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Representation and constraints: the inverse problem and the structure of visual space

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Abstract

Visual space can be distinguished from physical space. The first is found in visual experience, while the second is defined independently of perception. Theorists have wondered about the relation between the two. Some investigators have concluded that visual space is non-Euclidean, and that it does not have a single metric structure. Here it is argued (1) that visual space exhibits contraction in all three dimensions with increasing distance from the observer, (2) that experienced features of this contraction (including the apparent convergence of lines in visual experience that are produced from physically parallel stimuli in ordinary viewing conditions) are not the same as would be the experience of a perspective projection onto a fronto-parallel plane, and (3) that such contraction is consistent with size constancy. These properties of visual space are different from those that would be predicted if spatial perception resulted from the successful solution of the inverse problem. They are consistent with the notion that optical constraints have been internalized. More generally, they are also consistent with the notion that visual spatial structures bear a resemblance relation to physical spatial structures. This notion supports a type of representational relation that is distinct from mere causal correspondence. The reticence of some philosophers and psychologists to discuss the structure of phenomenal space is diagnosed in terms of the simple materialism and the functionalism of the 1970s and 1980s.

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1. Introduction

At an ecologically relevant scale, the physical world is spatially three-dimensional, and human beings (along with many other animals) perceive a world in three dimensions when light appropriately affects the eyes. The light obeys known laws of transmission, which form a set of constraints (C) on the proximal stimulus patterns (S_p) that light reflected from surfaces of objects (distal stimuli, S_d) can present to the visual system. Perceptual psychologists have investigated the processes (P) that take those patterns (or aspects of them) as input and yield perceptual representations (R) as output. Various proposals have been made about the relations among objects O, environmental constraints C, processes P, and perceptual representations R (along with the use of such representations to guide action). These proposals constitute the various theories or subtheories of visual perception.

Various questions can be posed about the perceptual situation. In psychophysics, one asks how the properties of S_d are represented R. In information processing psychology, one seeks to characterize the processes (IP) that mediate between the proximal stimulus S_p and R. Theorists such as Gibson (1950) and Shepard (1984, 1994) have proposed that the existence of constraints C can provide a clue to the structure of representations R; Shepard would add that attention to C can point the way to a proper characterization of the task or end-goal as well as the structure of IP. Nonetheless, it may be useful to describe perceptual outcomes independently of a specific process mode. Leeuwenberg's structural information theory is one example (Leeuwenberg, 1969; van der Helm, 2000), and geometrical descriptions of visual space may provide another.

As a philosopher engaged by contemporary visual theories, my intention is to step back and pose some questions about the assumptions underlying the notion of environmental constraints and attendant conceptions of the representational task of perception. Taking a cue from Kubovy and Epstein (2001), I will examine the extent to which environmental constraints as discussed by Shepard (1984, 1994) can be said actually to have been "internalized" by the visual system. Taking a further cue from Buffart and Leeuwenberg (1978), I will ultimately frame this question in terms of the relation between representations R and distal stimuli S_d in spatial perception. My aim is to describe some general features of this relation, drawing on the experimental literature and my own observations. In so doing, I will challenge the widely held assumption that the global structure of visual space, or of the object structures presented in visual space, is Euclidean. I will also query a methodological premise about the relations among R, P, and S_d: that R is the result of solving an "inverse problem" of inferring the correct spatial structure of S_d from the proximal stimulus S_p along with various internal "principles" or "assumptions" about environmental structure and optical constraints (e.g., Palmer, 1999, pp. 23–24; Proffitt & Kaiser, 1998, pp. 177–182). This premise suggests that processes IP should be investigated under the assumption that they have the task of generating a veridical solution to the inverse problem.

Throughout the paper I discuss various relations between perceptual representations and physical stimuli. In these discussions I assume a realist perspective on the physical world: that it has the spatial properties ordinarily assigned to it in physical descriptions (at least at the mid-sized scale pertaining to perception), that light has properties of wavelength and frequency, and so on. The arguments I make do not require this realist perspective (they could be recast in other frameworks), [1] but adopting it makes for convenient exposition. I also discuss the phenomenal aspects of visual experience, and seek to characterize the sort of representational relation that might exist between spatial structures presented in visual experience and the spatial properties of physical objects. I do not assume a particular notion of that representational relation in advance, but introduce various notions as needed. In the meantime, the term "representation" will be employed in discussing the work of specific authors in accordance with their own usage.

2. The internalization of environmental constraints

In a series of articles, Shepard (1981, 1984, 1994) argued that many aspects of visual perception can be explained if the visual system is thought of as *internalizing* environmental regularities. He described these regularities as *constraints* on perception, or rather on successful perception and action. They are stable physical regularities that have been found in the environments of various species, perhaps for eons. Examples include the 24-h diurnal cycle of day and night, and the laws of geometrical or ecological optics (including that light is transmitted rectilinearly, and that the surfaces from which light is reflected typically belong to coherent, persisting objects). Shepard maintains that these regularities may be internalized by the perceptual system as constraints on the domain of acceptable visual representations. They would act as principles of perceptual processing, perhaps embodying sufficient information to reduce or negate the underdetermination of the distal scene by proximal stimulation.

In a careful examination of Shepard's (1994) notion of constraints, Kubovy and Epstein (2001) propose some terminological clarifications. They focus on Shepard's proposal that various principles of kinematic geometry governing the displacement of objects in three-dimensional space have been internalized. Using an apparent-motion paradigm, Shepard (1984, 1994) showed that apparent motion "solutions" to

[1] The argument of the paper can be recast within any framework that accepts that phenomenal experience is found in (at least) human perception. Beyond that, ontological commitments may vary. The arguments of the paper are, for instance, compatible with a phenomenalist perspective such as that of Ernst Mach, William James, and Bertrand Russell (see Hatfield, 2003), according to which primary reality consists of phenomenally characterized entities (Mach's elements, Russell's momentary particulars), and the physical word is, in Russell's terms, a logical construction from such entities. Questions about the representationality of spatial perception would be recast in terms of relations between (a) the spatial structures found in phenomenal experience, and (b) those posited through logical construction. Such questions can also be recast in a physicalist framework such as Dennett's (1988), which privileges physical description and treats the phenomenal as a logical (or intentional) construction. In either case, questions about the relations between phenomenal and physical spatial structure remain empirical.

various stroboscopically produced stimuli seem to embody the constraints of kinematic geometry on the displacement (including rotation and translation) of objects in physical space. Kubovy and Epstein distinguish three factors: constraints as physical regularities in the extraorganismic (or extracerebral) physical world; the internal representation of such constraints in the processes of perception, through rule following or rule instantiation (Hatfield, 1991; Kubovy & Epstein, 2001); and the internalization of such constraints through evolutionary selection. In their view, environmental constraints may set conditions on the successful operation of a visual system, and perceptual systems may meet those conditions, without the constraints being represented or instantiated in the internal processes, hence without their having been internalized through evolution. (In this case, they leave aside questions of why the perceptual system operates in accordance with environmental regularities.) They correctly portray Shepard as endorsing the contrasting view that a counterpart to environmental regularities (the principles of kinematic geometry) is both (1) internal, and (2) the result of internalization. Kubovy and Epstein (2001) argue that Shepard (1994) has not made an adequate case for these two points. They suggest that his findings could be accounted for if kinematic geometry were seen simply as a descriptive model used by the investigators to describe aspects of motion perception.

