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Open Peer Commentary

Authors' Response

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and seven – Maloney 1986). Moreover, the dimensionality of color space evidently varies between species. The conclusion drawn in the target article (sect. 1.4, para. 12) is that color cannot "be found in the (distal or proximal) physical stimuli." Instead, we are urged to give "more attention to the local, context-dependent features of perception than to the high-level, physically invariant properties of the environment" emphasized in "the original Gibsonian program" (sect. 1.4, para. 7; sect. 3, para. 9).

Taking the opposite tack, I have proposed that we search for invariances at still more general and abstract levels (Shepard 1987; 1990; 1991). For highly visual diurnal species, the single most important factor determining the dimensionality of its color space may not be the ill defined five to seven degrees of freedom of surface reflectances in its present local niche. Instead, it may be the more sharply delimited number of degrees of freedom that has long constrained natural illumination in the terrestrial environment as a whole. These three degrees of freedom correspond to (1) a *light-dark variation* between direct illumination from midday sun and clear sky versus reduced but spectrally similar illumination reaching an object only by scattering from achromatic clouds, cliffs, or moon, (2) a *red-green variation* between the long-wavelength-rich illumination direct from a low sun versus the long-wavelength-rich illumination penetrating an atmosphere loaded with water vapor, and (3) a *blue-yellow variation* between mostly short-wavelength-rich illumination scattered to an object from clear sky versus mostly short-wavelength-poor illumination reaching that object directly from the sun (see Judd et al. 1964; Dixon 1978; Shepard 1990; 1991). It may be no accident that these three degrees of freedom of terrestrial illumination also correspond to the light-dark, red-green, and blue-yellow opponent processes proposed for the human visual system, on quite different (psychophysical and neurophysiological) grounds, by Hering (1878) and Hurvich and Jameson (1957).

The target article does speak of the "perception" of conditions of illumination (sect. 1.4, para. 6; sect. 2.1, para. 4[iii]). But what is most important, I suggest, is not the *perception* of conditions of illumination, as such, but the perceptual *compensation* for variations in that illumination in order to recognize significant objects. On the basis of Maloney & Wandell's (1986) general linear model for color vision, I have argued that regardless of how much of the spectral reflectances of surfaces our visual systems represent, our systems must analyze visual input into three chromatic channels to correct for the illumination and, thereby, to achieve constancy of color (including lightness) under terrestrial conditions (Shepard 1990; 1991). Indeed, even if the chromatic colors of the objects themselves were irrelevant for us, even if we required a representation that (like a "black-and-white" photograph) was merely achromatic, we would still need an initial analysis into three chromatic channels for the resulting shades-of-gray representation to achieve lightness constancy.

Of course, the chromatic aspects of objects are not irrelevant for us. Like our ancestors, we benefit from the ability to detect red berries against green leaves even when these are of similar achromatic lightnesses. For the same reason, the need for constancy is almost certainly not the only factor influencing the dimensionalities of color representations. Species that are active only in nocturnal, deep sea, murky, or subterranean environments, for example, may manage with fewer than three dimensions of color representation because limitations on the quantity or quality of available light (or on the varieties of visible surfaces) either permits sufficient constancy with fewer than three dimensions or precludes analysis into as many as three chromatically distinct channels. For other species, dimensions of representation of spectral reflectances beyond the three needed for constancy may have become a significant factor in the identification of foods, mates, offspring, competitors, predators, or the like. In some species, more than three chromatic channels may also have been favored to compensate for additional, subtle degrees of freedom of lighting that are peculiar to their niches – for example, variations in illumination transmitted through media or scattered from surfaces (such as leafy canopies) having special, spectrally selective properties.

The structure of color space for each species may thus be shaped, in part, by "local, context-dependent features" of that species' niche. But such shaping must be understood in the context of an evolutionary explanation of color perception in terms of general constraints on objects, surfaces, and illumination in the world. In particular, the possibility should not be neglected that the three-dimensionality of the color spaces of such diverse and highly visual species as the human and the bee may most fundamentally reflect a long enduring abstract invariant of that world, namely, the prevailing three-dimensionality of variations in terrestrial illumination.

