Consider vision first. What we want to explain is why only a small number of cones are necessary. The source excitation will be due to direct sunlight, skylight, and reflected light from other objects, and the resulting excitation spectra of natural light at different times of day and locations is continuous and relatively smooth. Judd et al. found that the different excitations could be reproduced using different amounts of three independent functions: one function to represent the overall illumination level, one function to represent the blue-yellow contrast, and one function to represent the red-green contrast. The surface reflectance (the filter) is due to embedded particles that reflect the incident light. Somewhat surprisingly, the reflectance functions of most materials also are continuous and smooth, as illustrated in Figure 2 of the target article. Using diverse surfaces, most studies have found that the reflectance spectra can be reproduced with 3 to 7 independent functions (Wandell 1995) and that the first three functions usually represent (1) illumination, (2) red/green, and (3) blue/yellow contrasts. The fact that both the illumination and reflectance functions can be represented by a small number of independent functions suggests that only a small of number of receptors would be necessary to recover the illumination-independent color. However, even with three functions for both illumination and reflection there is not an explicit solution for trichromatic vision: there are six unknowns but only three data points from the cones. Maloney (1999) and Hurlbert (1998) present alternative simplifying assumptions that yield a solution for reflectance.

Now consider timbre. What we want to explain here is why there are roughly 2,000 sound receptors in the inner ear. The source excitation (e.g., bowing or plucking a violin, vocal fold vibration) occurs at discrete and typically harmonic frequencies, and the energy at each frequency depends on the precise ways the excitation is initiated. Bowing generates a different pattern of amplitudes than plucking, and the amplitudes of the higher harmonics are relatively greater at more intense excitation levels. The sound body resonances (the filters) also occur at discrete frequencies based on the shape and material of the sound body. In the case of the human voice, resonance peaks termed formants occur at frequencies determined by vocal tract shape and size, so the radiated sound usually contains multiple peaks at widely spread frequencies separated by regions of low amplitude (Fig. 1). What this means is that neither the source spectra nor the filter spectra can be modeled by a small number of independent linear functions, and timbre depends on the distribution of individual vibrations across frequency. To distinguish among different timbres (i.e., different sound objects) therefore requires many receptors, necessarily tuned to narrow frequency bands to pick up the resonance peaks; and that is what is found in the peripheral auditory system. The perceptual dimensions underlying similarity judgments between pairs of timbres are based on the amplitude pattern of the spectra. The dimensions include the spectral centroid (i.e., the weighted average of the frequencies), the number and frequency range of the harmonics, and the variance of the harmonics, particularly across the duration of the sound (Erickson, in press). All of these require a fine-grained analysis of the spectrum.

We believe this correspondence between the physical characteristics of light and sound and the characteristics of the visual and auditory sensory receptors support Byrne & Hilbert's (B&H's) contention that colors are physical properties, and support the analogous contention that timbres are physical properties.

NOTES

1. It is surprising that books rarely point out that sound waves are as "pitchless" as light rays are colorless. We suspect that writers are lulled by the correlation between frequency and pitch, which is not found for colors.

2. It is interesting that vocal pedagogues use the terms color and timbre interchangeably when referring to the quality of a voice (see Vennard 1967).

Byrne and Hilbert's chromatic ether

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Abstract: Because our only access to color qualities is through their appearance, Byrne & Hilbert's insistence on a strict distinction between apparent colors and real colors leaves them without a principled way of determining when, if ever, we see colors as they really are.

Hue differences are differences in quality. Spectral power differences are quantitative. This renders any putative identification of hues with spectral power distributions problematic. If the identification is to be made persuasively, it must be possible to show how hues – or hue magnitudes – can be mapped into spectral power distributions in a principled fashion. Byrne & Hilbert (B&H) propose to do this by relating hue magnitudes to relative cone response. For example, a light with a spectral power distribution that stimulates L-cones more than M-cones ("L-intensity") is to be denominated "reddish," whereas a light with a spectral power distribution that stimulates M-cones more than L-cones ("M-intensity") is to be deemed "greenish."