This distinction between environmental regularities and their representation is helpful as far as it goes. However, it needs to be supplemented in at least two ways. First, if (e.g.) kinematic geometry provides a useful "descriptive model" for aspects of motion perception, it is reasonable to ask what relation the descriptions of this model bear to the aspects of perception they describe. Candidate answers would include a mere relationship of analogy, or direct description (to some degree of accuracy) of aspects of perceptual structure (in this case, aspects of perceived shape and motion). If kinematic geometry provides a direct description of perceptual structures, then it can still be asked how such structures are generated in perception and why the perceptual system should exhibit precisely those structures in its representation of distal events. This question raises the second point, which is to ask what relation the perceptual structures themselves bear to their extraorganismic counterparts (physical objects moving in the world).

Kubovy and Epstein (2001, p. 621) use the term *homomorphism* to describe the relation between model and perception, and between perception and world. They do not define this term, but it is frequently used in vision science (e.g., Palmer, 1999, pp. 77–78). This term, and the earlier term *isomorphism*, can describe a variety of relations between theory (or model) and perceptual structures, and between perceptual structures and distal stimuli. Finer distinctions among these relations will allow more specific answers to our questions about theory-perception and perception-environment relations.

3. Representation and isomorphism

The original notion of perceptual isomorphism is due especially to the Gestalt psychologist Wolfgang Köhler (1929/1947); see Scheerer (1994). He proposed, as an empirical thesis, that during perception the shape of a spatial structure in the world causes brain events exhibiting similar shape ("isomorphism" means *same shape*), which yield phenomenal presentation in experience of that shape (as seen from a point of view). There is thus a threefold realization of the given spatial structure: in the extraorganismic world, in the pattern of brain events, and in the spatial structure present in perceptual experience.

The notion of isomorphism in perceptual and cognitive representation was further developed by Shepard (1975, 1981). Focusing on representation-environment relations, he distinguished three sorts of isomorphisms: first-order concrete, first-order abstract, and second-order. First-order isomorphisms involve concrete or abstract sameness of structure between two domains—in this case, between distal stimuli in perception and either brain events or functionally-defined mental representations. In Shepard's terms, Köhler and the Gestalt psychologists posited a concrete first-order spatial isomorphism between brain events and distal stimuli. He sought instead to characterize abstract first-order structural isomorphisms and second-order functional isomorphisms among representational elements. In the abstract first-order case, the representational elements would not "resemble" (in shape perception, *have the same shape as*) the distal stimulus. Rather, various brain events or representational elements would first be put in one-to-one correspondence with the elements of the stimulus; in the usual case, this would be done in virtue of the fact that the internal elements or events are in regular, causally-mediated correlation with the stimulus elements. Isomorphism now enters to describe the relations among the internal and external elements; the relations among internal elements are found to correspond (abstractly) to the relations among the external elements. The isomorphism is abstract because it consists in correspondences among logically or mathematically describable relations among elements, but does not posit an identity in the type of relation. Second-order isomorphism is then defined in terms of relations that first-order structures bear to further processing. A second-order isomorphism occurs if brain or representational structures exhibiting a first-order isomorphism yield similar results in further cognitive processing or the production of behavior.

Consider the example of a square (Shepard, 1975, 1981). A concrete first-order isomorphism would result if a square in the world gave rise, during visual perception, to a square pattern of activity in the visual cortex. Shepard (1981) follows Skinner (1963) in suggesting that the squareness of the brain process would not by itself be explanatory, because it would not explain further cognitive or behavioral responses. But he contends that the fact that some elements in the head were isomorphic to the distal rather than proximal stimulus would constitute a beginning for explanation. In order to fill out the explanation, an abstract first-order isomorphism (Shepard, 1981, p. 291) would suffice, and does not require literal sameness of shape but merely sameness of abstract structural relations. Thus, there might occur in the head four brain events that are deemed to be representational elements corresponding to the four corners of the square, and which stand in relation to one another internally in a way that represents external relations of next-to-ness and the like, without their needing to be literally next to one another. The next-to-ness relation might be represented in the brain by a specific neural-connectivity relation, and on the representational level by formal or logical relations among the representational elements corresponding to the four corners.

The notion of representation is here defined in terms of three different relations: (1) causal correlation (the representation is regularly produced by the external object); (2) abstract structure (the relations among internal elements in some way mirror the relations among external elements); and (3) functional role (representational structures enter into and guide further perceptual processing, to similar effect). The relation of causal correlation, which establishes the initial representational relation, does not depend on the notion of isomorphism. In Shepard's proposal, that notion is needed to describe the abstract correspondence between the relations among internal and external elements. This sort of abstract first-order isomorphism is what is now more typically called a *homomorphism* [2] (Palmer, 1999, p. 77), as in the usage of Kubovy and Epstein (2001).

4. Accommodating the phenomenal

In alluding to the spatial structures found in visual perception, I have been tacitly relying on a phenomenalist perspective. Thus, in mentioning a perceptual experience that presents a square, I have supposed that readers will understand what I am saying because they have experienced phenomenally present squares, and find it reasonable to describe this experienced structure using the term "square". This methodological attitude, which allows descriptions of direct experience into the ambit of perceptual research, was highly touted by the Gestalt psychologists (Köhler, 1929/1947, Chapter 1; Koffka, 1935, Chapter 2). In the period after 1950, the notion became suspect, especially outside the community of psychologists of perception. As I wish to build upon the methodological advice of the Gestaltists, these suspicions must be addressed.

Conveniently, Shepard (1975, 1981) can be taken as a representative theorist who voiced concerns that were shared by others. Although proclaiming himself a friend of phenomenology and introspection, philosophical reservations about objectivity precluded him from including phenomenal structures in the domain of scientific investigation. Having excluded the phenomenal, he defined representational relations and first- and second-order isomorphisms in terms of the physical or functional properties of brain events. By including functional relations, he abstracted away from concrete descriptions of brain activity, to a functional (and, in his terms, "mental") level of analysis of psychological processes and their behavioral upshot. When

[2] The change in terminology avoids the historical connotation of the prefix "iso" in the Gestalt notion, as signaling genuine sameness or identity of kind of relations within structures, by replacing it with the prefix "homo", which is intended to connote mere abstract similarity or alikeness of relation. In model theory an *isomorphism* implies identity of structure, whereas a *homomorphism* merely entails similarity of structure in some respects (Hodges, 1997, p. 5).

mentioning spatial representations (such as that of a square), he did not intend to describe phenomenal structures; he limited scientific discourse to functional relations among representations in the brain that could themselves be related to external physical objects (as in Place, 1956, and Smart, 1959). Phenomenal reports were to be regarded merely as instances of observable behavior. In line with the philosophical functionalism of the 1970s and 1980s (e.g., Fodor, 1975), he conceived psychological investigation as directed toward the inferred structure of internal processes, functionally conceived.