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Ecological subjectivism?

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Thompson et al. promise a new model of color vision that departs from two approaches: One (objectivism) is that color is a property of objects and that perception consists in the internalization of these physical properties; the other (subjectivism) is that colors are produced by and explainable in terms of neurophysiological functioning. The data cited are intriguing, the emphasis on a more biologically realistic, less anthropocentric approach to vision is important, and the discussion of the limitations of the two views is instructive, especially in scientific circles where theoretical presuppositions of this type go unnoticed but influence the direction taken by research. Unfortunately, however, the promised new model never materializes.

Thompson et al. argue convincingly against the objectivist view with data that show, for example, that what is perceived is determined by the sensory-motor properties of the animal. The view that vision is about "recovering" properties of objects ignores the fact that what counts as an object is determined in part by the structure and behavior of the animal. I have argued elsewhere (Skarda 1989) that if perception were about recovering the features of objects then whenever the same object impinges on receptors it should lead to neural processing that remains identical for that object over time. This does not happen. Perception is different from what the objectivist model would have us believe.

Against subjectivism, the authors point out that the facts about color vision do not all yield to a neurophysiological analysis. What are these facts? They include the observation that animals are adaptive as their organic environment is, and that they have coevolved: The animal's activity changes the environment and tells us about what it perceives and how it perceives it. Thus, to understand the perceptual object for any given animal, we must take this ecological information into account.

But the fact that we need this information to explain the perceptual *object*, does not automatically result in a new model of color vision. It is consistent with objectivism, for example, that the animal's neurophysiological structure affects what is perceived, that receptors act as "filters" for objective properties. Subjectivists, like Hardin, accept this point already. All researchers determine what is perceived on the basis of animal behavior, and no one I know of quarrels with the fact that animals and their environments coevolve. So what is new about Thompson et al.'s model of perception? How does it differ from the tradition they criticize?

In section 2.4 (para. 11) Thompson et al. claim that "the visual system must achieve" segmentation of the visual world and later (para. 14) they tell us that surfaces are properties of the world but "also figure as properties of the perceptual object." Underlying these claims is the traditional model of perception: Perception occurs when an object causally impinges on the organism, producing an internal counterpart ("perceptual object") of the world. Clearly, this perceptual object is animal-relative and hence evolutionarily determined; furthermore, if we want to know about *what the animal perceives*, then a "purely neurophysiological" account is unsatisfactory because it is pitched at the wrong level of description (I urge the authors to pay closer attention to this issue). None of this ensures that the authors' model represents a departure from the tradition, however.

The problem is a very difficult one. Thompson et al.'s "ecological subjectivism" is not a solution, even if it represents a move in the right direction. The problem is to find a new model of perception rather than to reject one "ism" in favor of its alternative. Significantly, most of the authors' arguments are directed against objectivism, and the subjectivism they criticize is a very weak and muddled version indeed, if their account is accurate. But there is nothing "new" about the authors' model of vision. They accept the traditional problem: The perceptual object is not identical with the physical object, so how does vision succeed? The tradition offers two options, subjectivism and objectivism. Thompson et al. opt for the subjectivist approach, but rather than reject the world outright, they attempt to "modify" it using evolution and interaction to get a better fit, to eliminate the gap or to make it less noticeable. The world, they tell us, has the form it has because it has been shaped by animal activity; it bears the imprint of this interaction. In effect, the authors have discovered a less subjective-appearing solution by transforming the world into a sensory-motor experience. This, however, is not a new solution to the problem of perception. It is an optical illusion.

