admit of *most typical* limits, with a *neutral* center. Such dimensions do not readily map on nonnegative physical quantities. For instance, the *white–black* opponent pair has *black* as one endpoint, and there are *degrees* of blackness as there are *degrees* of whiteness.

These considerations concerning the formal notions of dimensions, units, and scales raise various questions: What types of qualitative perceptual dimensions are mapped by the scales of antonyms? What similarities do patterns such as high/low, small/large, young/old share?

Ecological Factors in the Chromatic Domain

Colorimetry is the study of the discriminability of radiant power spectra; it ignores *qualia*. It has been known since the 19th century that human physiology causes the input to the brain to be of much lower dimensionality than the space of radiant spectra (Maxwell, 1865; von Helmholtz, 1867), generically only three, called *trichromacy*. A convenient description of representative radiant spectra for colors is couched in terms of RGB–space (*Red-Green-Blue–space*), roughly the low, medium, and high photon energy parts of the spectrum (Koenderink, 2003; Koenderink & van Doorn, 2003; Newton, 1704/1998; Schopenhauer, 1816).

Indeed, the spectral composition of retinal irradiance is one correlative factor in the psychogenesis of chromatic experiences. In this article, we predominantly consider color as *quale*. We are mainly concerned with so-called *object* or *surface colors*, as opposed to *aperture* or *film colors*, or *related colors* as opposed to *unrelated* ones. In this article, we will refer to *surface* and *film* colors throughout. Ecological physics yields some facts that are of possible interest to the present study (Koenderink, 2010b), such as bulk scattering, absorbing layers in front of light or dark backgrounds, and incidental factors like local shading due to vignetting and so on. Some frequent cases are the following:

- the Bayesian prior (Koenderink, 2010a, 2010b) is highest for achromatic (flat spectrum; R, G, and B about equal), less for *warm boundary colors* (spectrum skewed to the low photon energies; R greater than G greater than B), and least for *cold boundary colors* (spectrum skewed to the high photon energies; B greater than G greater than R);
- so-called tints are usually due to bulk scattering, and thus pertain to opaque objects, typically with matt surfaces. Thus, tints are often experienced as *pastel-like*. Consider scattering powders, chalk, and so on (Koenderink, 2010a, 2010b; Ostwald, 1916/1969);
- so-called shades are usually due to absorbing layers in front of light backgrounds. The objects are transparent in the bulk and have smooth surfaces. Thus, shades are often

experienced as *deep*, like the color of the clear sky or a deep lake (Koenderink, 2010a, 2010b; Ostwald, 1916/1969);
- *dull colors* are often related to translucent bulk scattering.

These correlates were the basis for Ostwald's (1916/1969) description of colors in the early 20th century. They make sound ecological sense. Ostwald's system is unique in combining physical optics, colorimetry, and experiential factors in a unified manner.

Chromatic Dimensions

Perhaps, the best known perceptual substructure that is structurally equivalent to the aforementioned Aristotelian framework of the four elements (earth, water, air, and fire) is the *color circle* showing the basic antonyms with their opponent colors such as cold/hot or acid/treacly. The question of whether or not the color circle somehow *maps* the Aristotelian framework, however, is a matter of phenomenological investigation. There are many such *maps* to be found in the literature: Among them von Goethe's *Theory of Colors* (1982) is a well-known example. And there are also various attempts by visual artists to consider the problem, in the 19th century (notably Runge, 1810) and in the 20th century as well (Albers, 2013; Arnheim, 1954; Kandinsky, 1914; Klee, 1920; Itten, 1963; Ostwald, 1916/1969; Thomas, 1980). The major feature shared by the various maps is the *hot–cold* antonym, which is known, and used, by all visual artists. It roughly maps on an *orange–blue* opponent dimension (Quiller, 1989), although the descriptions by artists vary appreciably. On the hot/cold partition of the Hue Circle, see Da Pos and Valenti (2007), Sivik (1974), and Wright (1962).

The Study

For a small number of antonyms, we investigate whether they are cross-modally or ideaesthetically related to the space of colors.

The main questions considered in our investigation are as follows:

- do there exist sets of antonyms that show a cross-modal relation to chromatic qualities?
- is the *cold–hot* antonym a basic dimension?
- is the *dry–wet* dimension transversal to the *cold–hot* dimension as in the ancient Aristotelian system?
- do there exist dimension(s) transverse to, and thus complementing, the *cold–hot* dimension?
- in what way and to what extent is an *achromatic* subspace special?

The study was restricted to young Italian subjects of both genders, although they were predominantly female.

Methods

Participants

Thirty-seven participants volunteered for the experiment: 24 women and 13 men (mean age 19 years, age range 18–22 years). They were students from Trento University and all native Italian speakers. The only exclusion criterion was self-reported defective color vision. It was not practical to run formal color tests, but the expected fraction of dichromats of less than a few percent should not have led to detectable differences in the results.

No subject declared a conscious condition of synaesthesia, a bias that might have influenced their choices. None had previously studied art sciences. All observers were also asked for their color preference. Not surprisingly, about 30% mentioned *blu* (blue), 14% *azzurro* (light blue), 8% *rosso* (red), and 8% *arancione* (orange); thus, coarse graining—about 44% bluish and 16% reddish—accounted for 60% of the responses. There was no significant gender difference. The remainder was either *none* (8%), or a variety of colors including greenish, purplish, white, black, and gray. An interesting instance is *antracite* (gray charcoal), which is not really a *color* at all but a dark gray with sparse white speckling (it is not a color in the same sense that *golden* is not *yellow*). This roundup of preferences is a fairly conventional result (Franklin et al., 2010).

The experiment was conducted after obtaining informed consent from the participants, and it was carried out in accordance with the relevant institutional and national regulations and legislation, and with the World Medical Association Helsinki Declaration as revised in October 2008.

Display

The experiment was conducted in a dark room. The stimuli were presented on the LCD screen of an Apple Powerbook. The screen was spectrophotometrically calibrated (see Appendix A). We used settings that have become a de facto standard for opto-electronic displays, that is to say a D65 white point and gamma 2.2.

The observers sat 57 cm from the screen, and the field of view subtended 33 by 21 degrees of visual angle.

A standard colorimetric method is to present uniform circular disks on a neutral uniform background, say black. This was not acceptable in our study, because it renders colors *ethereal* instead of *objectual*. To improve on this, we took a lead from common painting practices (Quiller, 1989). Painters often use a *limited palette* in their paintings, but this constraint does not mean that they use only a few fixed colors. Instead, each fiducial (or target) color is represented through a set of colors surrounding that fiducial color. This yields a liveliness and a feeling of substantiality that is usually sought (e.g., Quiller, 1989), but ubiquitous. We emulated the painter's procedure by drawing colors from a normal distribution, with standard deviation 0.5 (half the spacing of the cardinal hues on the color circle, see later) for the hues and 0.05 for the color, white, and black content (see later). This dithering was essential, because several of the response categories would not apply to the conventional ethereal presentations at all.

Fiducial colors were presented as circular patches on a textured background. The patches were textured by a random mosaic whose cells were filled with colors drawn from the dithered distribution (Figure 1).

Painting practice suggests that colors can only be judged in context: that is, on the almost finished canvas. They look different in isolation, say on the palette or on an almost empty canvas. To generate a neutral chromatic context, we used a textured background filled with colors generated from a generic model of *natural* colors (Koenderink, 2010b). Thus, the average background was a dark gray, but there existed accents of near white, black, and full colors. The distribution mimicked the generic distribution of *natural colors* as estimated from public databases (Koenderink, 2010a, 2010b).

This contextual information is essential, since—for instance—otherwise the family of grays would not even exist. For the *anchoring*, one needs at least black and white samples. The background contains colors from throughout the RGB–cube.