Many psychologists and philosophers have expressed skepticism about the usefulness of describing the features of phenomenal experience, or about its very existence (Dennett, 1988). Shepard (1981, pp. 280–281) offered a diagnosis for such skepticism when he described phenomenal experience as a "mental" entity that is "nonphysical", hence inaccessible to objective study. He offered two bases for this last conclusion, one ontological, one epistemological. Ontologically, visual experience presents a shape at a distance, and so on. And yet no one now believes that in the brain there is a physical event with a precisely corresponding shape, or a representation that varies in distance to some part of the brain precisely in accordance with perceived distance. It seemed to Shepard (1981, p. 280) and others that if brain states are not shaped in conformity with phenomenal content, then phenomenally experienced shape would have to be reckoned as "nonphysical". Shepard therefore restricted his discourse to abstract, functional descriptions of representational states in the brain, so as to avoid the (alleged) need to posit nonphysical entities (as in mind–body dualism or dualistic epiphenomenalism). On this way of viewing things, a materialistic psychologist who wanted to embrace phenomenal shapes would be forced to posit a neural image in the head (the physical image-in-the-head view disparaged in Shepard & Chipman, 1970)—a most unfashionable position.

This dilemma for the materialistic psychologist is based on an overly narrow conception of mind–body relations. On a broader conception, it is conceivable for a materialist to accept phenomenal structures into a materialistic framework. Such a materialist might posit that brain states have additional properties besides those presently explicable via physics and chemistry, such as the property of realizing conscious mental states with various spatially articulated phenomenal contents. This position (or a close relative) could be developed as a form of materialistic emergentism or materialistic property dualism (or as a dual-aspect monism)—none of which posit a separate substantial, nonphysical mind, and so none of which lead to Cartesian dualism. [3]

[3] According to materialistic emergentism, the ability of the brain to realize conscious, phenomenal experience is an as yet unexplained emergent property arising from the combination of physical and chemical properties found in the brain. According to materialistic property dualism (or perhaps n-alism), material things have, in addition to the properties now described by physics and chemistry, other properties, including mental properties. According to dual-aspect monism, the single basic stuff of the universe (not itself characterized as material) has both mental and physical properties. For a review of these positions, see Crane (2001, ch. 2); on the need to move beyond simplistic materialism, see Strawson (1994).

Accordingly, brain events that are not literally square might nonetheless realize the phenomenal experience of a square, which presents a squarely structured region.

The properties of brain events that serve to realize the conscious presentation of visual qualities, such as shapes or colors, are not at present known. But if, as seems reasonable to suppose, phenomenal experience is realized by brain events of some kind or other, then phenomenal contents such as color and shape can be realized by the brain without the brain itself taking on the shapes and colors found in phenomenal experience. Those shapes and colors have the status of *intentional content*—content that is present in a mental representation, but in such a way that the represented properties do not literally pertain to the brain state that realizes the representation (nor to some other ghostly entity such as a state of a soul). [4] A phenomenal square can be present in consciousness without requiring that anything physically square be present in the brain (or, for an imagined square, in the immediate environment), or that a substantial square patch occur in a separate mental substance.

The metaphysical accounts of the mind–body relation that permit phenomenal content without requiring either brain images or dualism have not been definitively established. But neither have the competing versions of materialism, including those that would exclude phenomenal content. Hence, current philosophical thinking on the mind–body problem does not require denying phenomenally spatial objects in subjective experience. In my view it would be a strategic error for psychology to require a definitive solution to the mind–body problem before permitting serious discussion of the properties of phenomenal experience. Those psychologists who posit a phenomenal domain (see next section) should be allowed to proceed with their investigations independently of predicted solutions to the mind–body problem. If such theorists would like to proceed consistently with the assumption of materialism (or, less contentiously, with a denial of substance dualism), they should know that various extant philosophical proposals regard phenomenal contents as realized by or emergent from brain activity (Crane, 2001; Strawson, 1994).

Shepard (1981) also raised an epistemological problem for phenomenal experience, the alleged privacy of each person's experience (the privacy of other minds). This led him to conclude that in any case phenomenal experience lies outside the domain of scientific investigation. In support, he referred to philosophical discussions of privacy and subjectivity. But this conclusion also is not forced by current philosophy. The assumption that one person's experience is like another's (beyond detectable abnormalities, such as color blindness) can be based on the notion of biological sameness of kind (Flanagan, 1992, Chapter 5). Further, on the assumption of a law-

[4] This notion of *intentional content* invokes Brentano (1874/1995). It accepts that a square spatial structure can be present in phenomenal experience without the brain (or some state of the soul) literally being square, and without the phenomenal content being wholly reducible to its relation to physical squares. It is distinct from the "intentionalism" of Dretske (1995) and Tye (1995), and applies the term "content" with a broader meaning than do they, who (along with others) equate content with informational content. Here, whatever is phenomenally present counts as phenomenal content.

ful universe, one might posit psychophysiological laws relating brain states to phenomenal experience (Chalmers, 1996, Chapter 6). In principle, as a matter of natural law things might be such that visual cortexes of the same biological kind produce color experience of similar kind under similar stimulation.

This excursus into metaphysics and epistemology is intended to loosen the grip of mid-20th century philosophy of mind, which retained vestiges of narrow behaviorism and physicalism even in Fodorean functionalism (Hatfield, 2002). The longstanding suspicion of phenomenal experience has abated in philosophy. Short of definitive word on the mind–body problem, psychologists might ask themselves why they should be unwilling to infer from the character of their own experience to that of other human beings. If they will make that inference, then in addition to inferring similarity of functional process from similarity in behavioral response, they should not hesitate to infer from such evidence to similarity of phenomenal experience under similar stimulus conditions.

5. Phenomenality and representation

Some contemporary theorists take phenomenal experience as an object of explanation in perceptual psychology (e.g., Buffart & Leeuwenberg, 1978; Hershenson, 1999; Indow, 1991; Palmer, 1999; Rock, 1975; Rock, 1983, p. 32, 52). The Gestalt psychologist Koffka (1935) posed as a central problem for perceptual theory the question "Why do things look as they do?" Rock (1975) and Palmer (1999), among others, refer to this question in formulating the tasks of perceptual theory. They interpret the question as Koffka intended—as a question about the visual experience of perceivers, and thus as requesting an explanation for the characteristics of visual experience itself.

