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# On specification and the senses

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**Abstract:** In this target article we question the assumption that perception is divided into separate domains of vision, hearing, touch, taste, and smell. We review implications of this assumption for theories of perception and for our understanding of ambient energy arrays (e.g., the optic and acoustic arrays) that are available to perceptual systems. We analyze three hypotheses about relations between ambient arrays and physical reality: (1) that there is an ambiguous relation between ambient energy arrays and physical reality, (2) that there is a unique relation between individual energy arrays and physical reality, and (3) that there is a redundant but unambiguous relation, within or across arrays, between energy arrays and physical reality. This is followed by a review of the physics of motion, focusing on the existence and status of referents for physical motion. Our review indicates that it is not possible, in principle, for there to be a unique relation between physical motion and the structure of individual energy arrays. We argue that physical motion relative to different referents is specified only in the *global array,* which consists of higher-order relations across different forms of energy. The existence of specificity in the global array is consistent with the idea of direct perception, and so poses a challenge to traditional, inference-based theories of perception and cognition. However, it also presents a challenge to much of the ecological approach to perception and action, which has accepted the assumption of separate senses.

**Keywords:** epistemology; information; intersensory; perception; perceptual learning; sensory neurophysiology; sensory systems; specification

## 1. Introduction

One of the fundamental questions of perceptual theory is whether the structured energy fields that are available to perceptual systems are sufficient, in and of themselves, for accurate perception. If potential sensory stimulation[1] is not sufficient, then accurate perception must depend upon operations carried out by the animal, such as inferential processing. Thus, the assumption that potential sensory stimulation is insufficient for accurate perception leads to the hypothesis that perception is indirect (i.e., accurate perception requires the addition, presumably mental, of information that is not available in sensory stimulation) which, in turn, leads theorists to focus on internal processing as the locus of the most important issues in perception. On the other hand, if potential sensory stimulation is sufficient for accurate perception, then perception can be direct, that is, accurate without the addition of information beyond what is available in sensory stimulation. The latter view is central to the ecological approach to perception and action (Gibson 1979/1986). Proponents of the ecological approach stress that ambient arrays are structured by the *animal-environment interaction* (that is, by the position and motion of the animal relative to its environment), and that this structuring is governed by physical law (i.e., laws of the propagation, reflection, and absorption of energy) in such a way that any given physical reality gives rise to a unique structure or pattern in ambient energy. This leads to the hypothesis that potential sensory stimulation is sufficient for accurate perception because the animal-environment interaction is *specified* in the spatiotemporal structure of ambient arrays. Specification refers to a lawful, 1:1 relation between patterns in ambient arrays and the aspects of the animal environment interaction that give rise to them (Shaw et al. 1982). The ecological approach to perception and action is an established theory with broad empirical support, and for this reason we do not review it at length here (for

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general presentations of the ecological approach see Gibson 1966; 1986; Goldfield 1995; Michaels & Carello 1981; Turvey et al. 1981).

Specification is an hypothesis about the nature and status of ambient arrays before the stimulation of sensory receptors. Thus, the debate about specificity is not a psychological debate. It is a debate about relations between states of the world and the energy patterns to which those states give rise, prior to and independent of sensory stimulation or any psychological process (Gibson 1986; Kugler & Turvey 1987; Reed 1996; Runeson & Frykholm 1983;).

In this target article we question existing approaches to the concept of specification, which are based on the assumption that specification exists (or does not exist) in individual forms of energy, such as the optic and acoustic arrays. We present a novel argument for the existence of specification. Because we question existing views that assume the existence of specification, our analysis presents a challenge to theories based on these views, such as the ecological approach to perception and action. At the same time, our argument for a new form of specification presents a challenge to theories that assume that potential sensory stimulation bears an ambiguous relation to reality. Thus, our analysis has consequences for theories of perception that are based on inferential processing. Our analysis implies that all theories of perception derived from existing views of specification are compromised by fundamental errors.

Discussions of specification, both pro and con, have focused on the structure of single forms of energy, such as light. However, behavior produces simultaneous changes in the structure of multiple forms of ambient energy. For example, locomotion produces changes in the stimulation of (at least) the visual, vestibular, and somatosensory systems. Even the most elementary and pervasive acts, such as breathing and controlling posture, produce changes in the stimulation of multiple perceptual systems. This basic fact has had little influence on general theories of perception, and it has received little attention in discussions of specification.

We suggest that the multisensory consequences of behavior may have fundamental implications for the nature of perception. We propose that perceptual systems do not function independently, and that any attempt to understand them independently must be fundamentally incomplete. Such a position has occasionally been argued (e.g., Sherrington 1906; Welch & Warren 1986); however, our argument differs from others in important ways. We will attempt to redefine perception, not as a process of picking up information through a group of disparate "channels," and not as a set of interactions among discrete modalities, but as the pick-up of information that exists in irreducible patterns across different forms of energy. Consistent with the ecological approach to perception and action (Gibson 1986) we assume that behaviorally relevant aspects of reality are specified. However, we will argue that specification exists only in patterns that extend across different forms of ambient energy.

Our position is inspired in part by James Gibson's (1966) theory of perceptual systems. However, we believe that with respect to relations between the senses there are some ambiguities in Gibson's presentation. In some instances, Gibson argued that information available to different perceptual systems is redundant (we discuss this in sect. 3.3.2), while in other cases he suggested that information exists in relations across forms of energy (sect. 6.1). We will argue that these positions are mutually exclusive. After presenting our view we discuss its relation to Gibson's (sect. 6.2.2). [See also Ullman: "Against Direct Perception" BBS 3(3) 1980.]

Our view of perception resembles contemporary dynamical theories of action, for which action consists of coordination between distinct units, and should be defined at the level of macroscopic variables, or *order parameters* (e.g., Haken 1983; Kelso 1995; Thelen & Smith 1994; Turvey et al. 1978). In dynamical theories of behavior, a given action cannot be understood as the motion of a single motor "unit," or as the additive contributions of the motions of multiple units (Reed 1982). Similarly, for perception, we propose that there exist macroscopic variables, consisting of relations between different forms of ambient energy, that these provide information about the animal-environment interaction; and that information exists only in these macroscopic variables, that is, that it does not exist in the structure of individual forms of energy. In the present article we do not claim that these informational macroscopic variables are order parameters per se, exhibiting properties such as circular causality, enslaving, or time-scale conventions. Rather, we argue that with respect to specification the whole is not only greater than, but qualitatively different from, the sum of the parts.

We begin with a discussion of the assumption that there exists a set of distinct perceptual systems that operate more or less independently of one another, which we call *the assumption of separate senses.* We suggest that this assumption may not be justified. This suggests the possibility of alternative views of the senses. In section 3 we argue that the assumption of separate senses leads to problems for existing views of specification. These problems arise from the assumption that specification exists in individual ambient arrays, that is, in structures that may be sampled by separate senses. In section 4 we show that these problems extend to the level of physics. In section 5 we conclude that the concept of specification is incompatible with the assumption of separate senses, and we discuss some general consequences of this for the interpretation of subjective judgments about motion. In section 6 we present an alternative view of specification, which requires the rejection of the assumption of separate senses. Our decision to begin with the assumption of separate senses is for purposes of explication, not from logical necessity. The argument could be presented in the reverse order, that is, our alternate view of specification could be used to motivate a reconsideration of the assumption of separate senses.

## 2. The assumption of separate senses

Throughout history, theories of perception have embodied an assumption that perception is achieved via several sensory modalities. The assumption of separate senses underlies virtually all theory and research on perception. It is assumed that there are multiple perceptual systems (the number typically is five, but this is of secondary importance). The senses are thought of as being "separate and interacting modalities" (Smith 1994, p. xi; cf. Bekesy 1959), such that the function of individual perceptual systems "provides *basic* information" that is needed in "under-



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standing the interaction between or among these modalities" (Welch & Warren 1986, p. 3; emphasis added). Boring (1950, p. 182) referred to the division of perception by senses as one of psychology's "primary principles of classification."

The assumption of separate senses may seem to be so self-evident as to be atheoretical (i.e., free of implications for theories of perception). We will argue that the assumption carries profound theoretical implications. In section 6 we will present an alternative view, in which perception is not divided into distinct perceptual systems. If there are credible alternatives to the assumption of separate senses, then some rationale must be offered to motivate its retention.

### 2.1. A pervasive assumption

The assumption of separate senses is so basic that it is implicit even at the introductory level. Undergraduate textbooks on psychology are organized in terms of individual senses, with chapters on vision, hearing, touch, and so on (e.g., Matlin & Foley 1992). No justification for this parsing is offered. The assumption of separate senses is reflected in the existence of sense-specific journals (e.g., *Vision Research*, *The Journal of Auditory Research*, *The Journal of Vestibular Research*) and in treatises attempting to account for perception within a single modality (e.g., Cutting 1986; Gibson 1986; Handel 1989). It is implicit in theory and research in areas of cognition such as learning, attention, memory, and imagery, each of which is commonly considered in the context of individual senses (e.g., "visual cognition," Pinker 1985; "auditory imagery," Reisberg 1992). We have been unable to locate an explicit justification of the assumption of separate senses in the philosophical, behavioral, or neurophysiological literatures (e.g., Ackerman 1990; Gibson 1966; Heil 1983; Milne & Milne 1962; Pieron 1952).

### 2.2. Historical origins

The assumption of separate senses has been handed down to modern science from protoscientific natural philosophers who received it, in turn, from pre-scientific epistemologists. Boring (1950) attributed it to Aristotle, Locke, and Berkeley. Yet none of these scholars approached the issue directly.

In the *de Anima,* Aristotle (1931, p. 425b) enumerated the senses, and asked "why we have more senses than one." He answered in terms of *special objects* and *common sensibles.* Each sense has its special object, "that which cannot be perceived by any other sense than that one in respect of which no error is possible; in this sense color is the special object of sight, sound of hearing, flavor of taste," (1931, p. 418a). This is in contrast with common sensibles, which are "perceptible by any and all of the senses" (1931, p. 418a). Among the common sensibles are movement, rest, number, figure, and magnitude (Marks 1978; cf. Gibson 1983). For Aristotle, multiple senses were required "to prevent a failure to apprehend the common sensibles . . . The fact that the common sensibles are given in the objects of more than one sense reveals their distinction from each and all of the special sensibles" (1931, p. 425b). Thus, Aristotle's view is that multiple perceptual systems are required in order for us to distinguish percepts that are general across senses from those that are peculiar to any one sense. However, this begs the question. Both his query and his argument assume the prior existence of separate senses. Only under this assumption does it make sense to ask why we have more than one.

Later philosophers have not addressed the issue at all. Locke (1689/1975), in discussing the origin of ideas, appeared to take for granted the existence of distinct senses:

> Our senses, conversant about particular sensible objects, do convey into the mind, several distinct perceptions of things, according to those various ways, wherein the objects do affect them: And thus we come by those ideas, we have of yellow, white, heat, cold, soft, hard, bitter, sweet, and all those which we call sensible qualities, which when I say the senses convey into the mind, I mean, they from external objects convey into the mind what produces there those perceptions. (p. 105)

Berkeley's position was similar:

> Sitting in my study I hear a coach drive along the street; I look through the casement and see it; I walk out and enter it. Thus, common speech would incline one to think I heard, saw, and touched the same thing, to wit, the coach. It is nevertheless certain the ideas intromitted by each sense are widely different and distinct from each other. (1709/1975 p. 22)

What is the source of this basic assumption? One source is the existence of anatomically distinct receptor systems. Another is the existence of different forms of stimulus energy. A third is neurophysiological differences between the senses. We consider these in turn.

### 2.3. Anatomy

Sensory receptors have different anatomy and different anatomical locations (e.g., eyes, ears, tongue, nasal cavity, skin, muscles, joints). However, classification on the basis of anatomy depends upon the prior acceptance of the assumption that the senses exist and operate either exclusively or primarily as independent units. The anatomical differences do not, by themselves, mandate this assumption.

Consider binaural sound localization. Sound often arrives at one ear before it arrives at the other. The time delay between arrival at the two ears constitutes an irreducible relation that is caused by the location of the sound source relative to the head (Gibson 1966). The two ears function as a single, indivisible unit in picking up this informative relation. Similarly, consider binocular stereopsis. The optic array differs at any two points of observation, such that relations between simultaneous samples of the optic array taken at two locations are influenced by the shape of objects and their spatial layout. The result is an irreducible relation between the two array samples: "The two eyes are not separate sense channels for which signals must be compared; rather they constitute a single binocular system" (Jones & Lee 1981, p. 39).

In these examples, anatomically distinct structures function in a unitary manner. In general, it is possible for anatomically distinct structures to work together to achieve irreducible, coordinated end products. By *irreducible* we mean that the activity in question ceases to exist, or is qualitatively altered, if not performed through the integrated action of anatomically distinct units.[2] The same may be true of stimulation of anatomically distinct structures in different perceptual systems (several examples of this are given in sect. 6). Thus, the anatomical differences between



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the two ears, the two eyes, and so on, are not a sufficient reason for parsing perception into distinct senses (cf. Gibson 1966, p. 42).[3]

### 2.4. Energy

A second possibility is that we might distinguish among the senses on the basis of stimulus energy:

> Seeing involves the activity of extracting information from light radiation; hearing occurs when a creature gains information from pressure waves of certain sorts; smell and taste involve the extraction of information from chemical features of the environment . . . touch incorporates the capacity to obtain information about things via mechanical contact of some sort. (Heil 1983, p. 8)

However, this is problematic, also. One cannot generate a list of stimulus energies without prior knowledge of perceptual systems. For example, defining vision as the pickup of information from light requires a definition of "light". The electromagnetic spectrum is a continuum that has no inherent partitions. Only a narrow band of the spectrum is associated with vision and thus called "light." Therefore, defining vision in terms of electromagnetic energy requires an appeal to *visible* light, at which point the definition becomes circular. Similarly, animals are sensitive to only a limited range of acoustic frequencies, and the range of audible frequencies differs across species. This means that defining hearing in terms of acoustic energy requires an appeal to audible vibrations, at which point this definition also becomes circular.

In addition, a given form of energy may stimulate anatomically distinct receptor systems. For example, in many species infrared radiation is perceived as warmth, but in some species of snakes it is used to "see"; this is dependent on receptors that are different and separate from both the eyes and the skin (Hartline et al. 1978). Similarly, certain forms of mechanical energy are involved in touch, while others, differing only in frequency, are involved in hearing (e.g., the concussion of fireworks can be felt as well as heard). What is considered to be vision for one organism is considered to be touch for another, and perhaps audition for yet another. Thus, it seems unlikely that we can develop an *a priori* argument for the existence of separate senses from the existence of different types of ambient energy.

### 2.5. Neurophysiology

It might be argued that there is a neurophysiological basis for the existence of distinct perceptual systems. However, the nervous system does not appear to be organized in a sense-specific fashion (cf. Alexandrov & Jarvilehto 1993). Many structures in the nervous system respond to activity originating in more than one sense modality (e.g., Fishman & Michael 1973). This is true even for "seemingly dedicated unimodal regions" (Stein & Meredith 1993, p. xi; cf. Weingarten & Spinelli 1966):

> Convergence of sensory inputs [has been found] in unicellular organisms, comparatively simple multicellular organisms such as flatworms, in the higher primates, and at all intervening levels of complexity. In fact, we know of no animal with a nervous system in which the different sensory representations are organized so that they maintain exclusivity from one another. (Stein & Meredith 1993, p. xii)

For example, neurons in higher levels of the so-called visual cortex (i.e., area V4) respond selectively to a preferred orientation when a line is presented visually, but also when an invisible line is felt with the hand (Maunsell et al. 1989). Similarly, the so-called vestibular nucleus is known to respond to activity in the visual system (Stein & Meredith 1993). Thus, our current knowledge of neurophysiology cannot be used as an *a priori* justification for the assumption of separate senses.

### 2.6. Summary

The previous discussion raises questions about the existence of separate perceptual systems. We use this uncertainty to reconsider existing views of perception that are based on the assumption of separate senses. In section 3, we examine contemporary concepts of specification.

## 3. Multiple senses and specification

In this section we focus on relations between the assumed existence of separate perceptual systems and the concept of specification. We discuss three approaches to relations between the senses, which we refer to as the *no specification, modal specification,* and *independent specification* views. In many respects, these three views differ from one another profoundly. However, we will argue that in the context of intersensory relations the three views share much of the same logic. We begin with a brief review of some consequences of the hypothesis that there is no specification. We then argue that these consequences are problematic for existing views that assume the existence of specification.