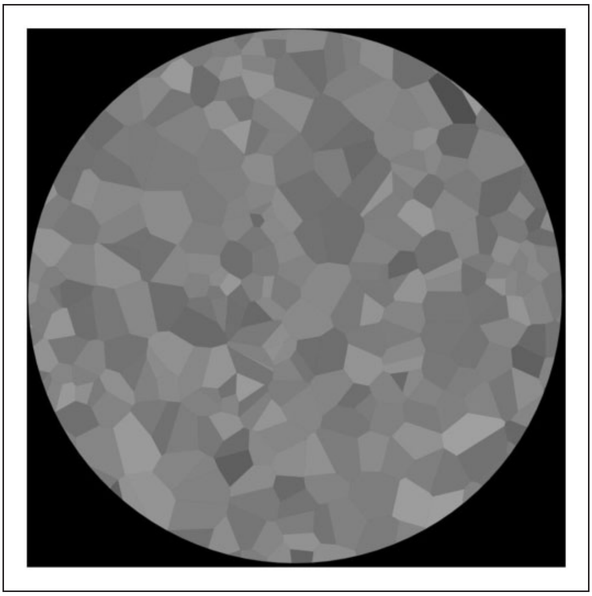

Figure 1. Example of a stimulus patch (background texture not represented). The varied gray yields an impression of the magnitude of the dithering.

The colors of the background were refreshed each time that the observer interacted with a new fiducial color: This ensured that the participants could not use any parts of the background as fixed anchors.

Gamut of fiducial color samples. The available color gamut was the RGB–cube subtended by the output of the LCD screen, which is similar to that of virtually any contemporary electronic display.

We did not use the RGB coordinates directly but employed a method that more closely fits the properties of human color vision: the conventional *HWB–system* (Smith & Lyons, 1996) of computer graphics. The reason is that the periodic sequence of yellow, green, cyan, blue, purple, and red yields by far the most intuitive description of hue. Understanding that $R = G = 1$, $B = 0$ indicates that *yellow* requires a cognitive reasoning that many naive observers do not spontaneously make. Of course, Luv or Lab coordinates are fully abstract to most people. The HWB system is like the Ostwald system for electronic displays (although not introduced as such), in which all coordinates have immediate intuitive appeal.

In the HWB system "H" stands for hue, "W" for white, and "B" for black. (The latter is unfortunate, since we want to reserve "B" for blue. Thus, we will use "K" for black in this article, taken from *key*, i.e., the black plate in color printing.) Any RGB–color is described in terms of a mixture of *full color*, white and black. Let (r,g,b) be the red, green, and blue coordinates of a RGB–color and let them take values in the range [0,1]. Then a color such as (1, 0.5, 0), which most people would call *orange*, would be a *full color* because it contains no black and there can be no white added to it. This is the case because the maximum value of the coordinates is one, and the minimum value is zero. The minimum is the *white content* (W in the HWB–system), and one minus the maximum is the *black content* (B in the HWB–system). Note that *adding white* means adding the same increment to all coordinates, whereas

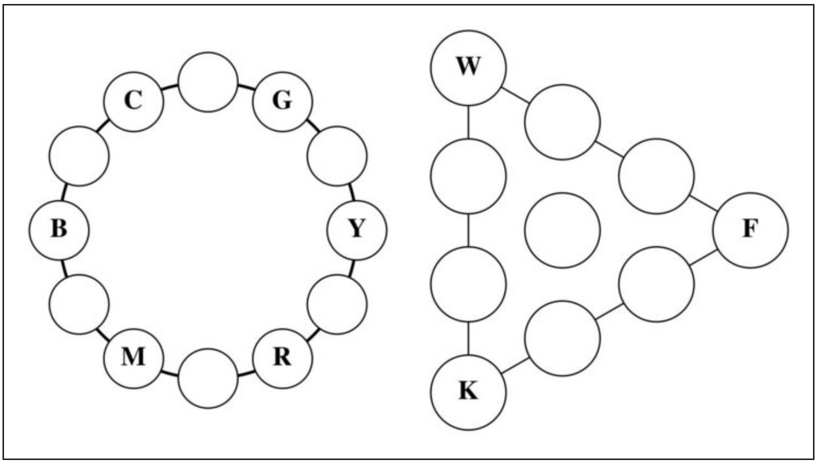

Figure 2. At *left*, The 12-step color circle used in the experiment. We index the steps counterclockwise from 0 to 11, starting at yellow and increasing toward green. The hue of any step is equal to the hue of the equal mix of its two flanking steps, so that the distribution is uniform in terms of affine arc length. At *right*, the HWB (color–white–black)–triangle for a specific full color F. The side K–W (i.e., black–white) of the triangle is the achromatic axis and thus identical for all full colors. The triangle contains 10 items, of which 4 (the achromatic colors) are shared between all full colors. Thus, there are 76 (i.e., $12 \times (10 - 4) + 4 = 76$) fiducial colors. Note that each point in the triangle is conveniently indicated through barycentric coordinates {c,w,k} (with $c + w + k = 1$), the color, white, and black contents. Thus, the full color F is at {1,0,0}, the white point W at {0,1,0} and the black point K at {0,0,1}. Just as a reminder, we indicate black with "K," not "B" as in the HWB–model. Thus, "B" is reserved for blue, as in the color circle at left.

adding black means decrementing all coordinates by the same amount. The full color (1, 0.5, 0) can neither be incremented (which would produce an r-value larger than one) nor decremented (which would produce a negative b-value): this is why it is called *full*. The space of full colors is a topological circle. Convenient anchor points are the *primary hues* red, green and blue (two color coordinates zero) and the *secondary hues* cyan, magenta and yellow (two coordinates one, one coordinate zero). Any full color is a linear combination of a primary hue and one of its two adjacent secondary hues. This enables one to parameterize the full colors with a periodic hue index, or—as is often done—an angle in the 0- to 360-degree range. The HWB–system of computer graphics is merely a simple specialization of the early 20th century central European Ostwald system.

The anchor points yield a uniform scale on the hue domain. Equal steps of hue, white, and black content lead perceptually to approximately even covering of the color circle. We used 76 fiducial colors to cover the full RGB gamut (Figure 2). This gamut contains grays, vivid colors, tints, shades, and dull colors.

Task and Procedure

The observer was presented with a stimulus (fiducial color patch on the background) at one side of the screen. Simultaneously, five possible responses of one category were presented as text, in both English and Italian, at the other side. The participants were asked to choose the descriptive term that goes best with the on screen color. These responses included a pair of extreme antonyms (e.g., *freddo-bollente*: *cold–hot*), a pair of intermediate connotations (e.g., *fresco-caldo*: *cool–warm*), and a *neutral* term. (see Appendix B for the complete bilingual list.) A response was selected by clicking with the computer mouse on a button next to the text. The moment after the observer made a response, the screen changed to either a new antonym category or a new color stimulus and new antonym category. There were seven response categories (antonyms) per color stimulus. For each color, they were presented in random order. For each fiducial color patch, the categories were presented sequentially in random order in a single block. These color patches themselves were also presented in randomized order. Since there were 7 categories and 76 fiducial colors, the observer was presented with a total of 532 trials in a session.

Results

With 37 observers, 7 categories, and 76 colors, we have a total of 19,684 responses, each on a 5-point scale. The overall distribution over the scales is somewhat uneven. As expected, observers apparently hesitated to use either extreme (Figure 3). Perhaps unexpectedly, they also somewhat avoided neutral responses. The tendency was to choose one side, though *not too much*.

A *full response* of a participant is a list of responses over all 76 colors. The full response matrix thus has 532 entries of 76-dimensional vectors. If all observers were perfectly consistent and in mutual agreement, there would be exactly seven nonzero singular values. In reality, we find that none of the expected 37 singular values (the number of observers) vanishes, whereas the values decrease only gradually and not precipitously after a much smaller number (say seven, the number of categories). We find the seven largest ones together explain 48% of the variance in the data.