Perceptual theorists who define phenomenal experience as an object of explanation regularly distinguish between the *physical properties* of objects and the *phenomenal presentation* (or *representation*) of those properties. [5] As a matter of physical description, objects may reflect light differently depending on its wavelength, may have a shape, be at a specific distance from the perceiver, in a particular direction, and so on. In visual experience, objects appear with phenomenal color, have a phenomenal shape, appear to be at a distance, in a direction, and so on. The phenomenal presentation of objects depends subjectively on the perceiver, while the object's physical properties may depend on the object alone (as with spectral reflectance properties) or on its physical relation to the environment or the perceiver's body. Phenomenal colors (reds, greens, etc.) are thus distinguished from their physical basis in objects, phenomenal shapes can be distinguished from the physical shapes

[5] I prefer the term "presentation" for describing the contents of phenomenal experience themselves, and here I use the term "representation" to pose questions about the information-carrying or representational relation between presented contents and distal objects.

of things, and so on. [6] All the same, we use similar terms to describe physical properties and their phenomenal counterparts; thus, we talk both of the squareness of the physical object, and of the phenomenally present square.

A distinction between phenomenal presentations and corresponding object properties permits questions to be posed about the relation between them. In particular, it allows discussion of whether, and how, phenomenal presentations of colors, shapes, and so on *represent* distal objects. Assuming that a primary function of perception is to represent the distal environment, it is plausible to consider at least some phenomenal presentations to be representations. Such representations fall within the immediately available content of visual experience, including phenomenally presented colors, shapes, sizes, and distances of things (this list is not exhaustive). Although earlier theorists held that the "real" phenomenally immediate experience is of a two-dimensional image, those visual theorists who adopt phenomenalist descriptions today typically take immediate experience to be as of a world in three-dimensions. Various spatial and chromatic aspects of visual experience can then be taken to represent the corresponding physical object properties.

Although phenomenal representations are tacitly endorsed by the theorists mentioned above—or explicitly acknowledged, as in Rock (1975)—the manner in which they represent typically is not discussed. The primary models of representation remain causal correspondence and (abstract) homomorphism (Palmer, 1999, p. 77). However, allowing representation via phenomenal spatial structures would permit a different kind of representational relation to be considered, that of *resemblance*. This opportunity can be clarified by contrast with standard causal and homomorphic accounts.

When representations are assigned their referents through causal correlation, they serve essentially as referring signs. As such, the alignment of elemental signs with their referents can be arbitrary. In Shepard's (1981, p. 290) terms, such signs are "unanalyzable" or "unitary". A homogeneous color is an unanalyzable or a unitary sign for a (class of) physical reflectance properties. In a spatial structure, the representation as a whole is analyzable into subparts, but Shepard emphasizes that the representational relation is not one of resemblance or concrete first-order isomorphism; perceptual representations of a square do not relate to distal squares by presenting the same structure (a square structure or its close relative). Rather, representational elements gain the referring relation through causal correspondence, and structural properties (such as squareness) are represented through abstract first-order isomorphisms and second-order functional isomorphisms (Shepard, 1981). Here again the representing elements can be arbitrarily related to their referents, as signs. The elements and relations in the representing world need not resemble the elements and relations in the represented world (Palmer, 1999, pp. 77–78).

[6] Several popular philosophical theories of representation, preserving the anti-phenomenalist bias of functionalism, deny any such distinction (Dretske, 1995, Chapter 3; Tye, 1995, Chapters 4–5). They take the content of perceptual representations to be exhaustively analyzable into the physical properties of distal objects (perhaps together with functional facts about the organism).

Now consider the relations between phenomenal presentations and represented objects or properties. We may agree with Rock (1975, pp. 4–5) and other theorists that phenomenal color does not resemble the corresponding surface property that causes us to see color. With phenomenal color, the representational relation might well depend on causal correspondence. In the case of spatial properties, however, resemblance can again enter the picture. [7] Phenomenally presented spatial structures exhibit objects with a shape, at a distance, in a direction, with or without a motion, and so on. Those are (phenomenally) spatially articulated presentational contents. The represented domain (of physical objects) includes objects that have a physical shape, are at a distance, in a physically defined direction, are moving or not, and so on. The types of phenomenally presented properties (various phenomenal spatial properties) exhibit homogenous kinds of structure by comparison with the represented properties (physical spatial properties), even if those structures are not realized in the same manner (intentionally in the one case, physically in the other).

6. Phenomenal representation, internalization, and constraints

With the concept of phenomenal spatial structure in place, we can consider more fully the relations among representations, constraints, and internalization. In the process, we can fill out the scheme of organism-environment and representation-environment relations.

Let us consider various ways in which environmental conditions, regularities, or universals might be internalized. We will begin with the general notion of internalization, and move on to cases of homomorphism and resemblance.

One sort of internalization would result from a literal incorporation of physical and chemical properties of the environment into the organism. Organisms are of course constructed from naturally occurring chemical elements, some of which conjoin to form organic molecules not otherwise found in nature. In the process of evolution, some features of the inorganic chemical environment were internalized. Many marine invertebrates show concentrations of common ions such as sodium, magnesium, calcium, potassium, chlorine, and sulfate in their body fluids that are very close to those of sea water (Schmidt-Nielsen, 1990, Chapter 8). Even amphibians and

[7] The notion of resemblance long provided a philosophically attractive means of accounting for the representational relation between the spatial properties of material objects and the spatial aspects of phenomenal experience. It fell out of favor in the 1950s and 1960s, with the rise of a simple version of the materialistic identity theory (e.g., Place, 1956; Smart, 1959). It was widely assumed that to take phenomenal spatial structure seriously, one would need to posit concretely isomorphic shaped structures in the brain (Shepard & Chipman, 1970). Further, Goodman (1968), relying on "new look" psychology of perception and radical empirism, mounted an apparently convincing challenge to the notion of resemblance itself as applied to pictorial representations, including the spatial aspect of perception. Recent philosophers (Hopkins, 1998) are rehabilitating the notion of resemblance as applied to spatial perception, emphasizing especially outline shape (from a point of view). Herein, resemblance will include 3-D surface-shape from a point of view, under the characteristic contraction of visual space (Section 7).

mammals show relative concentrations of sodium, potassium, and calcium ions very close to the relative concentrations of sea water (Loewy & Siekevitz, 1969, p. 87). Here, presumably, sea water was literally internalized from the ambient environment of early living cells, and some aspects of the internalized environment have been retained throughout the course of evolution.

This is not the sort of internalization that Shepard and his critics have been concerned with. They have been concerned with internalized regularities that show up as processing rules that internally constrain the structure of representations. However, comparing such cases with the literal internalization of ionic concentrations may help us to differentiate various relations obtaining between environmental regularities and an internalized counterpart.