### 3.1. No specification

The oldest view of specification is that there is none. This tradition is founded on the epistemological assumption that there is an ambiguous relation between sensory stimulation and physical reality (e.g., von Helmholtz 1962; Hochberg 1964; cf. Shaw et al. 1982): A given physical reality can give rise to multiple patterns in ambient arrays, and a given sensory pattern can be caused by multiple physical realities; the mapping between physical reality and patterns in sensory stimulation is many:many (Fig. 1A). In this section we present some general corollaries of the assumption of separate senses which we discuss here because they are most widely acknowledged and discussed within the no specification view.

**3.1.1. Independent percepts.** An implication of the assumption of separate senses is that each perceptual system generates an independent indication of reality. There are "visual percepts" of an event, "auditory percepts," and so on. A percept generated by one system is simultaneous with but independent of a percept generated by a different system (e.g., Clifton et al. 1994; Marks 1987). One example would be perception of a person speaking, where it is assumed that there is a visual percept of the moving lips that is independent of an auditory percept of the speech. By *independen*t we mean that speech can be heard without being seen (i.e., with the eyes closed), or seen without being heard (i.e., when viewing a television with the sound turned off). Interactions between such independent percepts could occur (e. g., in the McGurk effect, in which "seen" activity of a speaker influences perception of "heard" speech; McGurk & MacDonald 1976), but these are logically posterior to the existence of a "visual



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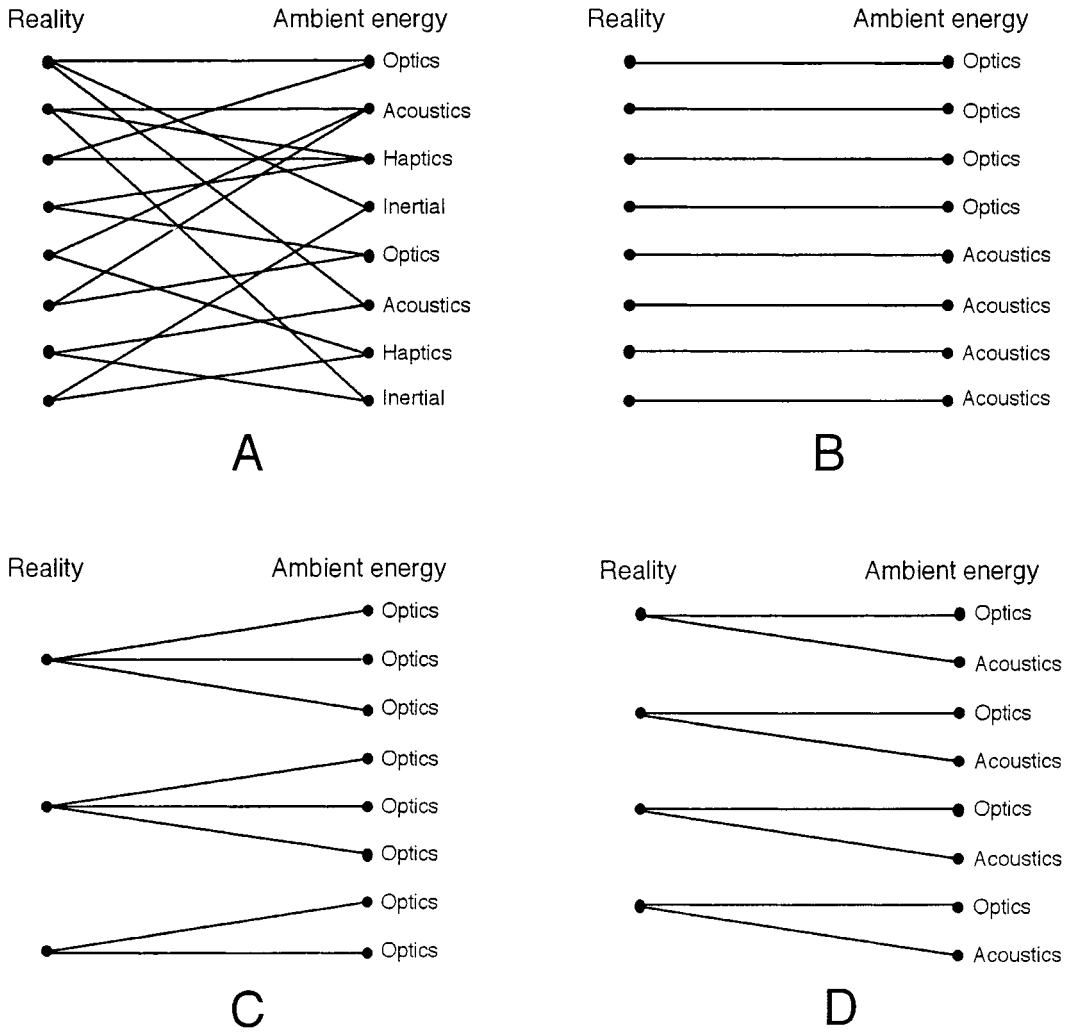



Figure 1. Some of the possible mappings between physical reality and the structure of ambient arrays. **A:** The no specification view assumes that the mapping is many:many, so that the structure in ambient arrays is ambiguous with respect to reality. **B:** The modal specification view posits 1:1 mappings, but assumes that these exist within individual ambient arrays. **C:** The multiple specification version of the independent specification view suggests that a given aspect of reality redundantly structures several parameters within a given ambient array. **D:** The amodal specification version of the independent specification view assumes that a given aspect of reality redundantly structures parameters within different ambient arrays.

percept" and an "auditory percept" of speech. Another example would be perception of one's own walking, in which there is stimulation of the visual, vestibular, and somatosensory systems, each of which is thought to be stimulated independent of the others (e.g., Lackner & DiZio 1988). "The multisensory nature of self-motion permits investigators to de-couple the relationship among sensory modalities in order to assess each one's contribution to perception" (Carpenter-Smith et al. 1995, p. 36). Interactions between the senses occur in the nervous system (i.e., "sensory convergence"), and are not properties of sensory stimulation.

In the McGurk effect, the influence of sight upon what is heard is believed to result from an internal, inferential comparison or matching of the visually perceived activity of the face and the auditorily perceived activity of the vocal tract. McGurk and MacDonald (1976, p. 747) argued that the visual-auditory interaction was produced by integration of "information from the two modalities." Green et al. (1991) argued that the presumed audio-visual integration occurs relatively late in phonetic processing, after the extraction of information about the voice characteristics of the speaker. Kuhl and Meltzoff (1984; Meltzoff & Kuhl 1994) discussed two mechanisms that might explain the McGurk effect. Each of these (identity matching and supramodal representations) is based on the assumption that integration of vision and hearing occurs within the observer. Ecologically based accounts of the McGurk effect stress that the speech event naturally structures both the optic and acoustic arrays, but continue to accept the assumption that the resulting patterns are detected via "integration of the information from the two modalities" (Fowler & Dekle 1991, p. 822; Rosenblum & Saldana 1996). These examples from divergent research domains illustrate the general implication of the assumption of separate senses, that initially (at least) each perceptual system generates an independent indication of reality.

**3.1.2. Frames of reference.** Perception can be understood as a form of measurement and, like any system of measurement, it must be conducted relative to some referent or metric. Ideally, the referents for perception should be physical; the surface of the earth, another person, and so on.



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However, if there is no specification, then there can be no direct access to physical referents (Oman 1982); any knowledge of physical referents must be a product of internal processing. This inferential processing, or unconscious inference, requires its own referents. For example, Lakatos (1993, p. 143) argued that each sense relies upon its "principal sensory dimension as the basis for interpretation." For this reason, within traditional views it is widely hypothesized that the referents for perception are properties of sensory stimulation, or *sensory reference frames* (e.g., Soechting & Flanders 1992; cf. Feldman & Levin 1995).

Different frames of reference are believed to exist for each perceptual system; acoustic structure for the auditory system, gravito-inertial force for the vestibule, anisotropic optical structure for the visual system (luminous lines, carpentered environments), and patterns of pressure within and at the surface of the body for somatosensory systems. Because they are based on qualitatively different forms of energy, these frames of reference are mutually exclusive; optical structure is qualitatively unrelated to acoustic or gravito-inertial structure, for instance. Thus, object motion (e.g., the movement of the vocal tract during speech) would be perceived by the visual system relative to an optical frame of reference, while it would be perceived by the auditory system relative to an acoustic frame of reference. Similarly, walking would give rise to changes in optical stimulation that differ qualitatively from changes in stimulation of the vestibular and somatosensory systems.

**3.1.3. Input conflict.** When a single event influences multiple ambient arrays, it will often be the case that separate arrays suggest different and incompatible (i.e., mutually exclusive) realities. In such cases, the patterns in different arrays are said to conflict with one another (e.g., Bushnell & Weinberger 1987; Harris 1965; McGurk & MacDonald 1976; Nashner et al. 1982); we refer to this as *input conflict* (Stoffregen & Riccio 1991).[4] Consider driving a car at constant velocity. Mechanical properties of the vehicle and the road produce low-amplitude vibration, which is transmitted to the body and propagates upward through the body to the head. Due to the nonrigidity of the body, there are differences in the phase and amplitude of vibration of the torso and head. Somatosensory stimulation (i.e., patterns of pressure on the torso) suggests vibration, but is ambiguous with respect to translation. Vestibular stimulation (patterns of gravito-inertial force at the head) also suggests vibration (and is ambiguous with respect to translation), but the vibration is not the same as that suggested by the somatosensory system. Visual stimulation (i.e., optical flow) suggests linear translation coupled with low-amplitude vibration. Vision will conflict with the other two systems because only vision suggests translation. In addition, there will be input conflict between patterns available to the somatosensory and vestibular systems, since these suggest different vibratory motions.

**3.1.4. Antagonistic interaction.** When there is input conflict, the organism must make a choice (usually construed as unconscious inference) about the actual state of reality. The choice must be internal because the structure of the ambient arrays is assumed to be ambiguous with respect to reality. In most theories the determination of a single percept (i.e., the resolution of conflict) is believed to rely on antagonistic interactions between the perceptual systems. One form of antagonistic interaction is sensory suppression, in which perceivers resolve conflict "by responding selectively to input in one modality and ignoring inputs in other modalities" (Lewkowicz 1994, p. 166). For example, when there is conflict between vision and touch, it often is believed that vision dominates touch in determining a single percept (e.g., Harris 1965; Marks 1978; Warren & Rossano 1991). Alternately, the antagonistic interaction may consist of a calculation in which different weights are assigned to inputs from each perceptual system (e.g., Oman 1982; Parker & Poston 1984).

**3.1.5. Illusory percepts.** If the dominant input is not correct or if there are errors in the weighting scheme, then the final percept will be inaccurate. For this reason, differences in stimulation across perceptual systems can lead to perceptual errors, or illusions (e.g., Dichgans & Brandt 1978; Warren & Rossano 1991; Witkin & Asch 1948). A large portion of perceptual research relies on subjective reports that are believed to reflect erroneous or illusory percepts (e.g., Dichgans & Brandt 1978; Leibowitz et al. 1986; Wertheim 1994).

The no specification view leads to theories of perception in which sensory stimulation is ambiguous with respect to reality, so that accurate perception depends upon internal processing to resolve the ambiguity. Given that virtually all behavior gives rise to multimodal stimulation and that much of this stimulation is nonredundant, a pervasive role of this processing must be the resolution of input conflict (Oman 1982). Proponents of the no specification view have directly addressed many of the resulting problems, and have proposed a variety of internal processes to deal with them. In the remainder of this section we argue that these problems apply equally to existing views that assume the existence of specification.

### *3.2. Modal specification*

The ecological approach to perception and action constitutes a fundamental contrast to traditional theories. Part of the contrast exists at the level of epistemology. The ecological approach rejects the assumption that the relation between potential sensory stimulation and physical reality is ambiguous. Within the ecological approach it is assumed that there is a lawful 1:1 relation, or mapping, between potential sensory stimulation and reality such that properties in ambient arrays specify the underlying physical reality (e.g., Shaw et al. 1982). Specification would make it possible for perception to be direct, that is, for veridical information about reality to be picked up without mediation by unconscious inference. We noted in section 3.1 that sensory reference frames are required in the no specification view. When specification is assumed to exist, sensory reference frames are unnecessary: If perception is direct, then perceivables can be measured relative to physical referents.

The concept of specification has been applied in a variety of ways. The most common interpretation is what we refer to as the hypothesis of modal specification. The modal specification hypothesis asserts that specificity exists in individual energy arrays (e.g., Fowler 1986; Kugler & Turvey 1987, p. 9; see Fig. 1B). The argument is that for reasons of natural law each ambient array bears a specificational relation to the underlying physical reality. Considerable effort has been directed to identifying the quantifiable parame-



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ters of ambient arrays that may have the essential 1:1 relation with aspects of physical reality. Examples include global optical flow (Gibson 1966), which is created by self-motion through an illuminated environment, patterns in the haptic array produced by the inertia tensor (Solomon & Turvey 1988), which is a property of handheld objects; and $\tau$ and its time-derivatives (e.g., Lee 1980), which can be influenced by temporal properties of impending collision, such as time-to-contact ($T_c$). Presentations of the modal specification hypothesis generally have not addressed (i.e., have neither accepted nor rejected) the possibility that information may exist in patterns that extend across different energy arrays (e.g., Fowler 1986; Kugler & Turvey 1987; Lee 1980; cf. Smith 1994).

The modal specification view does not posit relations between patterns in different ambient arrays. What are the implications of this view for situations involving simultaneous stimulation of multiple perceptual systems? By framing its premises in terms of distinct ambient arrays, the modal specification view embraces the assumption that separate senses exist. This causes problems for intersensory relations, which can be illustrated by again considering driving at constant velocity. The discrepancy (i.e., nonredundancy) between stimulation of the visual, vestibular, and somatosensory systems would constitute ambiguity concerning physical reality, that is, input conflict. If a given reality gives rise to different structures in two or more senses, then at least one of the structures must be wrong, in other words, *not* specific to reality.

This problem has not been addressed in discussions of modal specification. For example, in the literature on optical flow it is common to suppose that the optical specification of self-motion is independent of (Warren 1995) or will dominate (Lee & Lishman 1975) information about self-motion that is picked up by other sensory modalities, but there has been little discussion of the input conflict that this implies or its consequences for the concept of specification.

### 3.3. Independent specification

We have seen that in the no specification view the mapping between reality and potential sensory stimulation is assumed to be many:many, while in the modal specification view the mapping is assumed to be 1:1. The third view, which we refer to as the independent specification hypothesis (Stoffregen & Pittenger 1995), proposes that the mapping is 1:many. In this view, each aspect of physical reality gives rise to multiple, independent structures or patterns in one or more ambient arrays, yet each pattern is individually specific to the underlying reality. In the behavioral science literature this proposal has taken two forms, one positing 1:many mappings within a given ambient array (multiple specification), and the other positing 1:many mappings between arrays (amodal specification). We will argue that these two views are logically identical.

**3.3.1. Multiple specification.** In this view, a given aspect of reality is believed to influence the structure of multiple aspects of a given ambient array (Fig. 1C). These different aspects constitute "multiple sources of information" about reality, and it is hypothesized that perception can be achieved with equal fidelity on the basis of any one (Cutting & Vishton 1995). Optical examples include multiple specification of $T_c$ (Laurent et al. 1996), and multiple specification of heading (Warren et al. 1991). The most general development of this view has been presented by Cutting, who argued that observers "select among multiple sources of information" (Cutting 1986, p. 241), each of which "equally specifies the physics of a situation for an object or event" (Cutting 1991, p. 29). The result is that "all sources equally specify the object or event perceived" (Cutting 1986, p. 248).

**3.3.2. Amodal specification.** James Gibson (1966; see also Gibson 1969; 1983) argued that information can be *amodal,* or available redundantly to more than one perceptual system (as we noted earlier, James Gibson also endorsed a different position; this is discussed in sect. 6). Thus, the amodal specification view posits a 1:many mapping, with properties of reality being specified by patterns existing redundantly in different ambient arrays (Fig. 1D). James Gibson presented this as a general assertion:

> Different stimulus energies – acoustical, chemical, radiant – can all carry the same stimulus information . . . patterns in the flux of sound, touch, and light from the environment may be equivalent to one another by invariant laws of nature. (Gibson 1966, p. 55; cf. Gibson 1986, p. 115)

The concept of amodal information has a strong appeal for many ecological psychologists, who argue that it "does away completely with the paradox of detecting cross-modal correspondences when the patterns of energy formally have nothing in common. If a person is detecting information and not stimulus cues, the same information is available in various forms" (Pick 1986, p. 235). Within the ecological approach, research addressing relations between the senses has concentrated almost exclusively on the concept of amodal specification (e.g., Bahrick 1988; Fitzpatrick et al. 1994; Lee 1990; Rosenblum & Saldana 1996; cf. Smith 1994).