We find that a clustering algorithm does not reveal significant clusters. We consequently consider the contribution of the singular values above the seventh to be noise. Removing these superfluous singular values is perhaps the simplest way to filter out noise, because it obviates the need to grade observers. We subsequently average over participants, ending up

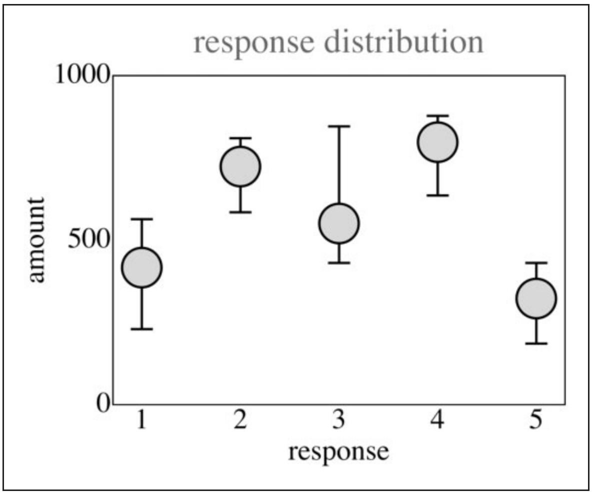

Figure 3. The overall distribution of responses. Note that observers are apparently hesitant to use the extreme responses (the end points 1 and 5 of the scale) as well as the neutral one.

with 7 vectors of length 76. Our analysis is based on this data matrix. It is only a coarse analysis, with the advantage of being rather robust. Grading observers and omitting obvious outliers yields almost identical results but has the disadvantage that it may be mistrusted because of a certain degree of arbitrariness. The analysis presented here is fully automatic and thus objective.

The concordance varies greatly over the categories (Figure 4, left). The concordance is highest for the *cold–hot*, *dull–radiant*, and *dead–vivid* categories, still significant for the other categories, except for *soft–hard*. A correlation with the group average is another measure that one might consider (Figure 4, right). Here, the *cold–hot*, the *dry–wet*, and perhaps the *acid–treacly* antonyms are most revealing.

We used a dendrogram to reveal overall structure in the data, using Ward's objective function (Ward, 1963). The resulting structure is shown in Figure 5. The first split isolates a group {*acid–treacly*, *dry–wet*}. The other branch then splits off {*transparent–chalky*} as an isolated case. The remainder is composed of two groups, namely {*soft–hard*, *dead–vivid*} and {*dull–radiant*, *cold–hot*}.

To investigate the nature of the distinctions suggested by the dendrogram in more detail, we need to consider the distribution of the responses over the space of colors. As discussed earlier, we take advantage of the chromatic representation in terms of hue and the color, white, and black contents (the "WB" of the HWB–system, the color content is one minus the white and black contents). This is much more likely to yield interpretable results than a raw principle component analysis, which yields arbitrary linear combinations of factors. We consider two types of analysis. The first centers on the hue dependence, and the second focuses on the color, white, and black contents. (See Figure 2 for the hue and color, white, and black contents samples used in the experiment.)

We analyze the hue dependency by fitting the responses with a constant plus a trigonometric function of the hue angle (Figure 6). The constant is not very informative (approximately the neutral response), so we ignore it. The variation can be expressed in terms of an amplitude and a phase. Simulation of a fully random observer yields baseline

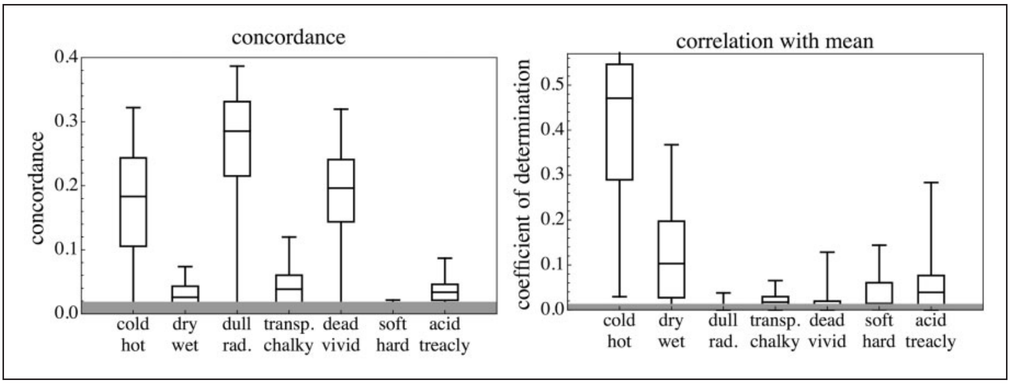

Figure 4. At *left*, the concordance between participants over categories. The *concordance* for a given participant is defined as median of the coefficient of determination (*R*-squared) for the correlation of the responses with all other participants. Here we show quartiles and limits over observers. At *right*, the coefficient of determination (*R*-squared) with the overall mean. Again, we show quartiles and limits over observers. The gray level specifies a fully random observer.

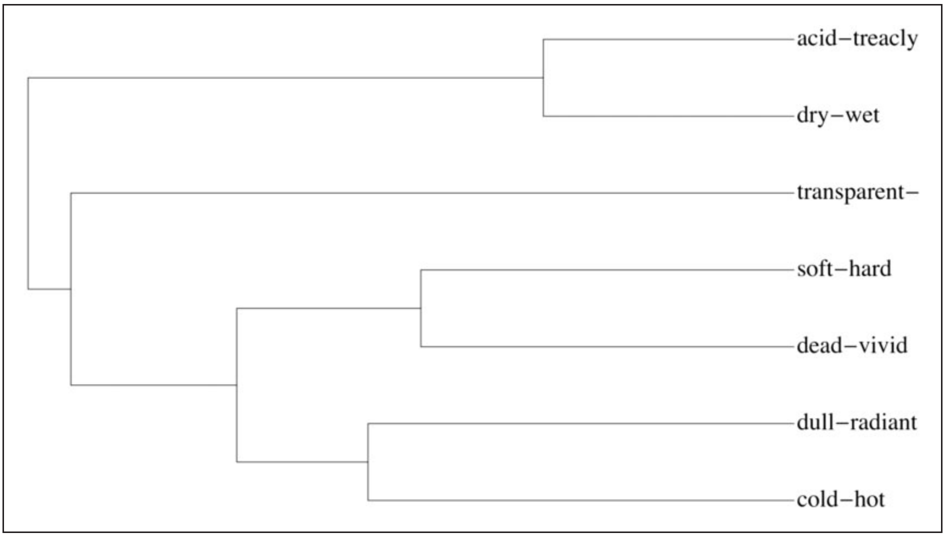

Figure 5. A dendrogram of all data using Ward's objective function. This representation is perhaps most sensibly interpreted in conjunction with the data presented in figure 4.

statistics on the amplitude, so that a z-test gives us a p-value (Table 1). We find that only the antonyms *cold–hot*, *dry–wet*, and *acid–treacly* have significant hue dependence. For the *cold–hot* dimension, the amplitude is high, and the p-value is very low: this is a very salient dimension.

The phase of the cold–hot dimension is such that the neutral axis is roughly green–purple (Figure 6). Red is hot and blue is cold. The phase difference between the cold–hot and dry–wet dimensions is 198 degrees, so that these dimensions are almost in counter-phase. As perhaps to be expected, dry and hot correspond, and so do wet and cold. The acid–treacly dimension is 57 degrees out of phase with the cold–hot dimension. The neutral axis is roughly bluish–reddish yellow, sour corresponds to bluish green, sweet to reddish purple.

We analyze the color, white, or black content dependency by fitting a linear function with constant term (Figure 7). Again, the constant term is not interesting (approximately the neutral response) and we ignore it. The interesting term is the slope. As there will always be *some* slope, we need to set some threshold. We arbitrarily pick a minimum coefficient of determination (*R-squared*) of .5. This is highly significant in all cases, as is evident from a random observer simulation. We find that there are only a few interesting cases (Figure 7), all involving the black content. They occur for the {*dull–radiant*, *transparent–chalky*, *dead–vivid*} dimensions. Especially the *dull–radiant* and *dead–vivid* dimensions are very similar, with shiny and lively corresponding to zero (that means white or full color), dead and dull to maximum blackness.

A noteworthy feature of Table 1 is the row for *soft–hard*, which is completely empty. Apparently, the responses significantly depend neither on hue nor on color, white, or black content: that is to say, not on any chromatic structure at all. This is apparently an instance of an antonym that had, on average, no chromatic *meaning* to the participants. It would be interesting to analyze this result further in light of the associations that have been found between touch and color (Martino & Marks, 2000; Ward & Mattingley, 2008).

Also remarkable is that the columns for color content and white content are empty, whereas the black content occurs as the significant parameter in some cases.