Shepard's favorite example of internalization is the diurnal cycle (Shepard, 1984, 1994). Keeping in mind internalized ion concentrations, we may ask if this is a case of internalized representation, or simply the internalization of a physical regularity by mimicking or re-instantiating it. Organisms have internal processes that show a 24-h cycle, which can cause them to exhibit waking and sleeping behavior on a 24-h schedule even under unvarying ambient light (as in an enclosed laboratory with constant lighting). Such animals have an internal physicochemical process that cycles diurnally. Does this internal process *represent* the diurnal time cycle, or simply *correspond* to it physically? The answer is not obvious. There are clear cases of internal states that do serve as representations (many states of the perceptual and cognitive systems, or so I am assuming for present purposes). In the diurnal regulation of behavior, however, the basis for choosing between saying a system *represents* the 24-h cycle or merely *mimics* that cycle is not clear. Presumably, further investigation would proceed by examining, species by species, the role that diurnally-cycling internal states play in the regulation behavior, the extent to which such states engage with systems that are paradigmatically psychological, and so on.

The notion of internalized environmental regularities can suggest a variety of representation-environment relations even in perceptual and cognitive cases. The most complete form of internalization would be for the perceiver to produce an internal model of the three-dimensional environment, down to its physical and chemical details. Clearly, perceptual systems do not make accessible such complete representations, whether via phenomenal structures or abstract homomorphisms. Rather, perception represents only some features of the environment.

Which features of the environment does perception represent, and how does it do so? This question concerns the function or task of perception, [8] and its manner of realization in specific cases (here, in human visual perception). A common assumption of many recent theorists is that perception aims at *veridicality*; that is, it aims to form representations that present the properties of the environment truthfully, so as

[8] The notion of *function* invoked here is to be distinguished from Fodorean functionalism. The latter concerned input-output relations (whether for processing units postulated within a system, or between stimulus and response). The former notion builds upon the concept of biological function and the related notion of task analysis; see Hatfield (1991) and Shapiro (1994).

to guide behavior (Palmer, 1999, p. 6, 24; Rock, 1975, p. 3, 274). The notion of *truth* here is not that of the proposition or judgment, but of accurately conforming to a standard, as when wood is planed *true*.

Granting this description of the aim of perception, the manner of accomplishment can vary greatly. Consider the sense of taste. Recent work suggests that taste receptors are responsive to the shapes of molecules, not to their specific chemical composition (Lindemann, 2001). Shall we say that experienced tastes represent molecule shapes, or that they merely partition gustatory stimuli into contrast classes? In the latter case, a specific phenomenal taste could represent each class as an arbitrary sign; it would not need to be ascribed the function of conveying information about molecular shape. Accordingly, the function of taste would not be to detect specific chemical structures, but to establish regular gustatory contrasts among naturally occurring ingestants. The existence of relevantly different soluble substances would constrain the possibilities of taste, but not so as to tempt one to say that such constraints were internalized as process rules or as specific representational content.

For vision, even assuming veridicality as the primary aim, conceptions vary concerning which environmental features are to be represented and in what manner. According to one prominent conception, the task of visual perception is to accomplish an *inverse inference* from the ambient light received at the eyes to the various physical properties that have structured the light (making use of auxiliary principles or assumptions to reduce or eliminate the ambiguity of the proximal stimulus S_p). Accordingly, the features of the world that perception is presumed to represent are the precise physical features that structure light. Some theories of color perception propose that its task is to specify a spectral reflectance distribution (Palmer, 1999, Chapter 3; Shepard, 1994). This is to conceive color vision by analogy with a physical instrument. Such theories suggest that color vision aims to represent the unique spectral reflectance distribution seen on a given occasion. To the extent that the visual system does not provide such representations (as happens with metamerism, where different distributions can look the same under a given illuminant), it fails to achieve its representational goal (for discussion, see Hatfield, 1992).

A second way of asking what is represented in vision (and how it is represented) refines Koffka's (1935) classical question. Asking why things look as they do invites consideration of the phenomenal. We can refine the question by asking a prior one: "How do things look?" This more basic question also concerns the phenomenal. In responding to his question, Koffka rejected the answer that things look as they do because they are as they are. Phenomenally speaking, perception groups things, it enhances figure/ground relations, and it represents reflectances with phenomenal colors. These are ways things look. By comparing them with a physical description of how things are, we can make progress toward understanding how things are represented in visual experience.

How do things look? Typically, we see surfaces spatially arrayed and imbued with color. Surface colors exhibit considerable perceptual constancy, though not perfectly. Not only does metamerism occur, but a single colored surface that retains "the same" color across changes in illumination does not remain phenomenally unchanged (Mausfeld, 1998). If we do not regard color perception as having the function of fully decoupling reflectance from illumination and so solving the inverse problem, these facts need not signal perceptual failure. We might instead see color perception as having the function of yielding comparatively stable distinctions of objects from one another by their differing reflectance properties. The existence of classes of objects that differ in reflectance properties would still be necessary for color vision, and to that extent would serve as an environmental constraint. But perfect inverse inference to the exact spectrophotometric properties of objects would not be required as output. Nor would one need to think of vision as having internalized the photic regularities of natural illuminants (as in Shepard, 1994); it would be enough for the visual system to have hit upon representational processes and mechanisms that permitted a stable division of naturally occurring objects by reflectance groupings (Hatfield, 1992; Thompson, 1995). For this, the various models that achieve less than perfect constancy would well suffice (Mausfeld, 1998).

How do things look spatially? One answer can be generated from the supposition, held by some theorists (e.g., Epstein, 1995; Shepard, 1994, pp. 16), that spatial perception successfully solves the inverse problem, and so infers back to the three-dimensional (nearly) Euclidean objects of the ambient physical environment. This conception of the outcome spatial perception, as presenting a phenomenally Euclidean world (under full cue conditions), has frequently been expressed (Gibson, 1950, p. 12; Heelan, 1983, pp. 27–28; Palmer, 1999, p. 23; Toye, 1986, p. 91;Wagner, 1985, p. 493). But does it match visual phenomenology? Do things actually appear with their Euclidean structure?