**3.3.3. Problems with independent specification.** For both independent specification views, the interpretation of driving at constant velocity appears to be similar to the interpretation of the no specification and modal specification views. The multiple specification view does not posit any comparison between modalities, but if such a comparison took place it would reveal a discrepancy or ambiguity concerning reality in the arrays available to the visual, somatosensory, and vestibular systems, in other words, input conflict (cf. Cutting & Vishton 1995, p. 98). If stimulus parameters can vary independently of one another, then at least one of them will vary independently of the relevant reality; hence, that variable (at least) does not bear a lawful relation to reality. This is implicit in the statement that "one can in principle vary one without varying another" (Cutting 1991, p. 29). Cutting's assertion refers to variations that might be caused by an experimenter. However, the concept of specification is based on the physics of energy propagation, which applies both within as well as beyond the laboratory. If such variations are possible in the laboratory, then they must be possible in general. This problem is reflected in empirical evaluations of the multiple specification hypothesis. For example, Laurent et al. (1996) described optical variables that, they argued, are independently specific to $T_c$. One of these was the rate of change of expansion of an optical contour, and another was the rate change of ocular convergence required to maintain binocular fixation on an approaching object. Laurent et al. (1996) proposed evaluating the relative effectiveness of these variables by using



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an experimental manipulation that altered the relation of one optical variable to $T_c$ while not influencing the other variable. By its nature, this manipulation violates the definition of specification: If it is possible to alter the relation between a stimulus variable and reality, then the stimulus variable does not have a unique, determinate relation to that reality. Thus, the multiple specification view appears to imply a lack of specificity and so implies a need for inferential processing to resolve conflict between inputs.

The concept of amodal specification is commonly used to explain crossmodal influences on the perception of objects or events that naturally structure more than one form of ambient energy. Examples include objects that influence the structure of the optic array and, when touched, of pressure on the skin (e.g., Gibson & Walker 1984); support surfaces, which influence the structure of the optic and mechanical arrays (e.g., Fitzpatrick et al. 1994); and speech, which structures the optic and acoustic arrays (e.g., Rosenblum & Saldana 1996). In such situations the concept implies a comparison between information obtained via different perceptual systems. The postulation of such a crossmodal comparison requires a prior assumption that the senses work separately in such a way that their outputs can be compared. Thus, there must be, for example, a visual perception of an event that is then compared with an independently generated haptic perception of the same event (e.g., Gibson & Walker 1984). Fowler and Dekle (1991, p. 822) proposed that speech perception is based on the "joint specification" of speech in the optic and acoustic arrays, while Rosenblum and Saldana (1996, p. 328) discussed speech in the context of "modality neutral kinematic patterns."

Among proponents of amodal specification, there has been little discussion of what happens when structures in different ambient arrays are discrepant rather than redundant. Cases where discrepancies exist, such as driving, would appear to constitute input conflict, with its attendant implication of the lack of specificity and need for inferential processing. When patterns in different arrays are caused by different events (as in studies of the McGurk effect), then the patterns must also be discrepant or conflicting (e.g., Rosenblum & Saldana 1996). The resolution of this conflict has not been discussed (e.g., Fowler & Dekle 1991; Rosenblum & Saldana 1996), but it would appear to imply an internal process. Thus, with respect to specification, the hypothesis of amodality appears to be logically identical to the hypothesis of multiple specification within a modality.

The independent specification hypothesis can be true only if each candidate stimulus parameter *always* varies uniquely with the corresponding physical event. Only then would specification be preserved, and input conflict avoided. Given that this is not true, it is not clear whether either form of the independent specification hypothesis can be correct.

### 3.4. Summary

Each view of specification is confronted with problems that arise from the existence of discrepancies among the patterns of energy available to different perceptual systems. Supporters of the no specification view have not provided a justification for the assumption of separate senses, but they have moved to address many of the issues that arise from the concept of input conflict. There has been no similar movement among supporters of the modal specification and independent specification views. We have argued that by accepting the assumption of separate senses, the modal specification and independent specification views implicitly accept the existence of input conflict, which is incompatible with the concept of specification.

## 4. Physical referents for physical motion

In section 3, our analysis focused on the possibility of a lawful relation between ambient arrays and reality. We argued that the assumption of separate senses leads to problems for theories of perception that assume the existence of specification in ambient arrays. In this section we pursue this argument at a more fundamental level. We will argue that concepts of specification that are based on individual forms of ambient energy are problematic at a level of physics that is logically prior to the structuring of ambient energy. That is, we will argue that even if there were lawful relations between some aspects of reality and the structure of individual forms of ambient energy, this would not imply that these structures bear a 1:1 relation to reality, in general. While our focus is on the concept of specification, our analysis has general implications for the interpretation (by behavioral scientists) of physical motion.

If specification exists, then it should be possible for perceivables to be measured relative to physical referents (sect. 3.2). What are these physical referents?[5] In this section we discuss referents that are used by physicists. Each of the referents that we discuss could serve as a referent for a formal (physical) analysis of motion, independent of any psychology.

### 4.1. All motion is relative

Behavior consists of motion. Perception involves motion of receptor systems (often including the whole body), and action involves motion of effectors (often including the whole body). Thus, the perception and control of behavior is largely equivalent to the perception and control of motion. This raises questions about the physics of motion.

How do we define motion? A common concept within the behavioral sciences is the idea of *absolute motion.* Behavioral scientists often refer to "absolute motion" (Wertheim 1994, p. 302) or "objective motion" (Held & Leibowitz 1994, p. 451). Yet in physics absolute motion is not a meaningful concept. In general relativity, the concept of absolute motion has no meaning (Becker 1954; Einstein & Infeld 1938). Motion can be defined only relative to some referent: for example, motion relative to the earth, motion relative to the sun, motion relative to an object (Wade & Swanston 1991, pp. 96–97).

While these physics are well understood, their consequences for analyses of behavior have not been fully addressed. We know that the earth moves relative to the sun and has a different motion relative to the galaxy, but a powerful and widespread intuition remains that at the level of behavior the earth and its gravitational field constitute an absolute referent for motion. For example, Wertheim (1994, p. 302) defined absolute motion as "motion relative to external space (i.e., 3-D 'Newtonian' space, as defined by the horizontal surface of the earth and its gravitational



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field)." Similarly, Dichgans and Brandt (1978, p. 758), equated "orientation with respect to . . . gravity" with "position of objects and the observer on the earth's surface." In both cases, the concept of absolute motion assumes that motion relative to earth gravity is equivalent to motion relative to the earth. Since the earth is a source of gravity, and since gravity does not move relative to the earth, this assumption is unquestioned. Nevertheless, it is incorrect. It is possible to be in motion relative to the earth and stationary relative to earth gravity at the same time.

### 4.2. The earth and its gravity

Earth gravity is an accelerative force that tends to move masses toward the earth's center of mass. At any point on or above the earth, gravity points toward the center of the earth (Fig. 2). A consequence of this is that a person aligned with gravity in Cincinnati will be at an angle relative to a person aligned with gravity in Paris. This is true for points arbitrarily close together: Upright people on opposite sides of town are at a slight angle relative to one another. In addition, a person traveling along a gravitational equipotential (an arc at constant distance from the earth's center of mass) will have a constant alignment relative to gravity; his instantaneous alignment relative to the instantaneous (i.e., local) direction of gravity will always be the same. If the person moves along the equipotential at constant velocity, there will be no acceleration relative to gravity, and so the body will be gravito-inertially identical to one at rest relative to the earth (Goldstein 1980). Under these conditions, the person is moving relative to the earth, but stationary relative to the earth's gravitational field.

The requirement for constant velocity motion along a gravitational equipotential is restrictive in terms of real behavior. For example, it excludes many forms of biological motion or locomotion, because these are characterized by changes in velocity. However, the requirements can be met, sometimes with surprising ease. A person would need to be restrained to prevent small accelerations due to nonrigid body motion.[6] Such a person could then be placed in an aircraft during straight and level flight (i.e., flight at constant altitude and velocity). The same effect would obtain for a restrained person in an automobile traveling at fixed speed along a straight, flat road, or on a sled gliding across ice. In these cases the person would be in motion relative to the earth, but stationary relative to gravity. These examples show that the magnitude of velocity is irrelevant: A person can be stationary relative to gravity whether he is traveling at walking speed or at hundreds of kilometers per hour.

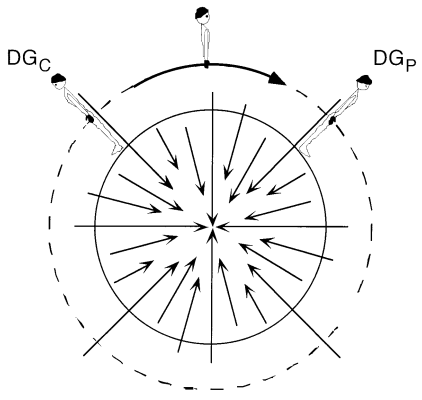



Figure 2. At any location on or above the earth's surface, earth gravity points toward the earth's center of mass. A person aligned with gravity in Cincinnati (DGC) is at an angle relative to a person aligned with gravity in Paris (DGP). A person traveling from Cincinnati to Paris at constant velocity (relative to the earth) along a gravitational equipotential is moving relative to earth but is stationary relative to gravity.

This analysis illustrates a fundamental error in any attempt to equate motion relative to the earth with motion relative to earth's gravity. The intuitively comfortable idea of absolute motion makes sense only if motion relative to gravity and motion relative to the earth's surface are identical. Given that they are not, which of these should be considered absolute, and why? This dilemma illustrates the meaninglessness of the concept of absolute motion (Becker 1954) and shows that any psychological construct of absolute motion, or of an absolute referent for motion, can have no basis in physical reality.

### 4.3. Motion relative to the direction of balance

Gravity is widely considered to be a fundamental constraint on the control of orientation and motion (e.g., Schone 1984). However, this assumption is incorrect. In general, the orientation of physical bodies (both animate and inanimate) is not influenced directly by the direction of gravity. Orientation is influenced directly by the direction of balance (Riccio & Stoffregen 1990).[7] In general, an object will remain balanced only when aligned with the direction of balance. If a pencil standing on its eraser is aligned with the direction of balance it will not fall over, even if the direction of balance differs from the direction of gravity.

For animals, changes in the direction of balance are most commonly created by their own behavior. These changes result from inertial forces that they apply to the support surface or medium in controlling orientation and locomotion. Animals often align their bodies relative to the direction of balance (Riccio 1995). For example, in curvlinear locomotion, the direction of balance is shifted out of alignment with gravity by the inertial forces generated by the animal (or vehicle) in creating the turn. When runners, cyclists, and motorcyclists lean into turns they do not fall over despite the fact that their bodies are out of alignment with gravity. This is because they remain aligned with the direction of balance as the latter rotates, just as tassels hung from a car's rearview mirror also "lean" during turns. The rotation of the direction of balance in turns results from the inertial forces that sustain the turn.

It might be argued that accelerations generated by animate behavior are of such low magnitude that they can be ignored. However, the magnitude of acceleration generated by living things commonly exceeds magnitudes that can be generated by most vehicles (Vogel 1988). Biologically generated accelerations are often brief, but this does not imply that they can be (or are) ignored. Linear acceleration changes the direction of balance (Riccio 1995), with the change being proportional to the magnitude of the acceleration. One common example concerns sprinters who prepare to begin a race by setting their body at an angle, with the torso partially supported by the hands. When the starting gun goes off they apply maximum acceleration. During a brief accelerative phase they can easily be observed (e.g., on slow-motion film) to be tilted forward (rel-



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ative to the ground) while running. As runners approach top speed, they straighten up. The initial lean prepares them to be aligned with the shift in the direction of balance that will result from their own efforts (imagine what would happen if they applied their full acceleration while standing erect). Horizontal acceleration decreases rapidly as they approach top speed. The decrease in acceleration causes the direction of balance to rotate toward the direction of gravity; as the runners straighten up, they should "track" this rotation.

The direction of balance has no fixed relation to the earth's surface, or to earth gravity. A consequence of this is that an animal can have one alignment or motion relative to the earth, another relative to gravity, and a third relative to the direction of balance. Equally important is the fact that the direction of balance is highly localized; it can differ for adjacent animals (depending of what they are doing), and it can change rapidly over time (e.g., brief changes brought about by the transient accelerations that characterize animate locomotion). This illustrates, at the level of behavior, the vacuity of any concept of absolute motion. It is to be stressed, again, that these referents (earth gravity, the direction of balance, and the earth's surface) are logically and physically distinct.

### 4.4. No privileged referent

The discussion in section 4.3 might seem to suggest that the local, instantaneous direction of balance is a fundamental or absolute referent for the control of behavior. We believe that this is not true. The reason is that the direction of balance is not always relevant to behavior. Two examples will make this point. First, orientation, and behavior in general, continue to be controlled effectively when there is no direction of balance (e.g., when the gravito-inertial force vector has a magnitude and direction of zero). This is true in orbital spaceflight, where gravity has a direction and nonzero magnitude, but the gravito-inertial force vector has a magnitude of zero and no direction. After a period of adjustment, humans and other animals control their orientation and motion very capably under such conditions. A related example occurs with water immersion. Under water, the gravito-inertial force vector has magnitude and direction, but for a person in a state of neutral buoyancy there is no direction of balance (i.e., at neutral buoyancy the gravito-inertial force vector imposes no directional constraints on orientation or behavior). People who are at neutral buoyancy have only a poor ability to perceive or control orientation and locomotion relative to the gravito-inertial force vector, but they have a good ability to perceive and control orientation and locomotion relative to other referents, such as objects or surfaces (Stoffregen & Riccio 1988). This indicates that neither the direction of balance nor the gravito-inertial force vector is a general or exclusive referent for the control of behavior.

Sometimes behavior is not controlled relative to the direction of balance even when the direction of balance is present; we sacrifice alignment with the direction of balance to some other goal. Examples include a soccer goalkeeper diving to catch a shot, and a baseball player diving to catch a fly ball. In such cases, once the player has left the ground, the ball may be the sole referent for both perception and control. Recent research on prehension suggests that reaching and grasping are organized directly with reference to the object, rather than by defining the object's position and motion relative to other referents (Garrett et al. 1998; Zaal et al. 1998).

### 4.5. Multiple, task-specific referents

The existence of logically independent referents does not imply that only one referent is relevant to behavior at any given time. It may be that animals control different aspects of their behavior relative to different referents (Riccio 1995; cf. Fouque et al. 1999). A person who is in motion relative to one referent and in stasis relative to another, for example, may simultaneously control their orientation and motion relative to both. Consider driving at constant velocity on a flat highway. During turns, as the direction of balance changes relative to the surface of the earth, the torso remains aligned with the direction of balance (that is, it rotates as the direction of balance rotates), but the head and eyes may maintain their orientation relative to the road (Fig. 3). A similar effect occurs in flight. During turns, the pilot must control the orientation (and position) of the aircraft relative to the surface of the earth (e.g., for navigation), while at the same time aircraft orientation must be maintained relative to the direction of balance (i.e., to maintain aerodynamic stability). Perception and control relative to multiple, simultaneous referents will be adaptive in most situations (Riccio 1995).

Our analysis reveals a general requirement for increased care in characterizations of motion. The existence of an unlimited number of independent physical referents means that a description of motion is meaningful if and only if it names the referent (or referents) relative to which the motion takes place. In turn, this means that across situations action may be perceived and controlled relative to different referents. The selection of referents should have a functional basis (Riccio 1995); that is, it should depend on the goals of action. One aspect of learning to perform new tasks will be the determination of which referents are relevant.

### 4.6. Summary

We have reviewed the fact that in physics there is no meaningful concept of absolute motion. We have shown this to be true in the case of motion relative to the earth, which

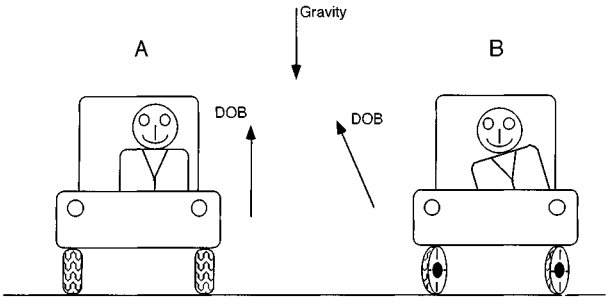



Figure 3. Multiple, simultaneous referents. The driver maintains his body in alignment with the direction of balance, while simultaneously maintaining his head and eyes in alignment with the illuminated environment (the road). During straight driving (A) the head and body are parallel, but in turns (B), when the direction of balance is not perpendicular to the road, the head and body remain aligned with their separate referents.