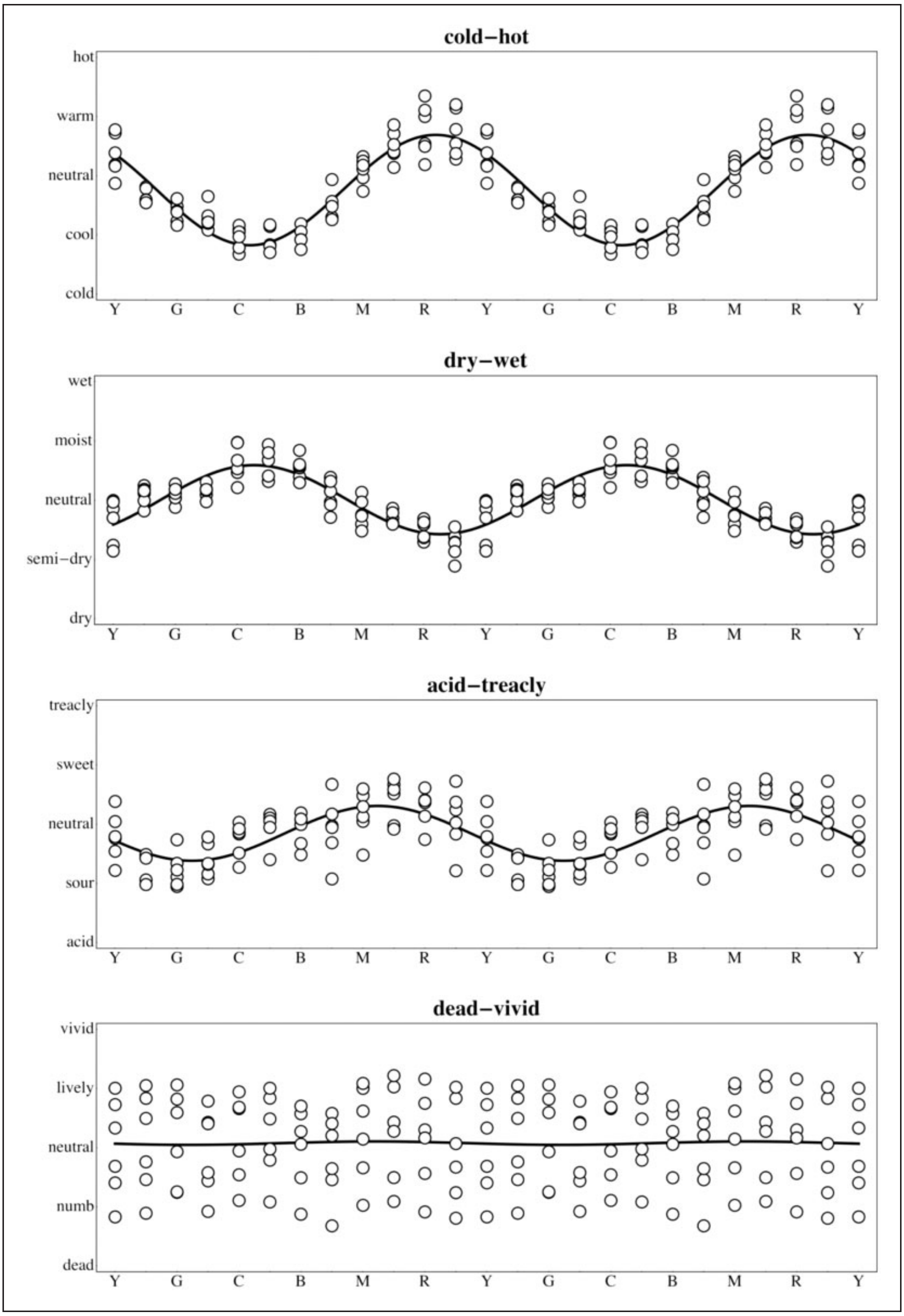

Figure 6. The hue variation for the *cold–hot*, *dry–wet*, *acid–treacly*, and *dead–vivid* categories. For better visual impression we plot two full hue cycles. The precise amplitude and phase data can be found in Table 1. The *dead–vivid* category is an example of insignificant hue dependence; the other three are (visually quite obvious) hue dependent. Note that the *cold–hot* and *dry–wet* dependencies are in almost exact counter-phase, whereas *acid–treacly* hue dependence is clearly out of step with these.

Table 1. Significant Fits of the Data in Terms of Hue and Color, White, and Black Content Variation.

	Significant structures								
	Hue			Color content		White content		Black content	
Category	Amplitude	*p*	Phase	Slope	R^2	Slope	R^2	Slope	R^2
Cold–hot	0.93	$<10^8$	4.4	—	—	—	—	—	—
Dry–wet	0.58	.0028	11.0	—	—	—	—	—	—
Dull–radiant	—	—	—	—	—	—	—	-3.0	0.86
Transparent–chalky	—	—	—	—	—	—	—	1.4	0.72
Dead–vivid	—	—	—	—	—	—	—	-2.7	0.85
Soft–hard	—	—	—	—	—	—	—	—	—
Acid–treacly	0.46	.0330	2.5	—	—	—	—	—	—

Note. A hyphen indicates lack of significant dependence. Criteria were a *p*-value exceeding .05 for the hue dependence, and a coefficient of determination (*R*-squared) exceeding .5 for the dependencies on the color, white, and black contents.

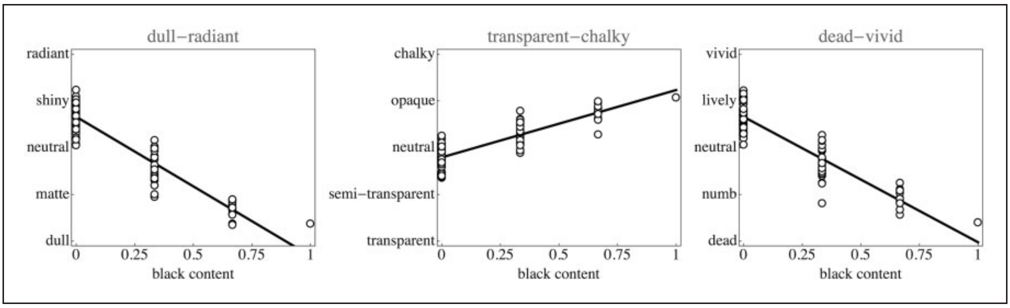

Figure 7. The linear dependence on black content for the *dull–radiant*, *transparent–chalky*, and *dead–vivid* categories. Values for the coefficients of determination can be found in Table 1. They all exceed .7.

The *dull–radiant*, *transparent–chalky*, and *dead–vivid* dimensions depend only upon the black content. Because color, white, and black contents always add up to one, this is equivalent to saying that they depend only upon the sum of color and white content. This again implies that color content and white content, in this instance, play equivalent roles.

Thus, a color is rated as more radiant, or less dull, if one increases either the color or the white content: a rather strong effect. A color becomes more opaque and less transparent when one increases the black content, although this is only a weak effect. A color becomes less lively and more dead when one increases the black content. Indeed, black itself was rated almost dead by all participants.

Of these *achromatic dimensions*, the *dead–vivid* and *dull–radiant* antonyms are the only ones in our set of categories that have a high interobserver concordance and similar black content dependence. On the basis of our data, they may be considered as essentially equivalent dimensions.

The relations revealed by the formal analysis are immediately obvious on inspection of the graphical representations of the data (Figures 8 through 15).