This question can be approached via size constancy. Descriptions of size constancy typically say that despite the fact that retinal image size (or visual angle) varies with distance for a given object, "perceived size is not affected by distance" (Gordon, 1997, p. 11; also Schwartz, 1994, p. 59). This makes it sound as if, when size constancy obtains, the same physical thing at different distances *looks exactly the same* as regards size, as if the inverse problem had been perfectly solved. Data show that perceivers, when asked to attend to true size, match perceived test stimuli at a distance to standards close at hand much more nearly according to true (physical) size than retinal image size. At the same time, some theorists who are very familiar with these results are troubled by the fact that, phenomenally, objects of the same physical size take up less of the visual field with increased distance. As Rock (1975, pp. 38–39) observed, even under conditions of constancy the same physical thing, when farther away, exhibits a smaller phenomenal extensity, or takes up less of the visual field. [9]

[9] Rock (1975) made this observation under conditions of constancy, as opposed to conditions in which observers have been asked to adopt a special attitude, such as the "painter's attitude". He explained the point about visual extensity as follows: "The reader can appreciate what is meant here by noting that when he holds a finger a few inches from his eye, it looms large, filling almost the entire visual field, despite the fact that it still appears to be the size of a finger. By contrast, a finger (perhaps someone else's) viewed at a distance, is sensed as filling only a small sector of the field, although its size is perceived to be the same as when it was viewed nearby" (Rock, 1975, pp. 37–38). Extensity pertains to visual angle; as described here, it is not equivalent to the phenomenology of imagining the features of objects projected in perspective onto a plane in front of the observer.

Consider further that when looking down a street of constant physical width, or a straight hallway, or railroad tracks, the curb, the walls, and the rails phenomenally converge. They take up less of the horizontal visual field farther away. Also, an area of flat ground takes up less of the field farther away than a physically equal area nearer to the observer. By comparison with physical measurements, there is contraction along the dimension stretching away from the observer (see Toye, 1986; Wagner, 1985). At the same time, the edges of the street, the walls of the hall, and the rails do not seem themselves to be approaching one another, nor do they appear to shrink physically; for near to middle distances, constancy prevails. Nonetheless, phenomenally the scene is not an accurate Euclidean portrayal of the physical structures, since parallels converge and surfaces contract with distance. The phenomenal world is not unproblematically Euclidean. Solving the inverse problem cannot be the whole story in spatial vision. If it were, there would be no spatial contraction and no phenomenal convergence under conditions of constancy.

7. Visual space

Some theorists regard visual experience as presenting a *visual space* (French, 1987; Heelan, 1983; Hershenson, 1999; Indow, 1991, 1995; Luneburg, 1947; Suppes, 1977). Consonant with our phenomenal approach, we will assume the existence of such a space and examine more closely its relation to physical space. I will take visual space to be defined by the spatial structures that are presented phenomenally, including the experience of empty volume between bounding surfaces. Such phenomenal structures are found in everyday perceptions of ground and sky or walls and furniture. Physical space includes the spatial structure of the ground and of atmospheric processes that yield the illusion of a domed sky, and that of the walls and furniture.

Considerable psychological work has been done on particular aspects of this relation, especially for distance, size, and shape perception. However, as Indow (1991) observes, the question of the relation of physical space to visual space overall has only rarely been examined. Haber (1986) notes that there have been few studies of the perception of an entire spatial layout, as opposed to imagining or remembering a layout (but see Toye, 1986; Wagner, 1985). By far the most intensive work in this area has concerned the geometry of visual space, although discussion of point-of-view in early vision (Marr, 1982) is also pertinent.

One way to think about the relation between visual space and physical space is to ask whether visual space has a metric structure and, if so, how that structure is related to physical space. Buffart and Leeuwenberg (1978, p. 4) posed the question as follows:

> It is attractive to imagine visual space as metric space… If one regards visual space as metric space, one must investigate whether and to what extent objects in the physical space determine these metrics. The fact that there are stimuli that are perceived differently from their physical existence gives rise to considering visual space as non-Euclidean space.

The question of what metric structure visual space itself has, if any, is distinct from a question about the relation between visual space and physical objects. Neither question need in itself make assumptions about the use or instantiation of geometrical formalisms in the perceptual process. Rather, these questions are usually seen as seeking the geometrical structures that correctly describe phenomenal spatial structures.

The question about the metric of visual space itself was investigated by Luneburg (1947), who concluded that it is a non-Euclidean hyperbolic space of constant negative curvature. Luneberg relied on earlier experiments in which subjects arranged black cords against a white ground (Hillebrand, 1902), or arranged small test lights in an otherwise dark alley (Blumenfeld, 1913). The subjects sought to achieve either phenomenally parallel rows or equidistant receding intervals. From the reported findings, Luneburg (1947) inferred a hyperbolic metric. Subsequent research has given him some support, though it is now questioned whether one should expect to find a single metric exhibited by structures in visual space (Indow, 1991, 1995). It may be that different metrics apply at different distances or for differing tasks, or when the environment is not reduced to a few lights against the dark. A recent finding suggests that while there may be no consistent metric to visual space, it internally satisfies the weaker constraints of affine geometrical structure (Todd, Oomes, Koenderink, & Kappers, 2001).

The second question concerns the relation between physical objects (or whole visual scenes) and visual space. Indow (1991, p. 450) emphasizes that when human beings view whole scenes, their visual space "is dynamic, not a solid empty container into which various percepts are put without affecting its contours and intrinsic structure". From observations taken in natural environments, investigators have concluded that there is no single metric relating physical space to visual space (Indow, 1991; Koenderink, van Doorn, & Lappin, 2000).

I wish to step back from the question of a precise metrical structure, and examine some general features of visual space in human perception. It will be helpful to do this from two perspectives. First, we can ask what we would expect about the general structure of visual space if the inverse problem were successfully solved and the results presented in phenomenal experience. Second, we can ask what picture arises if we pursue further Rock's (1975) comments about extensity and our own observations pertaining to visual space.

Human visual perception takes place from a point of view. Supposing that the world itself is (very close to) a three-dimensional Euclidean structure, a veridical *visual* representation of that world nonetheless has a point of view. While there may be "object-centered" representations at later stages of visual cognition (Marr, 1982), the primary visual spatial representation, Marr's "2 1/2-D sketch", has the characteristic that only the parts of objects that face the viewer are directly seen.

Accepting that point-of-view is intrinsic to specifically visual representation, we may still ask whether the spatial structure found in full-cue spatial perception is three-dimensionally Euclidean, or not. Let us investigate the properties we should expect to find in a phenomenal perceptual representation of a scene if the inverse problem were successfully solved and Euclidean structure were recovered fully.

Consider the view looking straight down a closed alley with physically parallel walls. Assume the viewer is located at one end of the alley, midway between the side walls. From this point of view, the facing walls of the alley would be seen, not the sides away from the viewer. With the perceiver fixating the horizontal center of the end wall at eye-height, each position along the visible portions of the end and side walls would be seen at an angle from the straight-ahead. Since, by hypothesis, the inverse problem has been solved and the results brought into phenomenal experience, each position would be phenomenally represented at its exact distance from the viewer, in full conformity with the physical Euclidean structure of the alley (Fig. 1). Further, the width and height of the alley would be represented with absolute constancy. The segment CD would therefore appear exactly the same size as the segment AB, and the heights of columns attached to the walls and rising vertically from A and C would appear to be the same, and so on.