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differs from motion relative to the earth's gravitational field. The absence of a single, fundamental referent for motion led us to consider the existence of a variety of referents, all independent and of equal reality: None can be regarded as primary or basic to any other. Finally, this leads to the idea that motion can be analyzed (and perceived and controlled) relative to multiple simultaneous physical referents. In the next section we will consider the implications of these facts of physics for the concept of specification.

## 5. Physics and specification

In this section we discuss some of the implications of our analysis of physical referents for theories of perception. The first implication applies only to theories that posit the existence of specificity between reality and the structure of ambient energy arrays. The second implication is more general.

### 5.1. Ambiguity in single-energy arrays

Our discussion of physical referents revealed that there are an unlimited number of possible referents, all of which are mutually independent at the level of physics. Motion relative to any one of these is equally real. How does this relate to the hypothesis that the structure of ambient energy arrays is specific to reality? The specificity hypothesis is not about the nature of reality, and so is not about the existence of, or relations between physical referents. Rather, specificity is about the mapping between the physics of the animal-environment interaction and the energy fields that are available to perceptual systems. Accordingly, this mapping is logically posterior to the existence, number, and independence of physical referents. This raises questions about relations between physical referents and the structuring of ambient arrays. Does motion relative to a given physical referent impart unique structure to a particular form of ambient energy? Can motion relative to a given physical referent impart unique structure to more than one form of energy?

While all physical referents are equally real, they do not have equivalent relations to various forms of ambient energy. For example, a given event may entail motion relative to the surfaces and media that generate, reflect, or propagate light (*the illuminated environment*), yet may entail simultaneous stasis or motion relative to the direction of balance (the *gravito-inertial environment*). Changes in position or motion relative to the illuminated environment will not necessarily produce changes in position or motion relative to the direction of balance, and vice versa. This means that a given pattern of optical structure may correspond to a variety of patterns of gravito-inertial structure, and vice versa. Consider an animal moving along a gravitational equipotential (see sect. 4). The animal would be in motion relative to the illuminated environment (producing spatiotemporal changes in optical structure) but stationary relative to the direction of balance (producing spatiotemporal stasis in what we might call the *gravito-inertial array*).[8] Consider also motion in an elevator, where there are changes in gravito-inertial structure (as the elevator accelerates), but stasis in optical structure. In these cases, the gravito-inertial array does not specify real changes in position and motion relative to the illuminated environment, and the optic array does not specify real changes in position and motion relative to the gravito-inertial environment.

Similarly, the structure of the gravito-inertial array is not specific to motion relative to the surface of the earth; this is true, also, of structure in the optic array, which can vary independent of motion relative to the earth's surface. Compare a situation in which a person flies along a gravitational equipotential with a situation in which a person in a fixed-base simulator is exposed to a simulation of flight along a gravitational equipotential. Although these situations differ dramatically in their consequences for behavior (e.g., an aircraft crash can be fatal, but a simulator crash is harmless), it would not be possible to differentiate them on the basis of structure in the optic array, or in the gravito-inertial array. This is because the structure of each array is identical in these two situations (leaving aside temporary limitations in the technology of optical simulation). In general, there will not be a unique mapping of physical referents onto forms of ambient energy; some referents structure only one form of energy, while others structure multiple forms. This means that there is no single form of ambient energy whose structure is specific to position or motion relative to all physical referents. For this reason, no single form of ambient energy (i.e., no *single-energy array*) can have a specificational relation to physical motion.

Our analysis brings into question the assumption that structure in light, sound, and other forms of ambient energy are (individually) specific to physical motion and, hence, to reality in general. Two possible interpretations may be drawn from this. One is that specificity does not exist, that sensory stimulation bears an ambiguous relation to reality, and, therefore, that any approach based on specification cannot explain perception and action. The other possible conclusion is that specificity exists in something other than arrays of a single form of energy. The latter possibility is addressed in section 6.

### 5.2. Reinterpreting subjective reports

Our analysis of physical referents has important consequences for the perception of physical motion, and for interpretation (by researchers) of subjective reports of physical motion. These implications apply equally to studies that assume or reject the existence of specification. For example, motion (or stasis) of the self relative to the illuminated environment is neither more nor less real than motion (or stasis) of the self relative to the gravito-inertial environment, relative to the surface of the earth, or relative to any other physical referent. A person who is stationary relative to the surface of the earth (e.g., a person standing inside a "moving room," Lishman & Lee 1973, or seated inside a rotating drum, Dichgans & Brandt 1978) can be in motion relative to the illuminated environment. The person's motion relative to the room or drum is real, just as his stasis relative to the earth is real.

This understanding of physical reference frames motivates a substantial reinterpretation of many widely accepted concepts of perceptual error (i.e., illusion). It is widely believed that there is erroneous or illusory perception of self-motion. To underscore the importance of the concept of perceptual error, Dichgans and Brandt (1978, p. 755) began their chapter with these words: "The sensation of self motion is a common visual illusion"; this interpreta-



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tion has been accepted generally (e.g., Howard 1982; Lee & Lishman 1975; Nashner et al. 1982; Wertheim 1994). In these cases the error may be with the experimenter's assumption of an "absolute" referent for motion, and not with participants' percepts (cf. van Ingen Schenau 1980).

The statements "I am moving" and "I feel like I'm moving" previously thought to be unambiguous, are now seen to be ambiguous. Consider the case of a person at rest relative to the earth's surface who is exposed to a display of optical flow, which occurs in the cinema, in fixed-base flight simulators, and in many laboratory experiments (e.g., Dichgans & Brandt 1978; Lishman & Lee 1973). In such experiments participants are often asked to state whether they feel themselves to be moving. If they say that they are moving, they are correct (this is because they are in motion, relative to the illuminated environment), but if they say they are stationary, they are also correct (this is because they are stationary relative to the earth). The fact that both responses can be correct illustrates the ambiguous nature of questions such as "Do you feel that you are in motion?" A better question, reflecting the physics of motion, would be "Do you feel that you are in motion relative to anything, and if so, relative to what?"

This reasoning applies as well to the control of self-motion. Dichgans and Brandt (1978, p. 787) noted that "illusions" of self-motion can affect the control of orientation (posture): "deceptive visual motion impressions cause a displacement of . . . postural vertical . . . and body sway." In other words, the body sway is an error based on a mistaken percept. The error interpretation has been retained, either explicitly or implicitly, in dynamical analyses of the perception and control of self-motion (e.g., Dijkstra et al. 1994), and is common in neurophysiological research (Stein & Meredith 1993). As an example, consider the experiments of Lishman and Lee (1973), in which standing participants were exposed to optical flow created by a moving room. In a variety of conditions, subjects were asked to "report what was happening when the apparatus was in motion" (p. 290). Lishman and Lee divided these reports into those consistent with "visual information," those consistent with "mechanical information," and "other" ("A report was classified as 'other' when it did not wholly correspond to either the visual or mechanical kinaesthetic information" [p. 290]). A report that "I am moving" would be classed as "visual," while a report that "the room is moving" would be classed as "mechanical." Our analysis has shown that each of these statements is ambiguous. Reports in the "other" category were not analyzed. However, this category would include reports that were factually correct, such as "I am in motion relative to the room, but stationary relative to the floor." Lishman and Lee assumed that motion would be perceived relative to only a single referent. This assumption may have lead them to exclude correct reports from their analysis, something that occurs routinely in studies of perceived self-motion (e.g., Dichgans & Brandt 1978; Graybiel 1952; Wertheim 1994). This suggests that errors in the experience of self-motion may be less common than generally is supposed.[9]

### 5.3. Summary

The physics of motion, and of referents for motion, have important implications for the perception of motion and the interpretation of subjective reports of motion. One implication is that percepts and behaviors that are not congruent with gravity or with the earth's surface are not necessarily erroneous or illusory. This should motivate a substantial reinterpretation of many existing data reports and changes in the way in which participants are asked to report their experiences of self-motion.

We have argued that the physics of motion are logically prior to the issue of the specification of motion in ambient energy arrays, and that motion relative to different physical referents will structure some ambient arrays but not others. A major implication of this is that specificity does not exist in the structure of individual forms of ambient energy. This is not a problem for the no specification view, but it poses a fundamental problem for views, such as the ecological approach to perception and action, which assume that specification exists. If the principle of specification is to be sustained, then it must take some form other than modal specification or independent specification. This is addressed in the section 6.

## 6. Specificity in the global array

If specification cannot exist in single-energy arrays, then it may not be possible to sustain a theory of direct perception within the assumption of separate senses. In this section, we offer a novel hypothesis about specification, which does not require the assumption of separate senses. We do not attempt a formal proof of our hypothesis. Rather, we argue that it is possible and that it deserves to be tested.

### 6.1. The global array

The concept of ambient arrays was developed in the context of single forms of energy, and there is wide acceptance of the existence of (at least) the optic array and the acoustic array. We now draw attention to the existence of an ambient array, which has previously received little consideration. This array, which we call the *global array,* consists of spatiotemporal structures that extend across multiple forms of ambient energy. These patterns are higher-order in the sense that they are superordinate to (and qualitatively different from) the patterns that exist within single-energy arrays. Thus, in principle, information in the global array may be detected without prior or concurrent sensitivity to structure in single-energy arrays (cf. Gibson 1986, p. 141). Like other ambient arrays, the global array is not an hypothesis, but a fact. The question is not whether it exists but, rather, whether it contains information, and whether that information is detected and used by animals.

The global array can be represented as an $n$-dimensional space. The number of dimensions is the sum of dimensions of the different forms of energy, minus those dimensions that are common across all forms of energy. The dimensions of space (i.e., position) and time are common across all forms of energy, while other dimensions are peculiar to individual forms of energy. Considering these jointly yields a global array with several dimensions. For purposes of illustration we reduce this to three (Fig. 4).

The structure of the global array (e.g. Fig. 4) is influenced by all events, objects, and surfaces that influence the structure of single-energy arrays. In addition, the global array is influenced by events that do not structure single-energy arrays; among these are motion relative to some of



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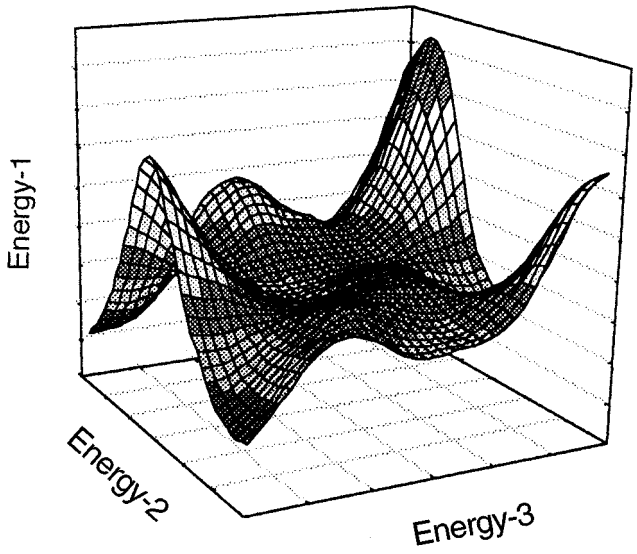



Figure 4. The global array, represented by a *n*-dimensional space (three in this example) of energy structures

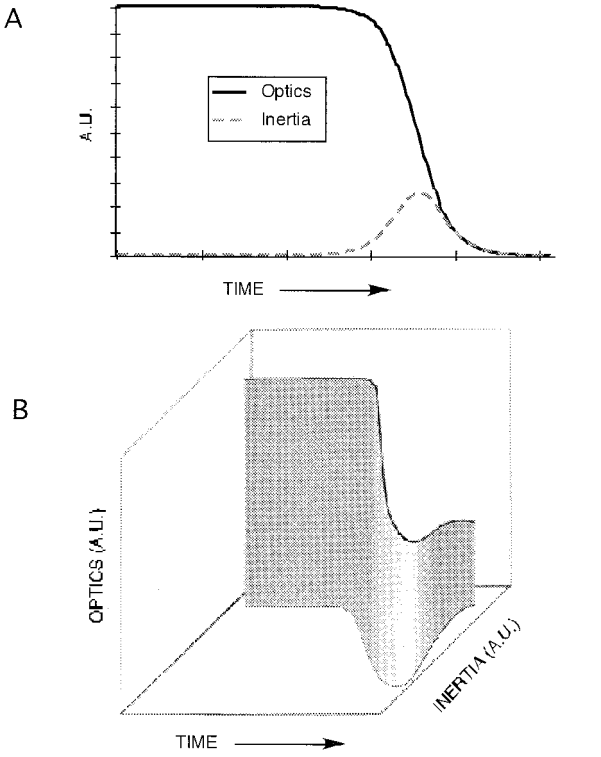



Figure 5. Evolution over time of (A) single energy arrays and (B) the related global array during braking a vehicle to a stop. (A.U. means arbitrary units.)

the referents discussed in section 4. Information about these relative motions is essential for many common behaviors, and so animals have a strong motivation for being sensitive to information in the global array. In the absence of such sensitivity, animals would be forced to obtain this information through inferential processing, that is, through internal comparisons of the patterns in single-energy arrays (i.e., those picked up by individual perceptual systems). The following examples illustrate the existence of information in patterns that extend across forms of energy. These examples focus on patterns that extend across two or three kinds of stimulus energy. However, each is also a structure in the global array. The events in question may vary the structures in several forms of energy. Our discussion in terms of a limited number of forms of ambient energy is for clarity of presentation only.

Consider a situation in which an automobile cruising at a constant velocity slows to a stop (Fig. 5); for simplicity we consider only motion relative to the illuminated environment (which influences optical structure) and relative to the gravito-inertial force environment. Figure 5A shows the consequences of this motion for structure in the optic array and in the gravito-inertial array. Optical structure is ambiguous with respect to motion relative to the gravito-inertial environment: The same optical patterns could be caused by deceleration of the body relative to the ground, or by deceleration of an illuminated enclosure (e.g., a moving room; Lee & Lishman 1975) relative to a gravito-inertially stationary observer. At the same time, gravito-inertial structure is ambiguous with respect to the nature of the motion: The same patterns of acceleration could be caused by deceleration to a stop, or by acceleration (in the opposite direction) to a constant nonzero velocity. Figure 5B shows the higher-order relation that exists in the global array between optics and gravito-inertial force. This "optical-gravitoinertial pattern" does not have the ambiguities of the patterns in single-energy arrays; it specifies that the observer is undergoing gravito-inertial deceleration relative to the illuminated environment. An animal that was sensitive to this higher-order pattern would be able to perceive its motion directly. An animal that was sensitive only to structure in single-energy arrays would need to relate these structures through internal processing.[10]

This example can be expanded to include patterns that extend across three or more forms of ambient energy. Consider a car moving at constant velocity in congested traffic, where some of the other cars are beyond the field of view but may still be heard as drivers honk their horns. Some of these other cars may be moving, while others may have stopped. The acoustic array, taken in isolation, does not differentiate between motion of the subject car (or other cars) relative to the gravito-inertial force environment and motion of cars relative to each other. Similarly, the optical-gravito-inertial pattern discussed here provides no information about motion relative to any audible referents. However, patterns that extend across optics, acoustics, and gravito-inertial force will provide information about the simultaneous motion or stasis of the subject car relative to the gravito-inertial force environment and relative to the audible and visible environments.

The original example of information in the global array was given by James Gibson (1966), who discussed an animal resting on a support surface. When the substratum is horizontal relative to the direction of balance, the reactive force that the surface generates against the dorsal surface of the animal is parallel to the direction of balance. If the animal is standing, the ankle angle that corresponds to a state of balance will be 90°. However, when the substratum is at an angle relative to the direction of balance (e.g., on sloping ground) the reactive force of the substratum is not parallel to the direction of balance. The angular difference between the direction of balance and the reactive force is the slope of the substratum rel-



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ative to the direction of balance. This difference will give rise to nonredundant stimulation of the vestibular and somatosensory systems. The nonredundancy will constitute a structure in the global array, specifying the slope of the ground relative to the direction of balance (Gibson 1966, p. 63). Gibson (1966, pp. 271–72) noted that "the combination is invariant and constitutes a stimulus of a higher-order." This means that for animals that are sensitive to the global array, perception of ground slope can be direct.