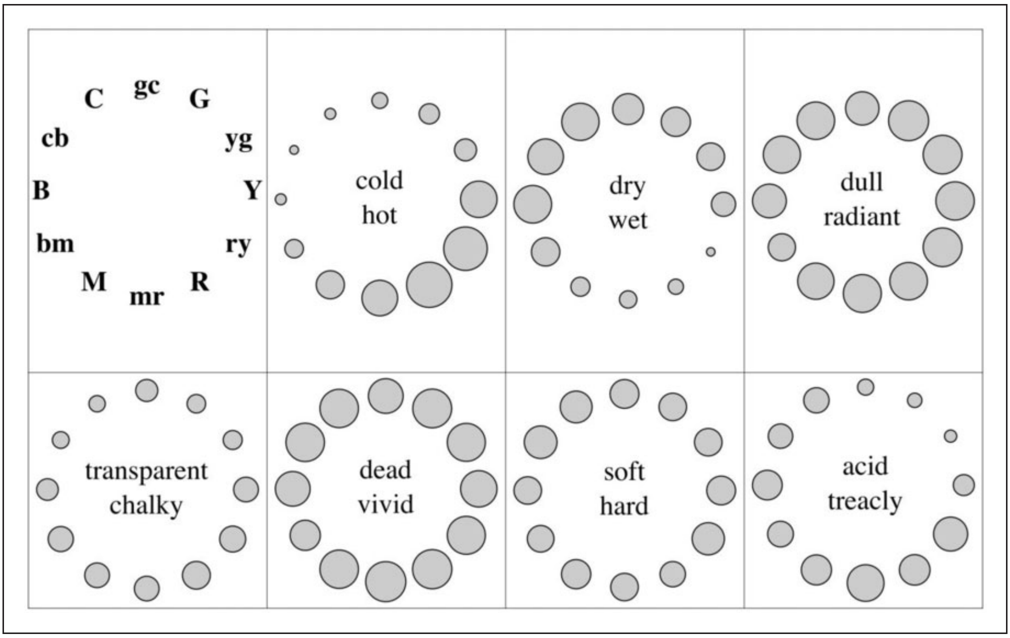

Figure 8. The hue dependence for the various categories. The radius of the disks is proportional to the mean response (index 1–5 mapped on the interval (0,1)). Thus, there is almost no hue dependence for *dead–vivid*, but a remarkable hue dependence *for cold–hot*. Note that *dry–wet* is merely the opposite of *cold–hot*, but that *acid–treacly* is in another dimension.

These graphical representations yield a convenient and full overview of the data which enables one to see a variety of subtle dependencies that complement the more overall representations as shown in Figures 6 and 7.

General Discussion

We investigated whether certain antonyms relate to the space of colors. Specifically, we investigated:

- whether these antonyms reveal a cross-modal relation to chromatic dimensions;
- whether there exist mutually transverse dimensions in the hue domain;
- whether there are dimensions specific to the *achromatic* subspace.

The study was necessarily of limited scope. We investigated seven antonyms for a culturally homogeneous local group. Consequently, we cannot draw *general* conclusions. However, the method proved rather informative, since it revealed significant and systematic trends. It was an analysis that bypassed the inherent limitations of standard psychophysical methodology and moved into the realm of experimental phenomenology.

We find that the *soft–hard* antonym does not depend upon chromatic structure at all, in comparison to other antonyms. Apparently, *some*, but *not all,* antonyms are in some way mapped on chromatic dimensions. This is an important finding because it is informative on the nature of cross-modal associations.

Of the six remaining categories, three depend mainly on hue, whereas the other three depend little upon hue but mainly on achromatic properties.

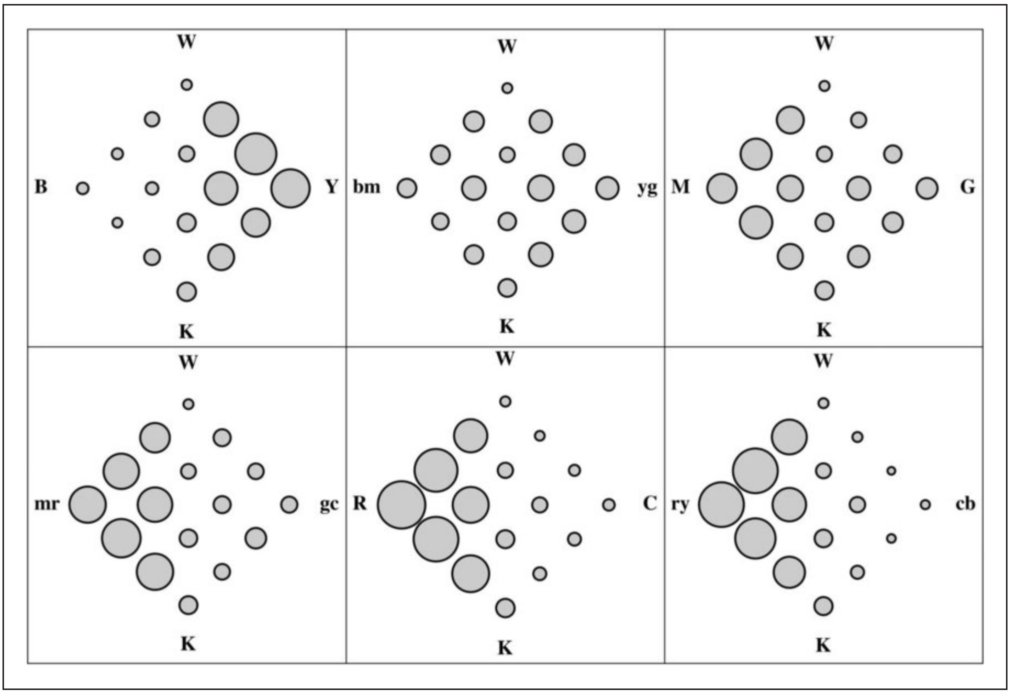

Figure 9. A complete overview of the *cold–hot* dimension. The diameter of the disks increases monotonically with the average response (index 1–5 mapped on the interval (0,1)). This dimension peaks roughly at red and is least at (again roughly) turquoise. These sections through the achromatic axis yield an overview of the full data. Each lozenge combines two triangles like that in Figure 2 right, connected via their common achromatic side (the K-W side of the triangles) and with one pointing left and the other right. These triangles have complementary full colors as vertices; thus they represent a planar section of color space representing a certain *opponent dimension*. Note that *complementary* simply implies that two colors add to white. Thus, (r,g,b) and (1 − r,1 − g,1 − b) are complementary RGB–colors. In this representation the *opponency* not only applies to the full colors but also pervades the volume of RGB–space.

As expected, the *cold–hot* category depends very strongly on hue, the neutral axis being the *green–purple* axis, with hot relating to red, cold to blue. This is fully in line with the general convictions of visual artists.

Since the *dry–wet* dimension has a hue dependence that is almost fully in counter-phase with the *cold–hot* dimension, we conclude that these dimensions essentially coincide, with dry corresponding to hot, and wet to cold. This is different from the relation encountered in the alchemical literature, essentially Aristotle's Four Elements, where these dimensions are treated as transverse, hence mutually complementary. But since these dimensions coincide, *dry–wet* fails to function as a complementary dimension to *cold–hot* in the chromatic domain.

From an evolutionary perspective, it is hardly surprising that the *red–blue* axis dominates the scene, because ecological physics reveals it to be the major dimension of the variation of spectral composition (Koenderink, 2010a, 2010b).

The *acid–treacly* dimension turns out to be transverse to the *cold–hot* dimension. It may thus be taken as a complementary dimension that serves to span the color circle (Figure 16). The *green–purple* opponent pair maps on the *sour–sweet* antinomy (the limit *acid–treacly* appears to be out of bounds). Thus, the *cool–warm* and *sour–sweet* antinomies are much like

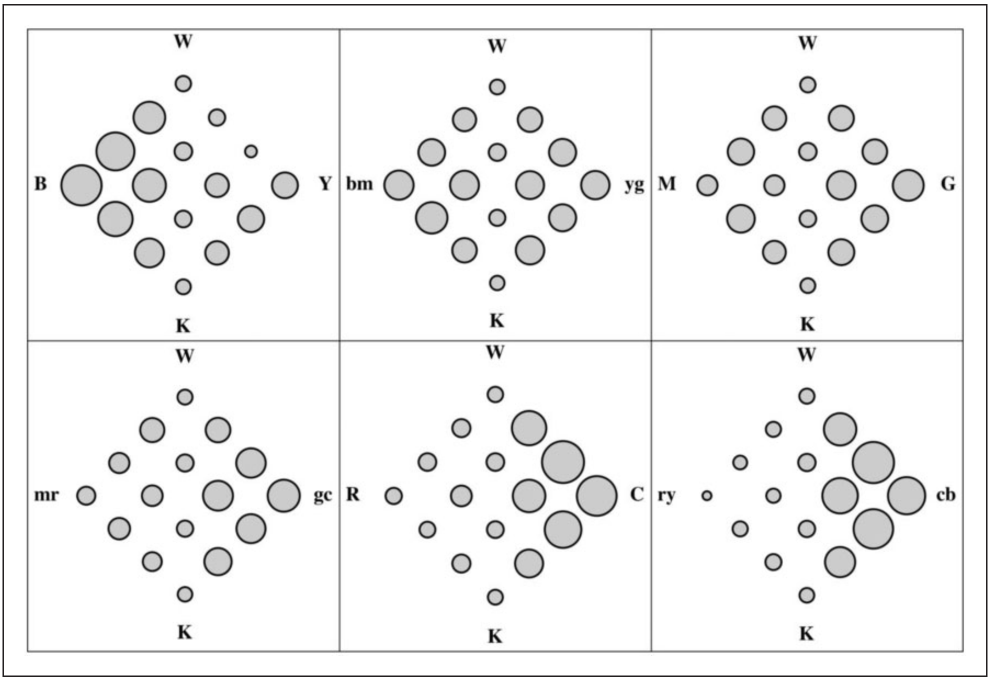

Figure 10. As Figure 9, but for the *dry–wet* dimension. Note that Figure 8 more immediately reveals the hue dependency.