Although some descriptions of size constancy suggest that the inverse problem is fully solved (Epstein, 1995; Kubovy & Epstein, 2001), the implications (drawn in the previous paragraph) do not match phenomenal descriptions of visual experience. Perhaps we can develop a description that takes into account both varying extensity and the tendency toward constancy.

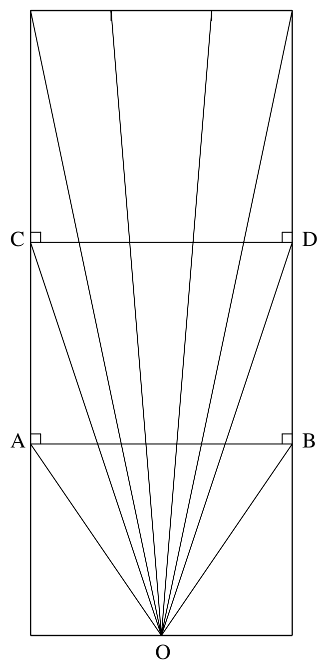

Fig. 1. Physical and visual space with the inverse problem fully and correctly solved. A top view of observer (O) looking down an alley with physically parallel sides, showing lines of sight at eye level. The structure presented in visual space is congruent with the structure in physical space.

Let us continue with perception of an alley. It will be best if the reader looks down an actual hallway. The sides of the walls facing the viewer are seen, and the various positions along the walls are phenomenally present under a specific angle; indeed, let us assume it is the same angle as previously. [10] However, we must now take into account the fact that, phenomenally, the parallel lines running away from the observer converge in the visual field. If we assume a constant phenomenal convergence in a projective transformation from one three-dimensional structure to another, we can generate Fig. 2. It shows the visual space (phenomenal space) of an observer O in dashed lines, by contrast with the physical space that reflects light into the perceiver's eyes (the alley structure itself). The phenomenal structure as described here is intended to capture common aspects of phenomenal experience in viewing a closed alley, though in a simplified and idealized way. Phenomenal segment *CD* now takes up less extent than segment *AB*, and the columns at *C* and *D* would take up correspondingly less extent vertically. The physical structure is represented in an ever more phenomenally contracted manner, in proportion to physical distance. [11]

Observation suggests that the gross structure of this phenomenal space is a projective transformation of physical space. In a projective transformation line segments map to line segments (preserving straightness), and junctions and between-ness relations are preserved. [12] For planes perpendicular to the line of sight, the plane in visual space is (in gross structure) related to a corresponding plane in physical space by a transformation known as a *similarity*. In this transformation, affine relations are preserved, hence, parallels map to parallels, and in addition shape is preserved; only size is different, and is here contracted in the phenomenal structure in relation to its physical counterpart. For planes along the line of sight (the floor and walls), the relation is merely projective (parallels are not conserved).

Two further points may clarify this phenomenal description and its graphic representation. First, the phenomenology represented in Fig. 2 is not of a two-dimen-

[10] For the situations represented in Figs. 1 and 2, let us assume a cyclopean viewpoint, so that the angles are defined from a point between the two eyes (Hershenson, 1999, ch. 2). Then, to assume that the points in the alley are seen under the same angle in both cases is just to assume that phenomenal visual direction is accurate in relation to physical direction, even if (as in Fig. 2) phenomenal distance contracts with respect to physical distance.

[11] Fig. 2 presents a generic representation of the gross structure of a particular visual space. It simplifies by assuming that the projection is from one Euclidean structure to another (from an isotropic, infinite Euclidean space to a finite model of a visual space); it may well be that a non-Euclidean model would better fit this visual space. To get some sense of the contraction, preliminary observations were taken in a hallway 1.5 m wide. Two observers, while standing in the center of the hallway, aligned a comparison stimulus placed directly in front of them just below eye level to match the perceived convergence of the left wall at 1.5–2 m in front of them, and again at 3.5 to 4 m; the mean value for two observations from each of two observers was 9° and 8°. Fig. 2, which is merely illustrative, shows each side wall converging at an angle of 5°.

[12] The projective relation here is a mathematical relation between geometrical descriptions of physical space and phenomenal space; although the relation between the two spaces is causally mediated by an optical projection into the observer's eyes, the present projective relation pertains exclusively to the two spaces as given structures, not to their causal relation. On projective geometry, see Yaglom (1962–1975).

sional or flat scene such as might result from taking the painter's attitude. Perceiving the alley as if projected onto a plane a few feet in front of the observer would be an instance of the painter's attitude. It yields a dramatically different spatial structure. For instance, the angles between a vertical line on the wall (not shown) and the line where wall and floor meet at A and B would be much more acute than when the base lines of the alley are experienced as receding in depth (as in Fig. 2). [13] The phenomenology of Fig. 2 is of three-dimensional depth. [14] Locations on the walls are seen at a distance, even though they are not phenomenally presented at the precise inverse or actual physical distance. Distances are contracted, but present. Perceived size does not reduce to visual angle; distance conditions it. Extensity alone does not determine phenomenally presented size; *CD* is phenomenally larger than would be $A'B'$, even though $A'B'$ would take up the same visual extent. [15]

Second, this description need not imply a lack of constancy, on two counts. First, according to the relational (or proportionality) hypothesis for size constancy (reviewed in Rock, 1975, Chapter 2, and Palmer, 1999, Chapter 7), constancy arises from the constant proportion objects bear to one another when viewed together at various distances. These proportions remain constant because all objects undergo the same contraction. If I observe a man and his dog, the dog remains knee-high whether I observe the pair at 5 or at 20 m. These objective proportions are preserved even though phenomenal space is contracted. Second, constancy judgments may be attained despite phenomenal contraction if part of what underlies such judgments is a further cognitive act, which uses phenomenally perceived layout to infer Euclidean size. Indow (1991) calls this the "Euclidean mapping", and he assumes that it goes on even if phenomenal space is non-Euclidean (or is projectively contracted). In the situation in Fig. 2, perceivers might treat the phenomenally contracted spatial structure as a representation of a physically Euclidean structure. In *personal space* (Cutting & Vishton, 1995), the effects of contraction are nonexistent or negligible (in the central portion of the visual field). Those sizes might be taken as standard sizes. The

[13] In preliminary observations in the hallway described in note 11, observers set a caliper to match (1) the perceived angle at which the floor–wall junction recedes from a vertical door frame 2.8 m in front of the observation post, and then (2) to match the angle for the same junction when imaginatively projected onto a plane at arm's length in front of them (they were allowed to close one eye if they wanted). In four observations, the mean value in the first condition was 85°, in the second condition, 29°.