A similar analysis applies to a support surface that moves independent of the direction of balance. Consider stance on a platform that can rotate around an axis parallel to the ankle joint (e.g., Nashner et al. 1982). When the platform is stationary relative to the direction of balance, ankle rotation will have a fixed relation to head displacement, so that somatosensory and vestibular stimulation will be redundant. When the platform rotates, ankle rotation occurs independent of head displacement. This is often interpreted as a situation in which there is conflict between structure available to the somatosensory and vestibular systems (e.g., Nashner et al. 1982). An alternative interpretation is that the discrepancy between mechanical and gravito-inertial structures constitutes a pattern in the global array that provides information for the fact that the person is standing on a rotating surface. Mechanical structure (available to the somatosensory system) taken alone is ambiguous with respect to the difference between body sway and rotation of the ground surface. Similarly, gravito-inertial structure (available to the vestibular system) taken alone is ambiguous with respect to this difference. Only the superordinate relation (that is, the structure in the global array) is uniquely related to each situation.

One of the major challenges for our view will be the formalization of structure in the global array. In this target article, we do not attempt such a formalization. However, several recent analyses have formalized informative patterns that exist as higher-order relations between forms of ambient energy, and so may be examples of structure in the global array. These formalizations are intended to illustrate the mathematically rigorous basis of structures in the global array; they need not be schemes for the weighting of sensory inputs within the perceiver. Rather than internally executing the calculations on the right-hand side of each equation, the left-hand side might be detected directly (this is the heart of our position).

Bingham and Stassen (1994) analyzed the structuring of ambient arrays that results when the head moves relative to illuminated objects. The purpose of their analysis was to identify information about the distance of illuminated objects from the observer. The optical parameter $\tau$ (i.e., the inverse of the relative rate of dilation of a contour in the optic array) is influenced by the physical $T_c$ of the head with the distal object or surface. However, Bingham and Stassen noted that optical flow created by oscillatory head motion is ambiguous with respect to distance unless there is independent information about the velocity of head motion. Head movement structures gravito-inertial patterns that are available to the vestibular system. This means that the higher-order relation between head velocity and optical flow is unambiguously related to object distance:

$$\tau_{pv}/T = (1/2\pi)(D/A) \quad (1)$$

where $\tau_{pv}$ is the value of the optical parameter $\tau$ at the peak velocity of head motion, $T$ is the period of head oscillation, $D$ the distance of the target, and $A$ the amplitude of head movement.

Peper et al. (1994) analyzed the perception of the location and timing of catching. In catching an object the catcher needs information not only about when the object will arrive, but also about where. Peper et al. identified a parameter in the global array that provides information about the velocity at which the hand must move in order to be at the right place at the right time to catch the object:

$$V_h = (X_b - X_h)/\tau, \quad (2)$$

where $V_h$ is the hand velocity necessary to intercept a moving object, $X_b$ is the instantaneous sideward position of the object, $X_h$ is the current position of the hand, and $\tau$ is the $T_c$ of the object with the fronto-parallel plane of the body (assuming constant velocity object motion). Optical structure is influenced by $X_b$ and $\tau$, while patterns of mechanical pressure are influenced by $X_h$. Some additional formalizations of structures in the global array have been presented by Stoffregen and Riccio (1988, Eqs. 4–6).

In each of these cases, animals that are sensitive to patterns in the global array can detect the relevant parameters directly, whereas animals that are sensitive only to structure in single-energy arrays can recover the necessary information only through internal computation. Researchers have typically assumed that accurate perceptions of relative motion in these situations are derived from sense-specific sensitivity to structures in optics, force, acoustics, and so on. That is, researchers have assumed that the patterns in the global array are not sensed directly, but are broken down at receptor surfaces, and then reconstructed inside the animal. Our argument is that patterns in the global array might be sensed directly, without reduction to structures in individual forms of energy.

### 6.2. Implications of the global array

The implications of the possible existence of specificity in the global array are numerous. In this section we discuss several of these.

**6.2.1. No specification?** If there is specificity in the global array, then the no specification view is not correct (cf. Gibson 1966; Shaw et al. 1982), and theories that use the no specification view to motivate hypotheses about internal processing of ambiguous sensory inputs lose this motivation. We have already noted (sect. 3.4) that proponents of the no specification view have not offered a justification for the assumption of separate senses. If none can be provided, and if specification exists in the global array, this would significantly undermine the general motivation for this view. It might be argued that specification exists but is not detected by animals (e.g., Proffitt & Gilden 1989). To evaluate this argument it would be necessary to identify informative structures in the global array and conduct new research to determine whether these are detected. Existing studies of sensitivity to structures in single-energy arrays may not be relevant.

**6.2.2. Independent specification?** The existence of the global array is a problem for the independent specification view (which comprises amodal specification and mulitple specification; see sect. 3.3), since higher-order structures tend to undermine the idea of the independence of lower



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order parameters. In addition, we have argued that patterns in single-energy arrays are not specific to reality (sect. 5.1). If specificity exists solely in the global array, then neither version of the independent specification view can be correct.

There can be redundancy across different forms of ambient energy, as postulated by the amodal specification view. In the amodal view, redundancy can be detected only by an internal comparison of patterns detected by different perceptual systems (sect. 3.3.3). In our view, redundancy is a higher-order relation in the global array that can be detected directly. The global array pattern that is created by redundancy across individual forms of energy is a limiting case of structure in the global array, but, like any other structure in the global array, it differs qualitatively from related structures in single-energy arrays.

We noted earlier (sect. 1) that James Gibson endorsed two positions with respect to the information available to different perceptual systems. Our position is not compatible with Gibson's endorsement of amodal specification (see sect. 3.3.2). However, our position is compatible with Gibson's claim that information exists in higher-order patterns that extend across different forms of ambient energy.

**6.2.3. Information, energy, and sensory loss.** It might be argued that the global array does not always exist because some forms of energy are not always present, such as in the dark, or when there is total silence. Such an argument is problematic because it relies on a confusion between energy and information. A lack of energy does not constitute a lack of information. Rather, the absence of a form of energy is information (at a minimum, it is information of the absence of energy, e.g., for the fact that it is dark). James Gibson made this argument in the context of single-energy arrays (e.g., Gibson 1966; for additional treatments, see, e.g., Michaels & Carello 1981; Turvey et al. 1981). He argued that information for perception exists in patterns in energy, not in energy per se. We believe that this argument holds in the context of the global array. If so, then the absence of any given form of energy would not imply the absence of the global array.

This has consequences for the loss of receptor systems, as occurs in blindness or deafness. In our view, all perceivers detect patterns in the global array. Individuals who have suffered perceptual loss have lost their sensitivity to a particular class of these patterns, but they remain sensitive to the remaining classes of patterns. Most people can detect patterns in the global array that extend across optics, acoustics, mechanical pressure, gravito-inertial force, and chemical energy. By contrast, blind people can detect only those global array patterns that extend across acoustics, mechanical pressure, gravito-inertial force, and chemical energy, while deaf people can detect only those patterns that extend across optics, mechanical pressure, gravito-inertial force, and chemical energy. Loss of sensitivity to certain patterns in the global array should have implications for performatory action. Consider walking. Normal walking is guided relative to the illuminated environment, and so depends upon sensitivity to patterns that extend across optics. When these patterns are not available (due to complete darkness or to blindness), walking is still possible but must be controlled on the basis of other patterns. These other patterns are available to normal animals (e.g., we can walk in complete darkness), but do not permit optimal control, and so are not preferred when there is a choice. We believe this accounts for behavioral changes that are observed with blindness, such as restricted walking. Note that a lack of sensitivity to information that includes structure in light is not necessarily a "sensory deficit." Species that have no eyes (e.g., worms and moles) cannot detect patterns in the global array that extend across the optic array and, like blind individuals, cannot control behavior in all of the ways that are available to the sighted. Given the behavioral success enjoyed by these species, it would appear to be inappropriate to refer to their perceptual experience as being deficient.

**6.2.4. Implications for research in neuroscience.** Rather than investigating the activity of neural units, the ecological approach to perception and action focuses on the interaction between the animal and the environment and on how this interaction structures ambient energy arrays. However, the hypothesis that specification exists, and that it exists solely in the global array, could have substantial implications for research on the nervous system. One implication is that neuroscientists might search for cells or nuclei that respond selectively to structures in the global array. In neurophysiological terms, this would mean searching for neural units that respond to patterns of activity that extend across different kinds of receptors, such as the retina and the vestibule. As we noted in section 2.5, many sites in the nervous system are known to be influenced by stimulation of different sensory organs (Stein & Meredith 1993). These sites are commonly interpreted as loci for inferential (e.g., associative) integration of inputs from different receptors, but they could be reinterpreted as loci of information picked up from the global array. Rather than forming associations between qualitatively different forms of stimulus energy, these sites may exhibit direct (i.e., nonassociative) sensitivity to qualitatively unitary patterns in the global array. With such a reinterpretation, the existing knowledge base could be built upon in studying neural sensitivity to structures in the global array. Research of this kind would be greatly facilitated by prior identification of such structures, so that they could be presented and manipulated in a controlled manner during recording of neural activity (research on the global array could also be conducted in clinical populations; cf. Lee et al. 1984). As an example, Equations 1 and 2 might be used to generate stimuli that could be used in studies of the nervous system.

**6.2.5. Perception of unimodal stimuli by stationary observers?** We have argued that the global array is the sole source of information sufficient for veridical perception, and that it contains information that is essential for the perception and control of motion relative to different physical referents. How does this argument relate to the perception of objects and events that influence the structure of individual forms of stimulus energy? Similarly, how does it relate to situations in which the perceiver appears to be a stationary observer?

There are extensive literatures on the perception of objects (e.g., Henderson 1992), events (e.g., Bingham et al. 1995), the location of sound sources (e.g., Guski 1990), and so on. In all these cases, experimenters ask observers to perceive things that structure individual forms of ambient energy, such as light or sound. Observers typically are stationary in the sense that they are asked to remain still, giving



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reports of their perceptual experience, rather than having physical interactions with the objects or events.

While the experimenter's interest may focus on a single modality, sensory stimulation is continuously multimodal. Changes in the structure of a given array occur in the context of ongoing, simultaneous patterns in other ambient arrays and, consequently, in the global array. In these situations, as in any other, the global array exists and is available to perceivers. The fact that the experimenter is concerned only with how perception is influenced by structure in one form of energy does not imply that observers have an equally narrow focus. We believe that even when asked to make perceptual judgments about so-called unimodal stimuli, observers are motivated to sample (and, in fact, rely upon), information that is available in the global array. It is almost certainly the case that observers perceive more than the experimental stimulus. Experimenters may present "an object or event," and observers may comply with instructions to give reports about "an object or event." However, rather than perceiving "an object or event," observers may perceive "an object or event that I am looking at (or listening to, etc.), in this place." That is, observers may perceive objects and events in relation to themselves and their surroundings. Information about these relations is found only in the global array. Perceptual reports may not include these relational facts because the experimenter has not requested reports of this kind.

Relational information in the global array may be critical for perceptual reports that are commonly assumed to reflect unimodal perception. This is because perceivers are active rather than passive; the success of perception requires adequate control of this act. In order to achieve and maintain visual fixation, for example, we must stabilize the eyes, the head, and the body. In order to explore objects or events, we must be able to organize and control stable movements of all of these. This suggests that observers are neither stationary nor passive (Gibson 1986). The actions needed for perception require information in the global array.

The need for action in perception has been documented at a variety of levels. Here we concentrate on subtle relations between perception and postural motion; these motions can provide information to "stationary" observers. Empirical research suggests that there is an intimate relation between body motion and perception in contexts that typically are analyzed without reference to motion of the observer.

As a first example, it is known that observational activities as simple as visual fixation of stationary objects are influenced by controllable variations in postural motion. Stoffregen et al. (1999a; 1999b; 2000b) instructed participants to fixate a distant target or a nearby target while standing. Reliable variations in parameters of postural sway were elicited by changes in the fixation task. These differences were observed across changes in the visual target (a blank target versus a block of printed text), in the nature of the visual task (simple fixation versus search for target letters), and changes in target distance (near vs. far). Variations in posture were functionally related to constraints imposed by the visual tasks, that is, modulations of postural sway facilitated visual performance.

Similarly, Kellman and Short (1987) investigated the role of body motion in the development of perception of three-dimensional form. Babies who were moved (oscillated briefly in a semicircle in front of the objects that they were fixating) could more easily differentiate form than babies who were stationary. Motion of the babies' bodies (relative to the gravito-inertial force environment and relative to the illuminated environment) altered the structure of the optic array (e.g., through motion parallax) of somatosensory stimulation and of vestibular stimulation (through variations in the direction of balance). Note that stimulation of the vestibular and somatosensory systems differed because the head is not rigidly attached to the torso (cf. Riccio 1995). In addition, body motion altered relations between patterns in these forms of energy, that is, structures in the global array.

Finally, Mark (1987; Mark et al. 1990) has shown that restriction of postural sway can inhibit learning of changes in affordances. Standing observers looked at a chair whose seatpan was height-adjustable and made judgments about the maximum seatpan height on which they could sit. In some conditions, observers' shoes were fitted with blocks that increased their height and so their maximum sitting height. Immediately after donning the blocks, judgments of maximum sitting height were inaccurate, but over a series of trials judgments gravitated toward the correct (new) value despite the fact that observers were not permitted to practice sitting (Mark 1987). In later experiments, Mark et al. (1990) found that this spontaneous learning did not occur in the absence of postural sway (when observers were required to stand with their body and head pressed against a wall).

On the basis of these studies we conclude that even "stationary, passive" observation depends upon successful control of movements of receptor systems and often of the whole body. We have argued that information for the control of motion relative to physical referents exists only in the global array. Accordingly, we conclude that information in the global array is required even for perception of objects and events that structure only a single form of ambient energy.

**6.2.6. Sensory interaction: The McGurk effect.** As a final example of the application of our theory to existing research, we reconsider the McGurk effect (see sect. 3.1.1), which is widely interpreted as reflecting general principles of intersensory interaction (e.g., Kuhl & Meltzoff 1988; Welch & Warren 1986). In studies of this effect, the visual portion of a videotape shows a speaker saying one syllable, while on the audio track a different syllable is presented. Observers are instructed to report the syllable on the audio track, and perceptual reports are strongly influenced by the nominally ignored visible speaker. One of the most consistent and dramatic findings is that perceptual reports frequently are not consistent with either the visible or the audible event. Rather, observers often report "a syllable that has not been presented to either modality and that represents a combination of both" (Green et al. 1991, p. 524). This presents a challenge to inference-based theories of speech perception (Green et al. 1991; McGurk & MacDonald 1976); the sustained interest in the McGurk effect arises in part from the need to explain how it is that the final percept differs qualitatively from the patterns in the optic and acoustic arrays.

In experiments on the McGurk effect, participants that are exposed to multimodal stimulation are asked to give perceptual reports that are unimodal, that is, they are asked



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to report only what they hear (e.g., McGurk & MacDonald 1976). Numerous studies have documented the fact that reports are not consistent with structure in the acoustic array .[11] This is consistent with our general premise that perceptual systems do not function independently, but work in a cooperative manner to pick up higher-order patterns in the global array. In fact, we would predict just such an outcome. If speech perception is based on information in the global array, then it must be unnatural (or at least uncommon) for observers who can both see and hear the speaker to be asked to report only what is audible; the global array provides information about what is being said, rather than about what is visible or what is audible. Our position is similar to that of Fowler and Dekle (1991) in that we stress the fact that multiple perceptual systems are stimulated simultaneously and that the stimulation has a single source (i.e., a speaker). Our position differs in that we do not assume that observers are separately sensitive to structures in the optic and acoustic arrays but, rather, propose that observers are directly sensitive to patterns that extend across these arrays, that is, to patterns in the global array. Because such patterns are external to the perceiver, perception of speech via information in the global array does not entail an internal process of integration. In research on the McGurk effect, the discrepancy between the visible and audible consequences of speech is commonly interpreted as a conflict between the two modalities, but it could also be interpreted as creating information in the global array that specifies the experimental manipulation, that is, the global array may specify that what is seen and what is heard arise from two different speech acts. This leaves the question of why observers often do not detect the manipulation. We regard this as an issue of perception (i.e., information pickup), rather than an issue of specification (i.e., the existence of information). This is addressed in the next section.

## 7. Conclusion

We have reconsidered traditional concepts of the senses. We have argued that there is no clear basis for the assumption that perception is accomplished by a set of distinct perceptual systems. This led us to reconsider concepts of potential sensory stimulation. We reviewed existing concepts of specification, that is, of the possibility that relations between reality and patterns in ambient energy are unique. We considered the hypothesis that specification does not exist, the hypothesis that specification exists within individual forms of ambient energy, and the hypothesis that specification exists redundantly within or across forms of energy. We argued that the assumption of separate senses creates problems for any theory that assumes the existence of specification. We then reviewed the physics of motion in an effort to determine whether the structure within a single form of ambient energy can have a specificational relation to physical motion. We concluded that this is not possible; that is, we concluded that specification cannot exist within the assumption of separate senses. In section 6 we proposed that specification exists. We proposed that structure exists in the global array, that this superordinate structure carries information that does not exist in any of the individual arrays, and that it is essential for accurate perception and control of behavior with respect to the multitude of real referents.