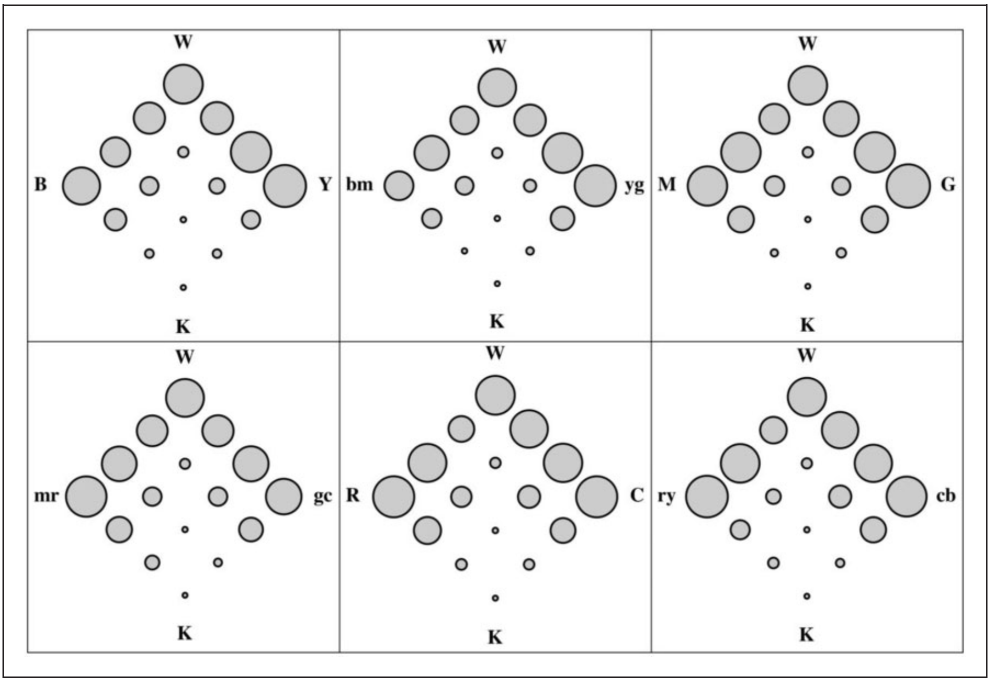

Figure 11. As Figure 9, but for the *dull–radiant* dimension. Note that Figure 8 more immediately reveals the hue dependency.

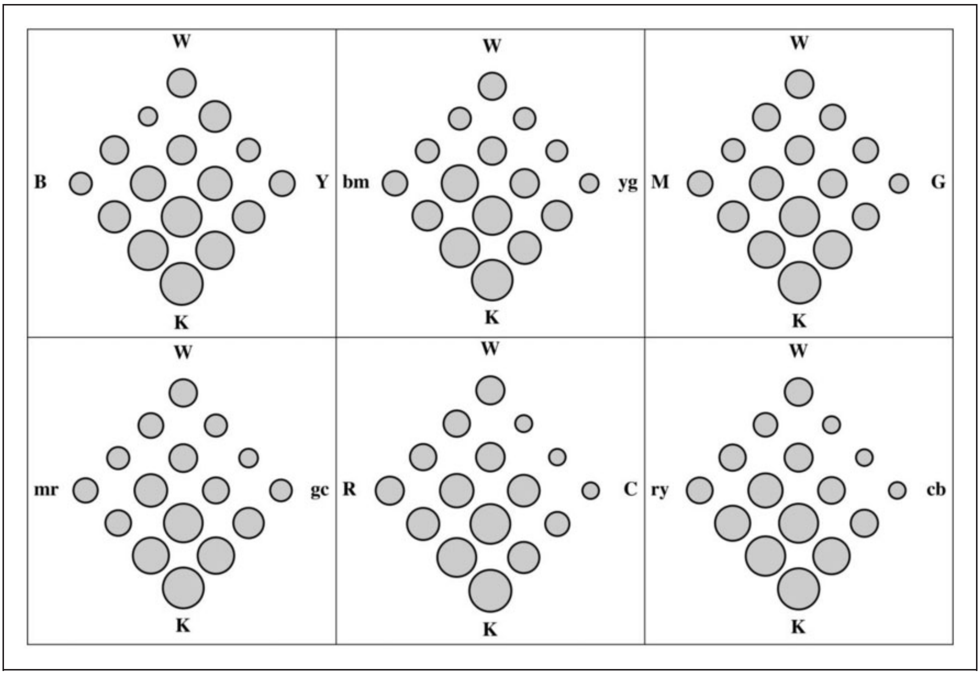

Figure 12. As Figure 9, but for the *transparent–chalky* dimension. Note that Figure 8 more immediately reveals the hue dependency.

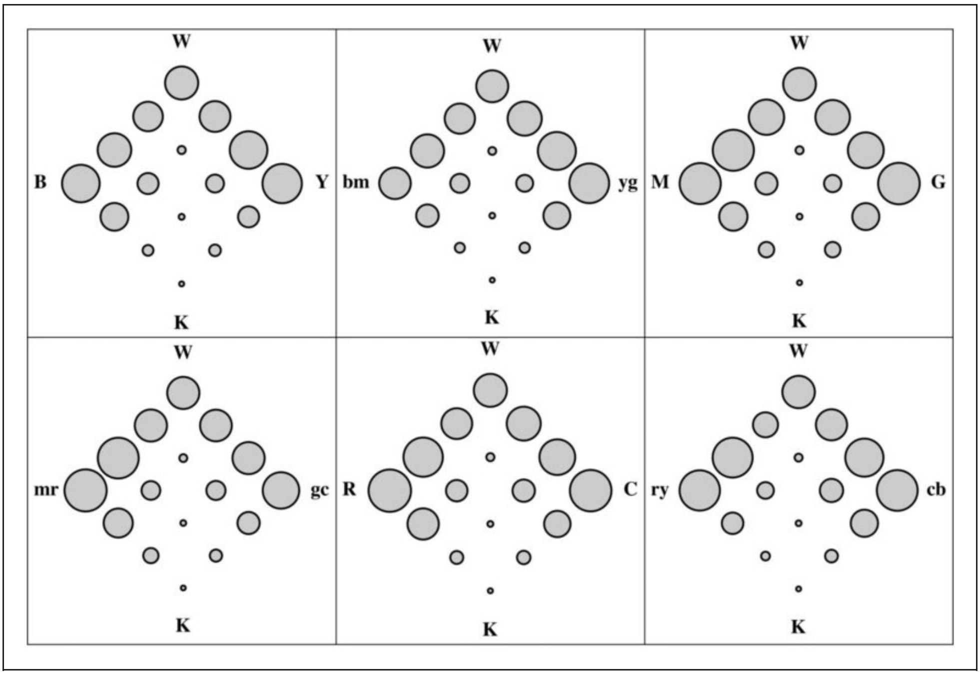

Figure 13. As Figure 9, but for the *dead–vivid* dimension. Note that Figure 8 more immediately reveals the hue dependency.