Confusing structure and function

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Thompson, Palacios & Varela lay out a case for the importance of comparative date in cognitive science. Using color vision, they contrast objectivism (presented as a computational variant of realism) and neurological subjectivism (a modern version of Muller's law of specific nerve energies). They conclude that an updated version of subjectivism, one that attends to ecological niche and evolutionary history, is most preferable. In this commentary, I make the point that Thompson et al. appear headed into a subjectivist swamp by too much emphasis on structural differences between the visual systems of pigeons and people. I suggest that the problem comes from the following two mistakes: They equate structure with function and explanation with intersubjective intercourse. I then discuss work on form/categorical perception by pigeons that underscores the importance of the distinction between structure and function, concluding that this line of work provides more support for objectivism than Thompson et al. would anticipate.

Structure and function are related, but they are not isomorphic. A new species was not created anew. It was cobbled together from old parts, now used in new situations. Those old parts were themselves cobbled. The path of speciation is a twist little maze, and reproductive success does not follow necessaril from design principles taught in the better engineering school (Gould & Lewontin 1979). But there is a common factor, a worl in which all designs must work satisfactorily. Vertebrate o invertebrate, all types of bodies reflect different mechanisms o adaptation to the common constant of gravity.

Thompson et al. document the differences in retinal physiology between people and pigeons, which suggest that there are fundamental differences in their color spaces. Althoug there will be arguments about the particular values of th minima, the potential of a pentachromatic system in the pigeo seems likely. It is also true that this produces a problem o commensurability, a pentachromatic (or even tetrachromatic space could not be completely mapped onto a trichromatic space without remainder. What concerns me is the meaning of th problem for Thompson et al. They do not seem to be so worried about accounting for what pigeons do, but what they "experience" (their discussion in section 2.3 is a clear example). On this point I suggest that they have fallen into the classical mire o solipsism in their speculative concern over the unbridgeable gaps between species. Their mistake is to attend too much to differences and to miss the common function. Their mistake is akin to worrying about the different number-worlds of slide rules and electronic calculators. The mechanisms of the two are very different; the errors each mechanism is liable to produce are different; and the types of problems for which each mechanism is most accurate are different. Examined very closely, slide rules and electronic calculators produce the fundamental problems of commensurability that exist between analog and digital systems. But the emphasis on differences misses the great commonality in function. It misses the important similarity over specified scales of problems. There may be several satisfactory paths to a common goal.

The alternative of multiple mechanisms for a common function is seen in operant conditioning research on form/categorical perception in pigeons. Operant research on form perception by pigeons has been historically *un*concerned with the structural differences between pigeons' and people's visual systems. Initially the question was whether pigeons could be trained to form perceptual categories that people used, such as the distinction between the presence and absence of a person in a photographic slide (Herrnstein & Loveland 1964). It has turned out that pigeons can be trained successfully with such discriminations – more easily than often assumed. The field quickly moved on to the question of mapping the borders of such categories. What were the domains of perceptual categories in pigeons that were exposed to such procedures? These turned out to be remarkably humanlike across many tasks. A pigeon's segmentation of categories with natural variation (such as fish or the leaves of trees) turned out to be quite similar to distinctions used by people (Cerella 1979; Herrnstein & de Villiers 1980). Multidimensional scaling and cluster analysis of discrimination performance with human-specific categories, like the American alphabet or geometric forms, also looked very similar to data from people (Blough 1982; 1990). More abstractly, the production of integral or configural stimulus effects in pigeons was driven by the factors of proximity and similarity in a manner similar to people (Steele 1990).

The similarities in performance between pigeons and people were close enough to justify the initial suggestion that the means underlying the performance were the same (Herrnstein et al. 1976). Pigeons see the way we see. That interpretation is now strongly in doubt. Pigeons do not seem to use information in the scene that we normally use (Cerella 1982; 1990). And pigeons use information in scenes that typically escapes our attention or is even hard for us to use when informed (Green 1983; Vaughn & Green 1983). Thus you have the following combination. On the one hand, similarity of categorization performance; on the other hand, dissimilarity of mechanisms underlying this performance.