The possibility that specificity exists solely in the global array provides the possibility of direct perception, but only if the senses function as a single unit. To accept this possibility requires rejection of the assumption of separate senses. A view emerges in which perception consists not of a group of systems working in parallel (and often in conflict), but of a single system whose parts operate as a unit to pick up information that is available only to the unit.

Our analysis has broad implications for research on perception and action. A few of these are briefly discussed here. In studies of perception researchers may need to take into account the global information that is always available. Researchers commonly present to subjects only a single form of energy. It is assumed that the application of stimulus energy to only one sense is grounds to ignore, methodologically and analytically, the energy available to other senses. However, when an experimenter stimulates a single modality, there is an influence on structure in the global array (e.g., Figs. 4 and 5). Research is needed to determine whether animals are directly sensitive to structure in the global array.

Such research will require novel experimental methodologies and novel analyses. Can we manipulate structure in the global array independent of structure in single-energy arrays? One promising strategy is to use the method of pairwise comparisons (Fouque et al. 1999). This method consists of fixing the structure in one or more single-energy arrays while systematically varying the structure in the global array (across experimental conditions) in situations that have consequences for behavior (Fouque et al. 1999). A reciprocal option is to fix parts of the structure of the global array while varying the structure of individual forms of energy. This might be achieved if variations in different forms of energy were appropriately coordinated. The possibility of additional methods should also be pursued.

It is essential that experimenters understand the physics underlying experimental work and the physical reference frames relevant to the task. For instance, when a judgment task involves the detection of stasis or motion, instructions given to the subjects should be very specific with respect to the referents that are to be used for the perception of motion. When the proper physics are employed, errors, illusions, and variability should decrease. In addition, behavioral measures should be primary to phenomenal measures for those studies that investigate perception and control of movement (Fouque et al. 1999; Riccio 1995).

Errors occur in both perception and performance, but the existence of errors does not imply a lack of specificity. Rather, errors may imply a need for perceptual-motor differentiation (learning) of those structures in the global array that are relevant to a given behavior. Errors can be expected when animals are prevented from exploring task-relevant dynamics of the animal-environment system (e.g., Mark et al. 1990). This may account for the common observation that observers in studies of the McGurk effect do not detect the experimental manipulation (i.e., the fact that the audible and visible events are different syllables). In the learning of perceptual-motor skills, one problem is to discover and exploit different structures in the global array. Learning a somersault, for example, appears to depend upon the discovery and control of higher-order relations between vestibular, mechanical, and optical patterns of energy (e.g., Bardy & Laurent 1998). To our knowledge, the literature on motor control and sport has not addressed the



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existence of the global array, the evolution of its structure during behavior, or the process of learning to pick up structures within it that are relevant to particular behaviors. We believe that a focus on the global array in the context of skill learning can reveal regularities and changes that may aid our understanding of the learning process, ultimately leading to enhanced performance. In general, the existence of the global array poses new challenges for the study of perceptual-motor learning and development. Are infants (and novices, in general) sensitive to patterns in the global array, and if so, how does this sensitivity develop with experience? It might be supposed that for infants and novices, initial sensitivity is to structure in single-energy arrays, with experience leading to the pickup of structure in the global array. One problem with this is that it requires the assumption of separate senses. Another is that it would require that novices begin with sensitivity to nonspecific structures, which is contrary to and unnecessary in ecological theory.

In this target article we have questioned some of the most fundamental assumptions that underlie theories of perception. Our rejection of the assumption of separate senses and our analysis of physical referents for perception and control pose challenges for any theory of perception. Our rejection of the hypothesis of specification in single-energy arrays poses challenges for the ecological approach to perception and action. Finally, our presentation of the global array offers the possibility of a theory of the perception and control of behavior that is based on the lawful specification of properties of the animal-environment system.

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We extend our grateful thanks to Gary Riccio for general ideas and discussions beginning in 1982, Karen Adolph and Stavros Valenti for helpful discussions of errors in perception-action, Steven B. Flynn for help with concepts of receptor anatomy, John Pittenger for help with the independent specification hypothesis, Patricia E. Murtha and Peter Suranyi for help with physics, and Michael Turvey for helpful conversations on law and specification. We are also grateful for illuminating discussions with Lorraine Bahrik, Gregory Burton, Arlene Walker-Andrews, Florent Fouque, Masato Sasaki, and students in Thomas A. Stoffregen's 1994 graduate seminar on intermodal perception.

NOTES

**1.** In this target article we distinguish between potential sensory stimulation and actual sensory stimulation. The former consists of patterns in ambient energy fields which exist outside the head and can be analyzed without reference to any psychological process. We refer to potential sensory stimulation in terms of arrays of ambient energy, such as the optic array. Actual sensory stimulation consists of portions of ambient arrays that are sampled by perceptual systems.

**2.** This is distinct from ways in which scientists might analyze a complex system. It is possible to study one hand of a violinist, but there are no one-handed violinists.

**3.** It might be argued that we have separate senses because the receptor systems have distinct evolutionary histories. However, this argument is circular because it begins with the assumption that there are separate systems.

**4.** Many researchers argue that input conflict is uncommon or rare (e.g.. Welch & Warren 1986), but in ordinary behavior input conflict must be the rule rather than the exception (Oman 1982; Stoffregen & Riccio 1988; 1991). The concepts of conflict and redundancy across perceptual systems are important across a broad range of research, including social psychology (e.g., Pennebaker & Roberts 1992) and neurophysiology (e.g., Maunsell et al. 1989; Stein & Meredith 1993). For a discussion of the relation between input conflict and other concepts of intersensory conflict, see Stoffregen and Riccio (1991).

**5.** Our discussion of physical referents might suggest that we believe that these referents are perceived. We do not argue that physical referents are perceived as such. Our argument is that behavior is perceived and controlled with reference to physical referents. In the ecological approach to perception and action, it is the relation between the animal and the referent that is perceived and controlled (that is, the affordances for behavior relative to the referent). Perception of "behavior relative to a physical referent" does not require prior or independent perception of the referent, per se, just as perception of a triangle does not require prior or independent perception of the lines that make up the triangle. For further discussion of this issue, see Gibson (1986) or Stoffregen and Riccio (1988).

**6.** Even small changes in velocity, such as those caused by head movements, can have profound effects on the perception of self-motion. This accounts for the fact that the experience of vection is more easily induced in restrained subjects (e.g., Dichgans & Brandt 1978; Wertheim 1994).

**7.** We refer to the direction of balance rather than to the direction of gravity (or, more properly, the direction of the gravito-inertial force vector). In most situations, the direction of balance is contraparallel to the gravito-inertial force vector. However, the two entities differ qualitatively (the direction of balance is defined in terms of kinematics, the gravito-inertial force vector in terms of kinetics), and recent research has shown that both the perception and control of body orientation are influenced more strongly by the direction of balance than by the gravito-inertial force vector (Riccio et al. 1992).

**8.** The fact that we can present optical flow in the absence of motion relative to the earth or relative to the gravito-inertial environment (e.g., in the cinema, in visual flight simulators, and in "virtual environments") shows that optical flow is not uniquely related to, and so provides no information about, motion relative to these referents (cf. Smets 1995, pp. 199–200).

**9.** This raises the question of why people sway in response to imposed optical flow in moving rooms. That is, if there is no perceptual error, then why do they sway? It may be that they have chosen to stabilize the head and eyes relative to the illuminated environment (the room), and that they use body sway to maintain this stabilization.

**10.** The optical and gravito-inertial patterns depicted in Figure 5a are not identical or redundant. In traditional approaches to visual-vestibular interaction, this type of nonredundancy is interpreted as intersensory conflict (see sect. 3.1.3). The global array structure depicted in Figure 5b implies that the nonidentity of optical and gravito-inertial structure does not need to be interpreted as conflict (Stoffregen & Riccio 1991). Nonredundancies exist in the stimulation of different perceptual systems, but the interpretation of these in terms of intersensory conflict is not obligatory. Conflict is an interpretation rather than a fact. If specificity exists in the global array, then sensory conflict may not exist. Intersensory conflict is widely believed to cause motion sickness, but if it does not exist then this cannot be true. This is part of the motivation for an alternative theory of motion sickness (Riccio & Stoffregen 1991), for which there is empirical support (Stoffregen et al., in press; Stoffregen & Smart 1998).

**11.** In studies of the McGurk effect, responses that are not consistent with the audio track are routinely classified as errors or illusions. No *a priori* basis for this classification has been offered; for example, McGurk and MacDonald (1976, p. 746) offered no justification for the error classification other than that it was done "for the purpose of analysis." As an alternative, observers' responses could be classified into different groups without the de-



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scription of any group as being either correct or incorrect, illusory or veridical. The common interpretation is credible only if it is assumed that "correct" responses are defined solely in terms of the soundtrack, that is, only if it is assumed that the experimenter's interpretation of the situation is shared by the observers. If, as students of the McGurk effect allege, speech perception is inherently cross-modal, then it could be argued that the natural definition of "correct" would be in terms of percepts that reflect the influence of both modalities. This, in turn, suggests that a more appropriate method for studying speech perception would be to ask observers to report "what you perceive" or "what was said," rather than "what you heard."

# Open Peer Commentary

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## Learning and exploration: Lessons from infants

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**Abstract:** Based on studies with infants, we expand on Stoffregen & Bardy's explanation of perceptual motor errors, given the global array. Information pick-up from the global array is not sufficient without adequate exploratory movements and learning to support perceptually guided activity.

The central point of Stoffregen & Bardy's (S&B's) intriguing article concerns the problem of specification (the information available in ambient arrays of energy). On S&B's account, information in the global array is essential for accurate perception and adaptive motor control. They claim that perceptual-motor errors result from inadequate information pick-up. This unhappy situation occurs when observers cannot differentiate the relevant structures in the global array (lack of perceptual-motor learning) or when task constraints prevent adequate exploration to pick-up the information (as is often the case in laboratory experiments).

Our commentary expands on the too brief explanation the authors provide for perceptual-motor errors. It is important to provide a clear explanation of how such errors might occur if, as the authors propose, information gleaned from the global array is sufficient to support perceptually guided activity. Our commentary aims to redress this deficiency. Like the authors, we draw our examples from studies of stance and locomotion. We show that results from studies of infants can inform the debate about specification. We begin with learning to differentiate the relevant structures in the global array.

Typically, motor development appears as a sequence of postural milestones – sitting, crawling, and walking. To maintain balance in each posture, infants must keep their bodies within a region of permissible postural sway (McCollum & Leen 1989; Riccio & Stoffregen 1988). The extent of this region changes depending on variations in the ground surface, functional changes in body characteristics, changes in the location of the center of mass due to body movements, and so on. Thus, perceptual control of balance is paramount. Adolph and Eppler (1998; in press) proposed that each postural milestone in development constitutes a different perception-action system with different relevant control variables that could presumably correspond to different structures in the global array. For example, sitting, crawling, and walking postures involve different regions of permissible sway for different key pivots around which the body rotates. In addition, each posture involves different muscle groups for executing movements and for generating compensatory sway; different vantage points for viewing the ground; different patterns of optic flow; different interactions between visual, somatosensory, and vestibular information; and so on. Thus, a protracted period of learning is required for infants to identify the relevant control variables for each posture in development and to master their on-line calibration.

As predicted by this account, recent experiments showed that infants must learn to calibrate actions to the changeable region of permissible sway, but that learning does not transfer from sitting to crawling (Adolph, in press) or from crawling to walking (Adolph 1997). When infants were tested at the edge of an adjustable gap (0–90 cm) in an experienced sitting posture, they leaned forward over safe gaps and carefully avoided leaning over risky ones. But, when the same infants were tested on the same gaps in an unfamiliar crawling posture, they fell into impossibly large gaps on multiple trials. Similarly, when infants were tested at the brink of an adjustable slope (0–36°) in an experienced crawling posture, they crawled down safe slopes but avoided risky ones. When the same infants were tested on the same slopes in an unfamiliar walking posture, they fell down impossibly steep slopes on multiple trials. In both gaps and slopes tasks, the pattern of errors was consistent with a differentiation learning process, as proposed by S&B. Errors decreased at the most extreme increments of gap and slope, where information for adaptive motor control was presumably most clear; errors increased at the middle range of increments, where information would be most difficult to differentiate. Apparently, experience with each new postural milestone provides infants with the opportunity to differentiate the relevant information in the new global array.

Now, we turn to the second source of errors mentioned by S&B: Inadequate exploration. Information in the global array does not come for free. As Gibson (1979) pointed out, actions are embedded in a continuous perception-action loop. Exploratory movements generate information that, in turn, elicits further exploration. Despite dozens of experimental manipulations of visual, vestibular, and somatosensory information (e.g., Bardy et al. 1999), surprisingly little is known about multimodal exploration in the service of guiding stance and locomotion. Which exploratory movements give rise to what sorts of information and what information elicits further exploration?

We propose that exploratory behaviors generate the necessary information for detecting upcoming threats to balance in a temporal and spatial sequence (Adolph & Eppler 1998). Exploration from a distance must occur first, yielding concurrent visual, vestibular, and somatosensory information from ongoing body sway (Mark et al. 1990; Riley et al. 1997). Information derived from direct contact with a surface provides a closer simulation of the relevant forces. But, exploring via direct contact must be elicited by prior long distance cues. Thus, errors should result when long distance cues about surface properties are unreliable. We argue that long distance cues for depth (slopes, cliffs, gaps, etc.) are reliable, but long distance cues for surface friction and rigidity are unreliable. Slippery surfaces can be shiny or matte. Squishy surfaces can be bumpy or smooth. Unfortunately for walkers, friction and rigidity are ubiquitous properties. Our account explains why variations in surface friction – not depth – are the leading cause of accidents from falling in adults (Lin et al. 1995). Like stepping into quicksand, often walkers do not realize that a surface is slippery until they have already stepped onto it. Similarly, infants do not respond adaptively to information for surface friction or rigidity without direct contact (Eppler et al. 2000; Gibson et al. 1987; Stoffregen et al. 1997). Without adequate exploratory movements, the global array is impoverished and insufficient for guiding activity.

In summary, empirical findings from studies of infants' stance



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and locomotion are consistent with S&B's specification hypothesis about the information available in the global array. Adaptive control of action requires adequate exploratory movements to generate the requisite information and a protracted period of learning to differentiate the relevant information structures. In other words, using the global array for perception and action requires exploration and learning.

## Physiological convergence of sensory signals as a prelude to perception

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**Abstract:** The global array may be a useful concept in studying behavior in a complex environment, especially in the context of dynamical systems theory. However, Stoffregen & Bardy's arguments are weakened by the conflation of sensation and perception, and by the lack of evidence for synergy between stimulus energy arrays; strong evidence places the convergence of sensory stimuli inside the head.

Stoffregen & Bardy (S&B) postulate that people are able to directly sample the global array (GA) of potential sensory stimuli and thereby perceive higher order patterns that single sensory systems are unable to discern. These superordinate patterns in the GA are claimed to specify or characterize the event being perceived in an unequivocal manner while single energy arrays (e.g., optic or acoustic) may be ambiguous. They conclude that future research in perception should pay special attention to the GA that the subject experiences, as the synergetic combination of signals in the GA may produce perceptions that single modality stimuli cannot evoke. Furthermore, since body motions and other subtle behaviors that enable sampling of the GA may be difficult to control in experiments, they should be recognized and incorporated into experimental designs rather than unsuccessfully controlled and ignored. S&B's recommendation to broaden the scope of perceptual and behavioral research is timely in light of the recent growth of whole brain functional imaging and high resolution MEG and EEG methods. Furthermore, their proposal to focus efforts on characterization of the GA may be an appropriate adjunct to the development of a dynamical systems theory formulation of agent-world interactions (Beer 1995); the agent (or individual) is a complex system, within the greater world-system, for whom the GA constitutes the total flux of input from world to agent. Nevertheless, elements of their discourse are problematic: they appear to conflate sensation and perception; they provide no evidence for the synergy between energy arrays they claim is the hallmark of the GA, nor do they provide evidence for novel sensors of higher order patterns; and they discount the behavioral and neurophysiological evidence that sensory integration occurs within the brain.