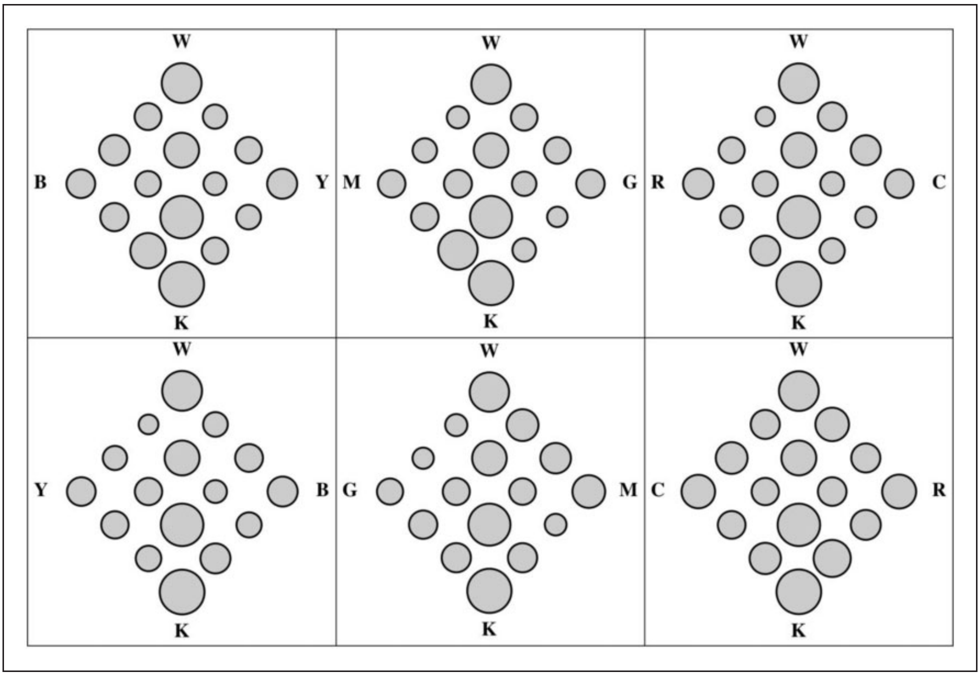

Figure 14. As Figure 9, but for the *soft–hard* dimension. Note that Figure 8 more immediately reveals the hue dependency.

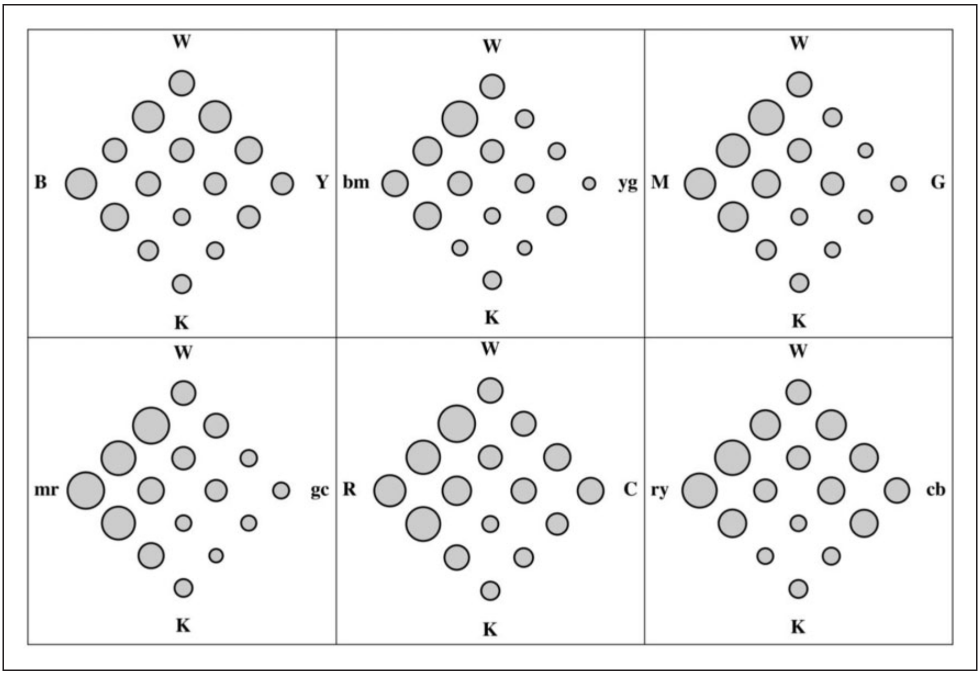

Figure 15. As figure 9, but for the *acid–treacly* dimension. Note that Figure 8 more immediately reveals the hue dependency.

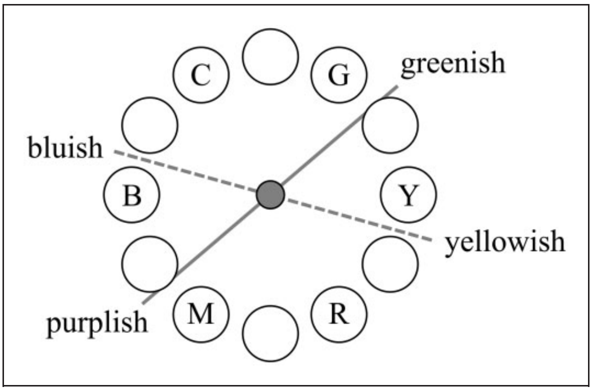

Figure 16. Neutral axes for *cool–warm* (drawn) and *sour–sweet* (dashed).

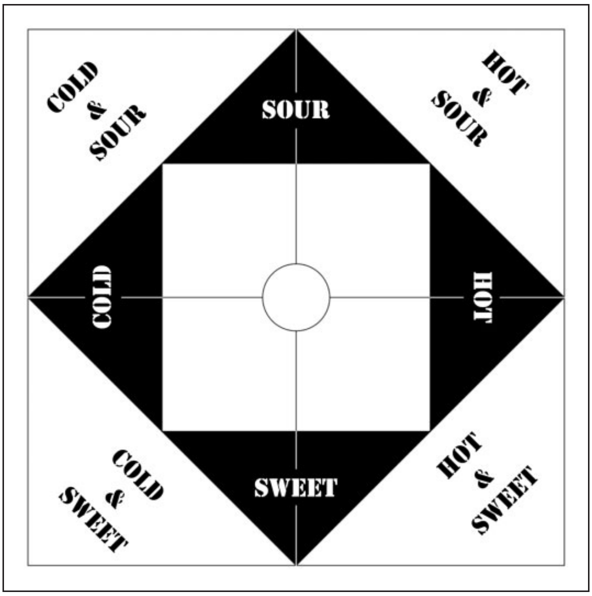

Figure 17. A diagram similar to the Aristotelian transmutation diagram commonly presented in alchemical texts. It shows the basic antonyms with their opponent colors. The alchemic diagram was designed as a tool to derive various related antonyms by analogous reasoning.

Hering's opponent color system. (We refer to the formal structure here, not to the exact axes suggested by Hering.)

Again, from an evolutionary perspective, this is hardly a surprise, because ecological physics reveals it to be the next most important dimension of spectral composition. The yellow–blue dimension is related to spectral slope, and the green–purple dimension to spectral curvature (Koenderink, 2010a, 2010b).

Interestingly, our findings can be related to the Aristotelian system of the Four Elements (fire, air, water, and earth) defined in terms of two qualitative antonyms, thus giving rise to a cyclic system (Aristotle, 1906; see Figure 17).

We also find two *achromatic dimensions*, which may be regarded as being equivalent semantic analogs of Hering's *black–white* opponent pair. Thus, *hot–cold*, *sweet–sour*, and *dead–vivid* are three antonyms that together cover the full space of colors as spanned by the opponent pairs *yellow–blue*, *purple–green*, and *black–white*. Perhaps surprisingly, the antonyms that span the color space are from domains as different as the thermal, gustatory and hedonic ones. Of course, there may well exist equivalent antonyms from different domains. The *antonym word lists* will easily suggest many potential contenders to investigate. The relation most likely applies to an extensive semantic network, rather than mere specific antonyms.

In summary, we have shown that our approach enables us to answer some of the questions posed in the introduction. Various, though not all, antonyms map on chromatic dimensions, confirming the role of color in sensory and ideasthetic cross-modal associations. A major finding is that the *cold–hot* and *sour–sweet* antonyms turn out to map approximately on Hering's opponent color system. More generally, some antonyms appear evidently related to color dimensions, other rather less so, or not at all.