This talk of "L-intensity" or "M-intensity" sounds as if it were subject-independent, but it isn't. Not only do individuals differ in their opponent systems, the balances between opponent systems in a given individual are subject to shifts depending on luminance level, stimulus size and duration, and state of adaptation. If one could find a plausible specification of "L-intensity," "M-intensity," and "S-intensity" based on spectral power distributions alone, one could speak of the accuracy or inaccuracy of a person's visual estimates of hue magnitude, just as one speaks of the accuracy or inaccuracy of a person's estimate of length or weight. We can, indeed, measure the ability that people have to resolve wavelength differences precisely because we have an independent way to measure wavelengths. But without such an independent measure, it is simply nonsense to speak of the accuracy with which someone estimates hue magnitudes. All we can do is determine the extent to which people agree or differ in their hue magnitude estimates.

B&H attempt to blunt this sort of criticism by appealing to the well-worn distinction between something's being F and our ability to know or gain epistemic access to F. For example, in discussing simultaneous contrast, they distinguish between an object's *appearing* brown and its *being* brown. "If an object looks brown against a light background then it will look orange against a dark one" (target article, sect. 3.1.3, para. 1). However, "the fact that brown is only ever seen as a related color tells us nothing about the nature of brown. It merely illustrates the fact that color perception works better under some conditions than others" (sect. 3.1.3, para. 4).

So under what conditions does "color perception work better" (presumably, come closer to showing us the colors of objects "as they are")? Is there, for example, a background that is best suited for displaying the "true colors" of a set of Munsell chips? One would look in vain in the literature of color technology for an answer to such a question, not because it is hard to answer, or unanswerable, but because it is ill-conceived. As every practitioner knows, the choice of background is as much a function of one's purposes, as it is of the particular, empirically accessible, characteristics of the materials at hand.

Because they insist on a distinction between apparent colors and real colors, while acknowledging that access to color qualities can only be gained through color appearance, B&H are forced to a damning admission: "Thus we are prepared to countenance 'unknowable color facts' – that a certain chip is unique green, for instance. And so should any color realist who accepts some assumptions that are (we think) highly plausible" (target article, note 50).

There is at least a whiff of ether here, the electromagnetic ether whose undulations were supposed to be the mechanical basis of electromagnetic phenomena. The null result of the Michaelson-Morley experiment left one with two choices: Regard the earth's

https://doi.org/10.1017/S0140525X03330018 Published online by Cambridge University Press

motion through the ether as an unknowable fact, or else dispense with the ether altogether. Empirical science opted for the second course. Have B&H opted for a chromatic ether?

In favor of an ecological account of color

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Abstract: Byrne & Hilbert understate the difficulties facing their version of color realism. We doubt that they can fix reflectance types and magnitudes in a way that does not invoke relations to perceivers. B&H's account, therefore, resembles the dispositional or ecological accounts that they dismiss. This is a good thing, for a dispositional account is promising if understood in an ecological framework.

We do not see that Byrne & Hilbert's (B&H's) account succeeds in identifying colors with observer-independent features of the world. Although the reflectance of a surface is observer-independent, reflectances alone are insufficient to explain color relations. B&H thus identify colors, not with reflectances, but instead with sets of reflectances. But, because every reflectance is a member of infinitely many sets, with which sets are colors identified? B&H identify a determinate color with such a set of reflectances that no normal human observer can, in normal circumstances, discriminate (on the basis of reflectance) between two surfaces that share that reflectance set. This introduces the familiar problems of relations to observers, which pose challenges for physicalism. And, the resulting motley set of reflectances, B&H admit, "will be quite uninteresting from the point of view of physics or any other branch of science unconcerned with the reactions of human perceivers." They continue, "This fact does not, however, imply that these categories are unreal or somehow subjective (Hilbert 1987)" (target article, sect. 3.1.1, para. 4). Yes and no.

Consider the set of all things that are more than two feet and less than three feet away from the authors of this commentary. Is this set subjective or real? Each member of the set exists quite independently of the authors, as does the set if sets exist at all. But the membership of the set depends on the authors, for it changes as we move about. Similarly, whereas reflectances and sets of reflectances are observer-independent properties or entities, the fact that particular reflectances belong to the set of reds is not observer-independent; instead it depends on what reflectances are discriminable to certain observers, under certain circumstances, and so forth. This sounds very much like a dispositional account.