Sensation is the transduction of ambient energy (whether electromagnetic, kinetic, or chemical potential) into a spatiotemporal pattern of neural activity. No meaning is conveyed by this process (Freeman 1995); it is entirely mechanistic. However, the result of sensory transduction is a perturbation of the state of the nervous system, which may lead to perception of the event producing the stimulus energy. This occurs because the sensory evoked pattern of neural activity interacts with a perceiver that has learned from experience and is therefore able to construct meaning from a familiar input pattern. In dynamical systems terminology, the input drives the brain-state into a basin of attraction (one that is shaped by experience and prior state). S&B assert that perception is undivided. This seems very likely true and resonates with Freeman's description of the unity of an intentional mind (Freeman 1995). The problem arises when the authors attempt to show that the senses are not separate. If completely different anatomical structures that respond to completely different forms of energy are not separate senses, then there may be no justification in differentiating any part of the human body from another. Their example of two eyes being necessary for binocular depth perception is not persuasive precisely because it is a perception, not sensory transduction. Monocular deprivation in early development prevents the proper connections in the cerebral cortex from forming that would allow the perception of depth due to optical disparity, despite the otherwise normal functioning of both eyes (Blake & Hirsch 1975). Furthermore, child behavioral studies show that the ability to use binocular disparity for depth perception follows, but does not coincide with, the ability to control vergence of the eyes, implicating an internal experience dependent process (Yonas & Granrud 1985). While there may be only one perceiver, there are certainly many sensors, and their relations to each other must develop with experience, that is, they must be learned.

S&B suggest that the GA is more than the sum of its parts, but provide no supporting evidence. It seems implausible that single energy arrays interact in any significant physical way. Sound and light emanating from an event are merely so much sound and light; no new form of energy is created. One possible explanation for their viewpoint is that different energy forms from one event, taken together, imply that event whereas taken singly they are ambiguous. This logic is predicated upon knowledge of the regularity of the environment (natural laws), about which individuals learn early in development and throughout life (Thelen & Smith 1994). Without a learned framework that allows the classification of multisensory input patterns, inputs could come from one of a hundred sources and only be so much noise. The aspect of the GA that is different from the sum of its parts is the association of stimulus patterns that the individual has built internally over a lifetime. Therefore, without a synergetic interaction between the energy arrays, there is no need to postulate special sense organs responsive to higher order aspects of the GA; the ordinary senses are enough.

S&B mention several examples of neurophysiological results indicating convergence of sensory input. There are certainly many more, but the limbic system is one whose importance for making associations between disparate stimuli has been repeatedly demonstrated (Agglet et al. 1997; Buckner et al. 1995; Wood et al. 1999). That damage to the limbic system can produce deficits in one's ability to learn associations supports the idea that the important relations between elements of the GA are laid down in neural circuitry by a physiological mechanism, but the question remains how sensation of multiple sensory inputs triggers perception of a single event. Studies of the binding problem in visual perception have implicated correlated neuronal activity in the perception of separate stimuli as a related group (Gray et al. 1989). Other studies have shown widespread patterns of activity correlated with the inferred meaning of stimuli (Barrie et al. 1996; Smart et al. 1997), and in conjunction with behavioral tasks (Bressler et al. 1993). These results are all consistent with a dynamical systems interpretation of brain activity, in which the multifaceted global input array nudges and cajoles the activity of this highly interconnected system from one basin of attraction to another in the elaboration of behavior.



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## We are better off without perfect perception

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**Abstract:** Stoffregen & Bardy's target article is based on the assumption that our senses' ultimate purpose is to provide us with perfect information about the outside world. We argue that it is often more important that information be available quickly than that it be perfect. Consequently our nervous system processes different aspects of information about our surrounding as separately as possible. The separation is not between the senses, but between separate aspects of our surrounding. This results in inconsistencies between judgments: sometimes because different frames of reference are used. Such inconsistencies are fundamental to the way the information is picked up, however, and hence cannot be avoided with clearer instructions to the subjects.

Since the Stoffregen & Bardy (S&B) target article deals with human interactions with the environment, it is impossible to ignore the physiology involved. Once one considers the physiology, it becomes evident that in practice there can be no "specification" of the kind described in the target article. For instance, in color vision it is well known that various combinations of wavelengths of light can stimulate the three kinds of cones in exactly the same manner, so that we are unable to distinguish between them. Similarly, various combinations of ego-motion and motion of the environment can give rise to the same global optical flow (sect. 5.1). These are examples of what S&B would call many-to-one mappings. Unless all information from all the senses is considered for every judgment, many-to-one mappings will give rise to conflicting judgments. S&B examine ways to avoid such conflicts. We question whether such conflicts have to be avoided.

Hidden behind worries about conflicting judgments is the assumption that our senses' ultimate purpose is to provide us with perfect information about the world "outside." To obtain such perfect information it makes sense to combine input from all the senses. However, attempting to gain access to perfect information has a price: time. For interacting with the environment, timing can be much more important than precision. There is no point knowing exactly when a ball will hit you if you only gain access to this information once it is too late to react to it.

We have shown that it takes 200 msec to react to a change in the speed of a target that one is trying to hit (Brenner et al. 1998), but only 110 msec to react to a change in its position (Brenner & Smeets 1997). Since these kinds of movements take only a few hundred milliseconds, this difference in timing is not negligible. When hitting moving targets the direction in which subjects move their hand does not appear to depend on the target's velocity (Brenner & Smeets 1996; Smeets & Brenner 1995), presumably because the disadvantages of waiting an additional 90 msec outweigh the advantages of having access to reliable velocity information.

In our opinion, the main task of our senses is to select the most suitable information for the task at hand, and to do so fast. From the moment the information reaches our senses separate aspects of the information are selected and analyzed for specific tasks, or parts of tasks. The selection starts even earlier if one considers the movements we make to obtain the information. Separate independent processing for different judgments can result in substantial conflicts between them (Abrams & Landgraf 1990; Brenner et al. 1996; Glennerster et al. 1996; Mack et al. 1985). Nevertheless, the separation seems be so complete that we even fail to notice conflicts between attributes when the conflicts themselves could give us valuable additional information (Brenner & Damme 1999; Brenner & Landy 1999). The main reason for our judgments normally being approximately consistent is presumably the consistency in the world "outside," in what S&B call the "global array."

Abandoning the need to avoid conflicts allows the nervous system to rely on different information for each judgment. We assume that each judgment is based on the most reliable information for that particular judgment. Thus, relative positions are judged from retinal information alone, but egocentric localization

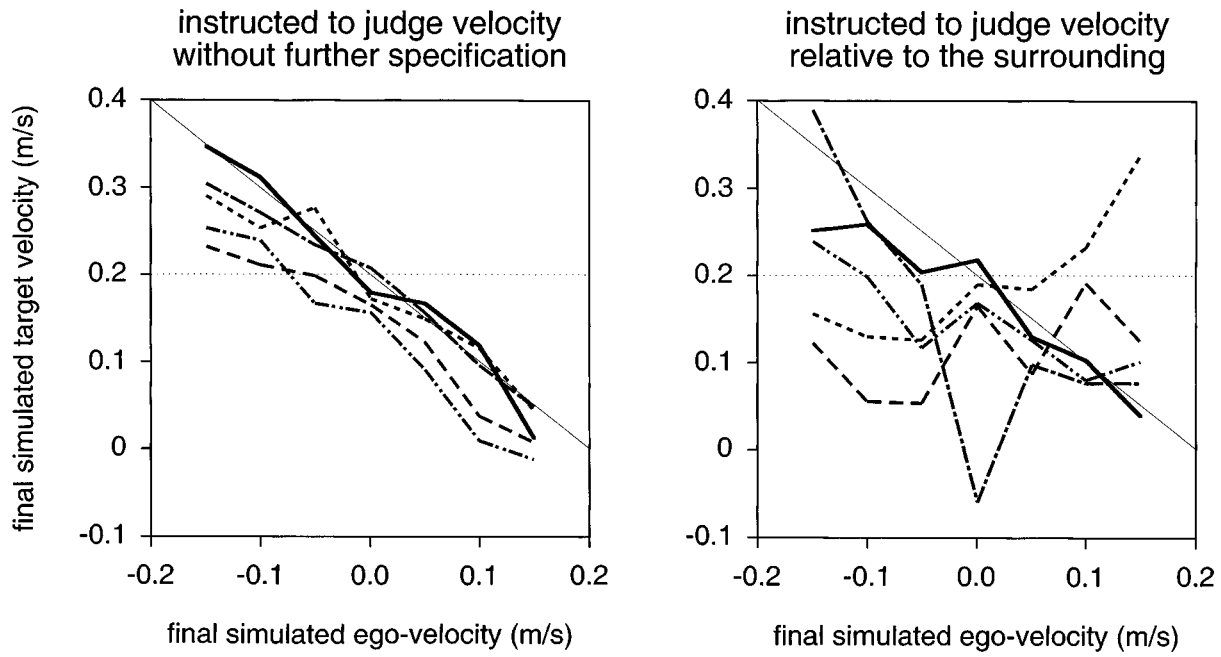



Figure 1 (Brenner & Smeets). Target velocity during simulated ego-motion that matched the simulated velocity in a preceding interval without simulated ego-motion. All velocities are relative to the visual surrounding. Each thick line connects the centres of the ranges of acceptable target velocities for the seven simulated ego-velocities for one of the five subjects. The thin diagonal line represents a constant velocity of 0.2 m/sec of the target relative to the observer, ignoring the visually simulated ego-motion. The thin dashed line represents a constant velocity of 0.2 m/sec of the target relative to the visual surrounding. The two panels show the same subjects' performance with two different instructions.



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needs extra-retinal information about the orientation of our eyes as well (Brenner & Cornelissen 2000) In this example the difference in information is associated with a difference in the referent that is involved (see sect. 4.5). Our view implies that the referent is fixed for any given judgment, rather than being something subjects can choose as S&B suggest in section 5.

We examined subjects' freedom in choosing a referent by asking them to compare the initial and final velocities of an approaching target (simulated with both monocular and binocular cues on a large screen). The methods were very similar to those used in a similar study on lateral motion (Brenner 1991) The target initially approached at 0.2 m/sec while the background was static. During the presentation the visual background started moving in depth so that the optic flow was consistent with forward or backward ego-motion of the subject. At the same time the target could change its velocity. We determined how fast the target had to move during the simulated ego-motion for it to appear to continue to move at the same speed.

The subjects were initially instructed to judge whether the targets' velocity changed, without explaining what we meant by "the velocity." Subjects had no difficulty with this task, and all five subjects spontaneously judged the target's velocity relative to themselves, ignoring the visually simulated ego-motion (left panel in Fig. 1). These results are consistent with previous work on lateral motion, in which velocity judgments also appeared to be related to oneself (Brenner 1991; Brenner & van den Berg 1996).

We then showed the subjects their data and explained to them that we were simulating ego-motion and that we wanted them to judge the target's velocity relative to the surrounding. Subjects found this much more difficult. The results are shown in the right panel of Figure 1. It is clear from the variability that none of the subjects was really able to do this task. Perhaps they would have been able to do so if they had actually experienced vection, or if the simulation was not only visual, but apparently they were not able to select the visual surrounding as a referent.

## How many systems make a global array?

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**Abstract:** Stoffregen & Bardy suggest that the global array provides the specification that is lacking when senses are considered in isolation. This seems to beg the question of the minimum number of senses in a global array. Individuals with sensory loss manage with fewer senses, and humans manage with fewer than electric fish; so specification, if it exists, cannot require all possible senses.

Stoffregen & Bardy's (S&B's) major theme is well worth endorsing, in principle. Nonetheless, I remain unconvinced that evidence against the assumption of separate senses is strong enough to demand changes in traditional perceptual experiments, or that the utility of their global array construct can survive the problematic question of the minimum number of "separate" senses that make a global array.

Here are three interesting contentions of S&B's. First, there is no airtight way to logically distinguish any two classic senses more definitively than any other two pieces of sensory equipment (like the two ears). Second, the "separate senses" construct is illogical, as is the prototypical experiment focusing on single senses, because distinct senses never work in isolation. Third, the concept of perceptual specification can only be saved by adherence to the global array construct.

S&B state the arbitrary-distinction argument most forcefully in section 2, analyzing whether the classic senses can be distinguished reliably by one of several means. I am afraid that I was unpersuaded by the repeated claim that a particular distinction is invalid because it presupposes the distinction it is supposed to demonstrate. One could use this strategy to disqualify any distinction whatsoever. Stronger arguments: anatomical distinctions will not work because there are other anatomical distinctions that definitely do not indicate a functional difference. Physical media and most brain centers are not generally dedicated to only one of the classic senses. Though these arguments seem solid, section 2 neglects some stronger justifications, like qualia-based distinctions (audition and vision are experienced differently), deficit based distinctions (people can be blind but not deaf), and evolutionary distinctions (electric fish have electric sense but humans do not). Two of these last are treated in other sections but their implications are more serious than S&B realize, as I will discuss later.

To support the second point of the analysis, that senses rarely work in isolation, S&B give examples of cooperation of the classic senses and present an important argument in section 6.2.5 about implicit cooperation when senses seem to work in isolation. However, evidence that sensory cooperation exists does not prove that the senses "operate as a unit" (sect. 7), nor does this cooperation necessarily follow from the arbitrary distinction argument. Furthermore, perceptual researchers are justified in believing that they have learned much from studies in which a particular sense or subsense is isolated; research that discovered pheremones useful in pest control might serve as one particularly practical example.

The third part of S&B's argument, that the global array concept is the only way to save perceptual specification, seems more like a wish. Their implication is that a qualitative difference exists between perception through a single sensory channel (if that is even possible) and by means of the global array. For S&B, perception through multiple integrated sensory channels provides a tighter and more trustworthy contact with the world than perception through a single channel.

With such implications, one cannot help but wonder how many systems are necessary to have a global array; one hopes the answer is not "all of them." Clearly, it is more than just two. The authors use the example of airplane simulators that include visual and inertial information. This environment that looks and feels like an airplane is not one, so optic and inertial information in isolation or even working as a set do not specify aircraft flight. Since S&B think the global array provides specificity in the simulator, some other system (which they do not name) must disambiguate the simulator from the real thing. So in this example at least three systems are necessary. Do all perceivables require three systems or more? Consider perception of cold. If I need to put on a coat, I do not think that haptic, olfactory or visual information should change my intention. If some perceivables require multiple systems but others can "get by" on one or two, will an animal or person actually know in any given situation whether a particular thing was perceived or whether they were "forced to obtain this information through inferential processing" (sect. 6.1)? If I perceive something critical but cannot distinguish whether it was specified or inferred, does the specification notion have any meaning at all?

Perhaps S&B would contend that specification always requires all systems, the whole global array, even in cases that superficially seem to require just one. A person under great stress may ignore the cold, so perhaps my perception of cold necessarily implies that I do not, through manifold other channels, perceive some more urgent source of stress. Aside from leaning toward tautology, this strategy seems contradicted by the authors' discussion of other distinctions in sensory resources, sensory deficits, and cross-species differences.

In section 6.2.3, it is suggested that blind people enjoy a global array that still includes numerous sources of information, even if one has been lost. Furthermore, the success of eyeless creatures is a demonstration (not to mention, I would add, poor electric-sense deprived humanity), that the global array of any particular individual of a particular species does not have to include any particular sense. If humans can enjoy specification without electric sense, then logically some perceivables in the Umwelt of the elec-



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tric fish can be specified without electric sense, that is, without the full global array. Therefore, specification is possible with something less than all available sensory systems. How many systems does it take?

The idea that there is a countable minimum number of systems to make a global array not only seems to violate the spirit of the global array construct but also to demand the very kind of hard distinctions among senses that S&B decry in the first part of their target article. For example, if two systems were the minimum for specification rather than inference, then the question of whether olfaction and gustation are two senses collaborating (say, on the perception of food) or one flavor system would have serious implications.

## Absolutist array specification and species survival: An ecological perspective on ecological perception

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**Abstract:** Stoffregen & Bardy propose an absolutist transmodal array structure model, intended to displace models of specification in all existing perceptual theories. Absolute specification of world structure in array structures, either unimodal or transmodal, may not be provable, but might be falsifiable. Absolute specification, moreover, may not be a necessary postulate in an ecological approach to understanding perception-action.

Stoffregen & Bardy (S&B) boldly propose an absolutist model of direct perception via transmodal structure in a "global array." That audacious venture underscores several critical issues for perception.

S&B discredit all existing perceptual theories, because each allows input conflict (input ambiguity) and therefore implies cognitive (indirect) processes. The syllogism is: If array structures (AS) conflict, then perceivers must choose between alternative world structure (WS) interpretations; choice implies cognitive processing; therefore, input conflict implies cognitive processing. The main focus is intersensory conflict, but any AS ambiguity yields the same conclusion. Because all existing perceptual theories entail such ambiguities, they all entail cognitive processes. The target article is silent about why cognitive processing is a fatal flaw, however.