Given these results, one may perhaps speculate on the viability of a dictionary of the various semantic dimensions of color that makes it possible to use some categories synonymously (and with internal gradations) according to the role performed in regard to Hue and CWK-content in the various polarities. Systematic analyses of this type might lead to the construction of a color atlas based on semantic dimensions, such as the one begun by Sivik (1974) but unfortunately never completed.

Research on qualities within the Aristotelian framework may perhaps find applications in various disciplinary fields, such as the perceptual roots of metaphorical thinking (Albertazzi, 2010; Cacciari, Massironi, & Corradini, 2004; Marks, 1982), and the study of personality as in the *four-color personality* of Lüscher's diagnostic (Holmes, Wurtz, Waln, Dungan, & Joseph, 1984; Jung, 1964; Lüscher, 1979).

Acknowledgements

The work was conducted at CIMeC (University of Trento), October 2013, during the visiting project of Jan Koenderink. Anna Dallavo assisted in running the experiment.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the Methusalem program of the Flemish Government (METH/08/02; awarded to Johan Wagemans).

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Appendix A: Spectrophotometric Calibration of the Display

The display was calibrated in the following way:

First, we linearized the display using the SuperCal application of BergDesign (http://bergdesign.com/supercal/), setting the gamma to 1.0, the white point to D65. This is a fully objective method where the eye is used as a null detector. The results are the same as a precise radiometric calibration, but the method is more precise, given the radiometric equipment at our disposal, especially at low luminances.

Subsequently, we performed a full spectroradiometric calibration. For the radiometric measurements, we used a Minolta CS-1000 (Minolta, http://www.ueen.feec.vutbr.cz/light-laboratory/files/manuals/CS-1000A.pdf) in a fully dark environment (matt black painted walls and so forth), taking various measures to avoid artifacts. We limited spectroradiometry to the 380 to 780 nm spectral region. Spectral resolution was set to 1 nm, which is sufficient to capture most structures in the LCD screen radiant power spectrum. We only mention the relevant data here.

We calibrated only the center part of the screen—about 5% of the stimulus width—but we know from spatially selective luminance measurements that the uniformity is much better than is required for the experiment.

A rather conservative assessment of the remaining uncertainties is that the chromaticities may be trusted to up to two decimal numbers, the luminance to better than 10%. These accuracies far exceed those needed for the correct interpretation of our results.

We performed radiometric measurements for black, white, the primary colors, and the secondary colors. This twofold overdetermination allows one to check on linearity and possible nonlinear cross talk between channels. The dynamic range is between 400 (for blue) and 800 (for green). In the actual experiment, the effective dynamic range was not limited by the stray light in the room.

The degree of linearity turns out to be so high that deviations cannot be represented at the level of accuracy reported here. The radiant power spectra of the primary colors (red, green, and blue channels) are shown in Figure A1.

The corresponding chromaticity coordinates using the CIE 1931 definition and the luminances (in candela per meter square) are given in Table A1.

Note that the luminance is in the ratio R: G: B = 0.215: 0.622: 0.163, thus very close to the usual rules of thumb. Of course, this could hardly be otherwise, since the primary colors combine to white.

In Figure A2, we have plotted the primary and secondary colors in the 1931 CIE chromaticity diagram. Note that we used six additional colors in the experiment, which have not been plotted for the sake of clarity. Although these are indeed *between* the indicated colors, they do not bisect them. Remember that the CIE diagram is a projective transformation of the CIE XYZ color space. This conventional representation is much less intuitively useful—indeed, it tends to be misleading to nonexperts—than that used in the main text. We give it for the sake of completeness.

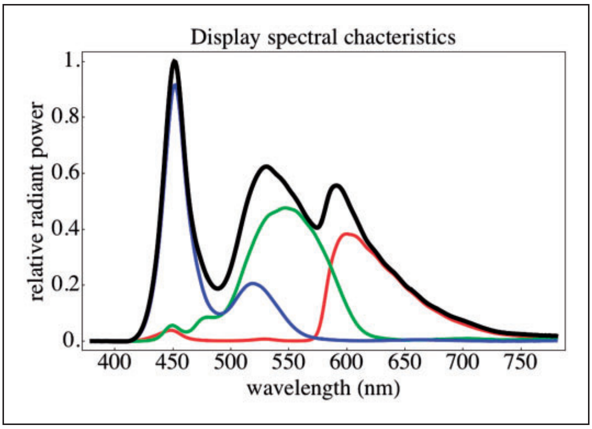

Figure A1. The radiant power spectra (normalized to the maximum of the combined-white-spectrum) of the red, green, and blue color channels of the display. Spectral resolution is 1 nm, random error of relative radiant power within about ±1%. The color channels are drawn in red, green, and blue, and the combined white is indicated with the black curve.

Table A1. The Chromaticity Coordinates x, y and the Luminances Y of the Red, Green, and Blue Color Channels.

	x	y	Y
Red	0.6049	0.3416	94.3
Green	0.3295	0.5750	272.7
Blue	0.1531	0.1382	71.1

Note. We would trust at least two digits of the chromaticity coordinates and the luminances to within ±10%.

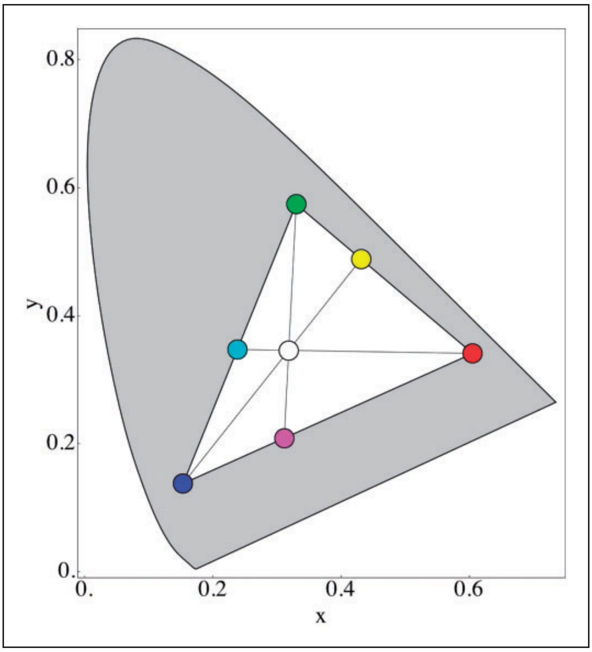

Figure A2. The primary colors (red, green, and blue color channels) as well as the secondary colors (cyan = green + blue, magenta = blue + red, and yellow = red + green) have been plotted in the conventional 1931 CYE xy-diagram.

The calibration data reported here had better not be critical in the interpretation of our data. If they were, then the data would be rather uninteresting. Indeed, we consider such to be highly unlikely and have little doubt that our results will be reproduced with virtually any modern electronic display and using conventional factory settings. In any case, these are the full spectrophotometric data for those who prefer to speculate that small colorimetric variations might matter.

Appendix B: List of Antonyms Used in This Study

I

(1)	cold	freddo
(2)	cool	fresco

(3)	neutral	neutrale
(4)	warm	caldo
(5)	hot	bollente

II

(1)	dull	spento
(2)	matt	semi-spento
(3)	neutral	neutrale
(4)	shiny	splendente
(5)	radiant	radiante

III

(1)	transparent	trasparente
(2)	semi-transparent	semi-trasparente
(3)	neutral	neutrale
(4)	opaque	opaco
(5)	chalky	gessoso

IV

(1)	soft	morbido
(2)	mellow	pastoso
(3)	neutral	neutrale
(4)	firm	solido
(5)	hard	duro

V

(1)	dry	asciutto
(2)	semi-dry	semi-asciutto
(3)	neutral	neutrale
(4)	moist	umido
(5)	wet	bagnato

VI

(1)	acid	acido
(2)	sour	amaro
(3)	neutral	neutrale
(4)	sweet	dolce
(5)	treacly	melassa

VII

(1)	dead	morto
(2)	numb	torpido
(3)	neutral	neutrale
(4)	lively	vivace
(5)	vivid	vivido