Even if B&H can successfully sever sets of reflectances from the perceptual equivalence relations that fixed their membership, they will still need to show that these sets can explain familiar observations concerning color relations. In particular, they must explain away data that seem to show that the physicalist account cannot address the color relations that characterize color spaces. B&H's elaborated theory says that vision represents objects as constituted from the values of four hue magnitudes, red, yellow, green, and blue. We don't know to what the magnitudes correspond, why there are four rather than more or fewer, or why these four are hue magnitudes rather than saturation or texture magnitudes. We doubt that these questions can be answered in an observer-independent manner. If not, B&H's account turns out to be similar to the dispositional or ecological accounts they dismiss.

It is seductive to think of simple physical properties of objects as being isomorphic with our experiences of them. As B&H note, squareness seems to be an intrinsic property, and not perceiver-relative. Yet, perceived shape depends on orientation and context, just as perceived reflectance depends on the surrounding scene, orientation, illumination, and object identity (e.g., Lotto & Purves 1999). Similarly, haptically perceived heaviness does not depend simply on an object's mass; it depends on the spatial layout or distribution of an object's mass (Turvey et al. 2001). This does not show that objects do not have properties such as shape, but it may be reason to resist the identification of perceived shape with the properties represented by perceived shape. The punchline is that we must be cautious about naïvely assuming that our experiences resemble the world.

If physicalism cannot explain color perception, what framework should take its place? We favor a dispositional account that makes use of ecological relations. Central to this account is the mutuality of animal and environment, as illustrated by the concept of affordances, which are behavioral possibilities of a given object or environment for a given animal (Gibson 1966; 1979/1986). Affordances capture the relation of an animal's action capabilities to the environment. Visually perceived affordances for climbability, for instance, are based on the intrinsic scaling of environmental properties (step height) by perceiver properties (leg length), as shown by Warren (1984). The perception of affordances in terms of naturally scaled environmental properties highlights the importance of animal-environment mutuality: Affordances are always relative to perceivers.

This can be appreciated in the context of Turvey's (1992) dispositional account of affordances. Turvey argued that an affordance is a disposition of an environment that is actualized in the presence of a complementary disposition of an animal (an effectivity, i.e., an action capability of a particular animal). Turvey (1992, p. 180) offered the following analysis of affordances:

Let W_{pq} (e.g., a person-climbing-stairs system) = $j(X_p, Z_q)$ be composed of different things, Z (person) and X (stairs). Let p be a property of X and q be a property of Z. Then p is said to be an affordance of X and q is the effectivity of Z (i.e., the complement of p), if and only if, there is a third property r such that

(i) $W_{pq} = j(X_p, Z_q)$ possesses r
(ii) $W_{pq} = j(X_p, Z_q)$ possesses neither p nor q
(iii) Neither Z nor X possesses r.

In this analysis, j is a function that expresses the joining of animal (Z) and environment (X). Each possess a complementary disposition q (an effectivity) and p (an affordance) to form W_{pq}. That joining results in the actualization r of the previously latent dispositions. By itself, p is not an affordance; it can only be an affordance for some creature. In the absence of the animal, p is a disposition, that is, a real possibility to be actualized as an affordance in the presence of an animal with dispositional property q. Property p is only an affordance with respect to animal property q when X and Z are joined.

We think that B&H's approach to color perception is, in fact, a dispositional account, because it cannot explain color vision without invoking properties of perceivers. A dispositional account positioned in an ecological framework carries considerable appeal, but it does not open the door to sense data or any of the other unnatural baggage of traditional subjective accounts of color. Nor does it deny that colors are real features of the world, and that they are the properties that are represented in color vision. Dispositional properties are relational, but nonetheless genuine. Salt really is water-soluble. Twigs, but not trees, are movable for birds. The world contains circles, and it contains cup-holders. The relational property that is the ratio of a stair's riser height to a person's leg length is no less a real, substantive property than stair height or leg length. Gibson (1979/1986, p. 129) said that the concept of "affordance cuts across the dichotomy of subjective-objective and helps us to understand its inadequacy." An ecologically motivated, dispositional account of color vision may do just that.

https://doi.org/10.1017/S0140525X03330018 Published online by Cambridge University Press