[14] French (1987) has argued that even if our experience includes the surface of the 2 1/2-D sketch (varying in depth), a two-dimensional topology is adequate to describe such a surface. (Helmholtz, 1910/1925, p. 159, made a similar point.) From this, he concludes that visual space is "really" two-dimensional. However, even in describing the surface present in the 2 1/2-D sketch, it is convenient to use a three-dimensional space in which the surface is embedded. More importantly, if distance from the perceiver is taken to be a part of phenomenal experience (and hence as an aspect of phenomenal space as presented in experience), as I have taken it here, then three dimensions are required for describing visual space.

[15] The present description thus differs from Rock's (1975) theoretical description of extensity. Rock equated perceived extensity with visual angle, and hence with "projective size, analytic size, or visual-field size" (Rock, 1975, p. 39, note). But Fig. 2 represents phenomenal size in accordance with both visual angle and (contracted) distance. Hence, things seen at different distances under the same angle vary in phenomenal size, as remarked above.

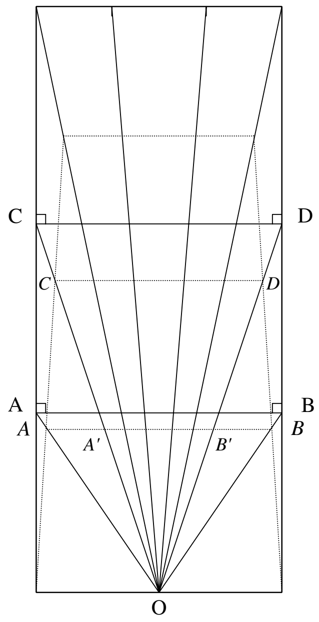

Fig. 2. Phenomenal space as a transformation (contraction) of physical space. The physical space, observer, and lines of sight are as in Fig. 1. Visual space is now represented by dotted lines, showing the phenomenal convergence of the sides of the alley and the contraction of distance. Phenomenal visual direction is assumed to match physical direction.

phenomenally contracted spatial structures with which more distant objects are presented would then be used to judge (or might tacitly be associated with) isotropic Euclidean physical structure. This might occur through conscious learning, unconscious association or judgment, or innately. The relation between phenomenal spatial structure and perceivers' judgments of spatial properties is complex (Carlson, 1977), and this Euclidean mapping has been little investigated.

The precise geometry of visual space remains unknown, and it may not have a homogeneous metric structure. Still, a phenomenological description of the sort associated with Fig. 2 illustrates how visual space can present us with objects in depth (preserving various objective proportions, and various nonmetric relations), without phenomenally presenting an isotropic Euclidean space. This sort of description is consistent with the notion that structures in visual space *resemble* (but are not congruent with) physical space; so are the more specific investigations of geometrical transformations between physical and visual space (e.g., Koenderink, Van Doorn, Kappers, & Todd, 2002; Todd et al., 2001). This resemblance relation rests on the projective relations described above between structures in visual and those in physical space (such as lines, angles, and surfaces). It can sustain a notion of veridicality in which information about physical spatial structure is phenomenally presented by a resembling spatial structure.

8. Representation and the tasks of visual perception

Visual perception allows sighted organisms to interact effectively with their environments. To serve that function perception must represent the environment with some degree of accuracy. Need it represent the environment "as it is"? That depends on the notion of accuracy or veridicality in play. Clearly, full and accurate representation of the physical, chemical, or biological properties of the environment is not required, nor does perceptual representation even remotely approach such completeness. Otherwise, knowledge of nature would be easier to attain.

In Section 5, I distinguished two sorts of relations between perceptual representation and the represented environment: a sign relation, and a relation of resemblance. In principle, it would be possible for the perceptual system to rely exclusively on a sign relation in carrying out its task. That is, perception might simply generate regular correspondences between types of environmental state and arbitrarily selected states of the organism. The organism would be well served if certain representational signs were realized in it *if and only if* certain biologically salient states of affairs obtained in the world. A flower of a certain reflectance property would induce one internal state, a shadow pattern with a certain rate of increase in area would induce another; these might then guide behavior (e.g., approach or avoidance).

Color is a good candidate for a sign-representational relation. Objects differentially reflect light of various wavelengths, but they appear phenomenally red, green, yellow, blue, and so on. These phenomenal colors do not resemble a spectral reflectance property, but they can serve as signs for various classes of reflectances.

Reflecting on this relationship, we might say that the world appears colored because we experience it that way. That is, the property presented as phenomenal color is not an intrinsic or basic physical property (as it was thought to be in Aristotelian physics). Phenomenal color has intentional or phenomenal existence as a sign for properties of physical surfaces. We see the world as colored because of the phenomenal properties of the vehicle that represents it to us, phenomenal color experience.

It would in principle also be possible for spatial relations to be represented entirely through sign relations. An arbitrarily complex homomorphism of elements and relations could represent arbitrarily complex spatial structures. Thus, triplets of numbers can represent locations in three-dimensional space. If these triplets are encoded as numerals (or sequences of neural spikes, or what have you), the spatial properties of the representational vehicle are irrelevant to their representing function. No resemblance relation would be needed. (Edelman, 1998, develops Shepard's second-order isomorphism along such lines.)

However, there are grounds for positing a resemblance relation in human spatial perception between the represented domain (Euclidean three-dimensional physical space from a point of view) and the representing domain (a contracted projective transformation, with or without homogeneous metric). Physical spatial structures are represented by phenomenal spatial structures. Unlike a mere sign-relation, both the representing and the represented domains exhibit spatial structure; the representing domain represents physical spatial structures via transformed but similar phenomenal spatial structures. It did not have to be that way, but it is. Why so? I am tempted to say that we see the world as spatial because it is that way. Assuming that the world actually has spatial structure, we may presume that human representational capacities have been shaped to present that structure via phenomenal visual space. Although philosophical skeptics or idealists might contend that space is no more "really" a property of the world than phenomenal color, and hence that we merely think the world is spatial because we experience it that way, a touch of realism about the physical world suggests the opposite.

During the mid-20th century, talk of phenomenal or visual space was nearly banned from psychology and philosophy. The arguments reviewed by Shepard (1981), examined in Section 4, offered some insight into this curious phenomenon. In those days, it seemed as if a simple materialism might suffice for thinking about the mind–body problem. At the same time, some perceptual psychologists continued to think and write about phenomenal experience (Rock, 1975), and some theorists distinguished between (phenomenally defined) visual space and physical space (Buffart & Leeuwenberg, 1978; Luneburg, 1947), a distinction much invoked of late (Hershenson, 1999; Indow, 1991; Koenderink et al., 2000, 2002; Todd et al., 2001). More recent discussions in philosophy of mind (e.g., Chalmers, 1996; Strawson, 1994) suggest that the considerations summarized by Shepard (1981) were less constraining on perceptual theory than he imagined. Perceptual theorizing is constrained not only by regularities in the environment (and possibly their internal representation). It is also constrained by philosophical presuppositions. In both domains, continuing research can reveal new features of constraints and create a new environment for theorizing.

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