But perception is inherently a matter of choice, of differentiation of information most relevant for the organism (Gibson 1969). Organisms that cannot choose cannot be said to perceive. One might grant that WS maps more completely to transmodal AS without conceding that the transmodal array mapping is absolute; the transmodal array, too, may map ambiguously to reality. Without physical-mathematical analysis to confirm absolute WS-AS mapping, the same criticism that S&B level against existing theory may – by the same syllogism – force us to reject their transmodal model.

Although the target article's central theme is specification, what that term connotes is not completely clear. S&B offer an absolutist definition: "Only if each stimulus parameter *always* [their emphasis] varies uniquely with the corresponding event . . . would specification be preserved and input conflict avoided." Theories they reject, however, assert non-absolutist specification. Is specification absolute or non-absolute; that is, can WS-AS mapping be more or less specific? If so, to what degree can species tolerate non-unique WS-AS mappings? Possibly the absolutist position is not absolutely required.

Perceptual theories all propose two mappings. The first is from WS (objects, surfaces, and events) to patterned energy flows (optic, acoustic, mechanical, and chemical AS). If that mapping is unique (at least 1:1 and probably mathematically "onto"; see Solomon et al. 1989), then it is absolute, and absolutely informative about WS. The second mapping is from AS to perception-action (PA); its primary endpoint is control of adaptive (survival-promoting) behavior. As S&B suggest, behavioral control is sometimes imperfectly adaptive. Every perceptual theory must somehow account for PA error.

The probability of adaptive control of behavior depends on the collective probability of WS-AS mapping sufficiently specific to afford adaptive control, of sensitivity to AS affording adaptive behavior, and of adequate performatory capability. Individual survival probabilities depend on the probability of adaptive control of individual behavior. Species survival requires only that enough individuals survive to reproduce, not that every individual survive. Some PA error is tolerable.

In essence, opposing theories parse PA error in different ways. Absolutists assert that the probability associated with WS-AS mapping is perfect; they deny any possibility that PA error arises from imperfect (non-absolute) WS-AS mapping. Alternatively, the WS-AS mapping itself might be imperfect, non-absolute: Multiple WSs may occasion the same AS; the same WS might yield multiple different ASs; or the WS-AS connection may be only partially reliable. Thus, some portion of PA error could result from non-unique WS-AS mapping.

Species survival ultimately requires only that WS map into AS sufficiently well to afford adaptive control of behavior. That mapping need not be absolute, so long as it is good enough to support individual survival well enough to promote survival at the species level (where it counts most ecologically). Ecological considerations, then, do not necessarily rule out non-absolute WS-AS mapping. Evolution is opportunistic: Whatever works to support species survival tends to be preserved across generations. In principle, if non-absolute WS-AS mapping can serve this survival end, organisms may actually have evolved to use non-absolute mapping.

The ecological perception community faces an enormous challenge here. The nature of WS-AS mapping – unimodal or transmodal, absolute or non-absolute – cannot be simply a matter of faith or fiat; it must rest squarely on solid physical-mathematical analysis. Absolute mapping demands a completeness proof that has never been offered, and may not even be possible because it would require showing one infinite (WS) set to be commensurate with another infinite (AS) set. Yet the absolutist position appears open in principle to disconfirmation (i.e., by showing that some aspect of WS does not map to any AS).

Even disconfirmation is problematic, however, because AS itself is only loosely defined. The trend in the literature seems to be to demonstrate only post hoc the positive existence and utility of some AS for perception. Gibson (1979) claimed that "inexhaustible" (p. 243) mathematically describable AS invariants exist. Such descriptions are as yet relatively sparse and not easily predictable a priori on any principled basis (Cutting 1993). Appropriate heuristics to guide array invariant searches remain to be developed (cf. Mace 1977; Neisser 1977), both for the current unimodal perspectives that S&B reject and surely for the more complicated transmodal view they defend.

Theories succeed when they state clearly under what circumstances they do and do not work. Lacking clarity on the key issue of specification, those boundaries cannot be drawn for ecological perception. The ecological approach, with its reliance on "higher order" (how high?) AS variables seems relatively immune to falsification.

The unimodal direct perceptual theory S&B dismiss has been partially successful, but remains a perplexing undertaking. The transmodal model advanced in the target article exacerbates that perplexity. At its present stage of development, S&B's proposal seems as open as other perceptual theories to many of the same criticisms that these authors outline. The major benefit of this target article may be simply to sharpen the focus on key issues that remain unresolved in perceptual theory.



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## The patterns of energy used for action are task-dependent

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**Abstract:** Is there any ecological purpose in assuming that perception for action exists only through a global array of energy? Unlike Stoffregen & Bardy, who assume that behavior consists of movements, we would argue that behavior consists of a stable coupling between perception and action achieved through experience in an adaptive context. Determining target position in an aiming manual task and temporal control of impact movement illustrate that patterns of energy used for action are task-dependent.

Beyond unusual postures and personal rendering, what characterizes a skilled pianist playing a new score is the fact that his gaze is alternately oriented toward the vertical music stand and the horizontal piano keyboard where the hands are performing. A careful observation emphasizes that the arms fall under visual control mainly when a significant lateral displacement of one hand is required to reach distant keys. What does this tell us about the way sensory signals are used for action? Obviously movements of short amplitude (say, one octave in the case of a piano keyboard) can be controlled through a coupling between visual (a set of music notes), and kinesthetic or somesthetic (changes in configuration or in position of hands) signals processed with respect to a nonvisual referent. Conversely, movement of significant amplitude cannot be accurately controlled on the basis of similar information. Vision of body segments is needed for accurate distant reaching, the goal of movement being achieved by estimating the hand to target visual gap including, presumably, a visual physical referent.

Beyond a prosaic illustration, the relevant question suggested by the pianist is how the spatio-temporal constraints of the task impose the selection of a specific source of information (or physical referent) which serves as the basis for smooth and accurate movement execution. According to Stroffegen & Bardy (S&B) (sect. 1), perception consists of picking up information that exists in irreducible patterns across different forms of energy. Physical aspects of the world are specified in energy patterns reaching the sensory systems, but direct perception of behaviorally relevant aspects of reality involves macroscopic patterns (variables) that extend across different forms of ambient energy. Some experimental data seem to favor this perspective, for example, the crossmodal perception of the location of a visible and noisy stimulus (e.g., in speech perception as suggested by the McGurk effect). However, perception and action cannot be dissociated, even in the case of speech perception (see Desjardin et al. 1997). This raises the question of whether there is any ecological purpose in assuming that perception for action exists only through the global array of energy.

The task for a perceptual psychologist is to uncover the information that specifies what we perceive (Gibson 2000). For the ecological psychologist, people perceive affordances, that is, properties of objects that have a value in terms of behavior (Gibson 1979; Sanders 1997; Stoffregen 2000). Hence, from an ontological viewpoint, an object affords a class of actions that have an adaptive function for the perceiver. However, taking this assumption for granted, three issues remain to be addressed: (1) What are the properties of the actor-environment interaction that would contribute to the emergence of affordances? (2) What makes an affordance effective at a particular time? and (3) How do affordances constrain action in such a way that behavior emanates from a continuous coupling between perception and action? With regard to the first two points, it seems obvious that a theory of perception or stimulus discrimination that would include action parameters is lacking, although some attempts to link behavioral changes with Skinner's principle of operant conditioning have been made in the past (e.g., Ingvalsden & Whiting 1997). Unlike S&B (sect. 4. 1), who assume that behavior consists of motions, we would argue that behavior consists of stable coupling between perception and action achieved through experience in an adaptive context.

With regard to the last point, it is apparent that adaptive behavior involves discerning a source of information (or invariant, Gibson 1979) that is relevant according to the goal and the spatio-temporal constraints of the task. Thus, an ecological psychologist would be interested in finding out not only what information is perceived, but also how information and action are inherently related. As emphasized by Grush (2000), "egocentric space exists in virtue of the mastery of a battery of sensorimotor skills" (p. 64). This is obviously in line with Gibson's idea that "the world is specified in the structure of light that reaches us, but it is entirely up to us to perceive it" (1979, p. 63).

Behavior consists of actions, and may be initiated without any prior motion. With regard to the global array hypothesis, S&B (sect. 6.1) suggest that perception is influenced by events that do not structure single-energy arrays. However a stationary person desiring to grasp an object in a static visual environment needs to determine the relative position of that object with respect to a point of observation, or a hand-starting position. An aiming manual movement requires the perception of physical properties that allow a distant object to be located egocentrically, with no need to move the head back and forth to generate optic flow (Bingham & Pagano, 1998). Furthermore, directing one hand towards a distant object usually requires continuous adjustment of hand displacement as distance is, in general, misperceived when vision conditions are limited (Coello & Grealy 1997; Coello & Magnet 2000; Foley & Held 1972; Goodale et al. 1986), or when the task is very stringent in terms of spatio-temporal accuracy (Pisella et al. 2000; Proteau 1992). In visuo-manual tasks, no energy patterns except the visual array would fulfil such constraints since the spatial target is inevitably specified in the visual ambient array (reaching movements in darkness towards a sonorous target are usually broadly inaccurate, Berthier et al. 1996). Two examples illustrate this, one relating to action initiation and the other to continuous action guiding.

From a given point of view, multiple energy arrays may contribute to the perception of a distant target. Though considerable effort has been expended on demonstrating the participation of extraretinal signal in distance perception (e.g., state of vergence, Treisilian et al. 1999), studies have recently shown that enriching the visual environment reduces perceptual underestimation of distance as observed otherwise (Coello & Grealy 1997; Coello & Magne 2000), even in monocular vision (Coello et al. 2000b). However, the most striking effect was that enriching the visual array had a positive effect on action accuracy only when elements structuring the visual scene spread out in the action space (Coello & Magne 2000). This was interpreted as denoting a dynamic aspect of space perception underlying the functional use of retinal input in the relative coding of target distance. In the context of a reaching movement, space perception accordingly seems to require probing the optical array to determine target distance, which cannot be accurately achieved otherwise (Treisilian et al. 1999). Again, in line with Gibson's ideas: "the reality underlying the dimension of space is the adjacent order of objects or surface parts" (1979, p. 101). On the other side of the hand-to-target action, the encoding of hand position does benefit from various sensory inputs, with respective contributions strongly dependent on the experimental conditions. Vision may provide a stronger (e.g., passive observation) or weaker input (e.g., prior to initiate an action) than proprioception (Rossetti et al. 1995), and, in the dark, the proprioceptive contribution can be strongly altered by the cognitive knowledge about experimental variables (Imanaka & Abernethy 2000).



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Experimental data seem to support the further notion that initiating an action also includes the capacity to prospectively tune the perceptual system to a specific source of information, so as to allow a continuous and accurate guiding of the motor act. A particular example of such perception-action coupling concerns the control of impact movement. Some activities, such as golf-putting, require a fine tuning of effector (putter) velocity at impact in order to make the object (ball) travel the expected path. In general, a controlled approach of distant objects in anticipation-coincidence tasks is considered to depend upon estimating the time remaining before contact with the destination point. A first-order approximation of time to contact can be achieved by extracting from the optic flow the inverse of the relative rate of expansion of the contour of the approaching object (Lee 1976), or the relative rate of constriction of the gap separating effector and target in the case of an aiming movement directed towards a stationary object (Lee 1997).

Applying this theory to impact movement (time to gap-closure, Craig et al. 2000) leads one to admit that absolute movement time is known prior to action onset, which needs further examination. Another way to understand the control of impact movement is to consider that the optical control variable is contingent on the task constraints. Analyzing temporal control of golf-putting has shown that the acceleration of arms during the downswing is indeed continuously coupled with the relative rate of change of the visual gap between the starting and actual position of the putter, with weak involvement of ball position (the time from departure control strategy, Coello et al. 2000a). This distinct way of using visual information for controlled approach or impact with a stationary object indicates that achieving adaptive behavior involves a continuous coupling between action and a specific, task-dependent source of information. This seems consistent with other observations relating to skill learning. For instance, in gymnastics, despite the high velocity reached, performing a somersault was found to rely primarily on visual information. As stated by Bardy and Laurent (1998), "because the body is in free fall during the jump, the vestibular and the somato-sensory systems are unable to furnish information about (changing) body orientation relative to the ground, and thus vision must play a crucial role" (p. 975). Their study suggested indeed that experts' somersaults are continuously regulated with respect to a prospective visual variable (the first order time to contact relating to the ground surface).

Coming back to the prosaic illustration brought forward in the introduction, one may conclude that for a pianist changes in hand posture are specified from visual chords as perceived on the score. However, achieving an accurate rendering would depend on the ability to identify the source of information that would enable the pianist to reach the correct keys smoothly and accurately with respect to the spatio-temporal contraints prescribed by the music precepts.

## Getting real about invariants

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**Abstract:** Stoffregen & Bardy argue that unimodal invariants do not exist, and that only "amodal" invariants are possible. But they confuse two separate issues. Amodal invariants, we argue, do indeed exist to specify features of the environment, but not even an amodal invariant, in isolation, could specify their "presence" or "reality."

If the textbooks are to be believed, "perception" is largely restricted to vision. Even the important message of James Gibson's *The senses considered as perceptual systems,* that the senses should be conceived "as interrelated rather than mutually exclusive" (Gibson 1966, p. 47), was eclipsed by his final and more widely cited text, *An ecological approach to visual perception* (Gibson 1979), a work that came dangerously close to celebrating the self-sufficiency of vision. So we welcome S&B's examination of the interrelatedness of the senses. Our commentary begins with a plea for terminological consistency in the light of past usage (S&B are not the first people since Aristotle, Locke, and Berkeley to discuss this issue), and then a plea for common sense. As we see it, their article conflates two distinct, if partially overlapping, arguments – one that takes things just a *bit* too far, and the other hardly far enough.

***Terminology.*** Long ago, Michotte and Metelli wrote about *amodal* perception or completion to characterize the experience of the continued existence of an object optically occluded by another, such as the concealment of an object by another object, or its disappearance behind a screen. They coined the term "amodal" because, as they argued, although we do not experience the concealed object as having gone "out of existence," it is nevertheless "out of *sight*" (Kanizsa & Gerbino 1982; Metelli 1940; Thines et al. 1991). In addition, there is the case of what we might call *transmodal* perception, where a quality proper to one sensory modality is experienced by means of another: *seeing* the coolness of the shade of a tree, or the softness of an object. Then there is what von Hornbostel (1925) and Werner (1934) called *supramodal* perception, where the same quality appears to be equally available to a whole range of different sensory modalities. Finally, in our very brief and preliminary analysis, there is *intermodal* perception, the simultaneous stimulation of the different senses (for this and related issues, see Marks 1978).

As S&B make clear, their article is not primarily concerned with perception but with the relation between ambient energy array and the environment. And they are concerned with *intermodal* arrays. Now, since Michotte and Metelli already have a just claim to the term "amodal," what specific term might we apply to S&B's proposed invariants? Since their argument is ambiguous, we will offer two alternatives: *multimodal* or *panmodal* invariants.

***Specification, representation, and reality.*** Given their commitment to holistic thinking, it is not suprising that the Gestalt psychologists questioned the possibility that *any* isolated energy pattern could be specific to its source:

> . . . just as ambiguous words become more specifically defined when they are placed in sentences that give them a contextual setting, the ambiguity of mediation events is reduced when the stimuli or manifestations referring to the distal stimulus are *embedded* in the total situation. (Heider 1958, p. 35 et seq.)

Although von Ehrenfel's (1980) classic statement of the Gestalt principle acknowledged the existence of intermodal Gestalten, much of the subsequent Gestaltist literature remained curiously limited to discussions of unimodal Gestalten, usually visual Gestalten. S&B therefore could be seen as pursuing the holistic logic of Gestaltism in their denial that any *unimodal* pattern of energy could constitute information in Gibson's sense. However, as we see it, they conflate two distinct arguments. The first argument is that no unimodal structure could be specific to any environmental property or event, an argument they base on a convincing but very limited example, that of proprioception: as they convincingly establish, neither optical nor mechanical stimulation would be sufficient *in this particular case.* Rather, *multimodal* stimulation (optical-vestibular) is necessary. But they also invoke a second and quite different argument: that no energy pattern disconnected from *all* possible additional energy patterns could specify the *presence* or *reality* of an environmental property or event, as in their example of an approaching boulder. And this calls for a *panmodal* array of a *limitless* kind.

We are not convinced that S&B have established their general claim that unimodal structures cannot ever be specific to environmental properties and events. A pheromone may be completely specific to the female silk-moth, or a fingerprint to a particular



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person. It is true that these structures do not, in themselves, specify the *presence* of a silk-moth or a person (the whole point of using fingerprints in forensic inquiry is that the culprit is no longer at the scene of the crime). Nevertheless, these structures are not cues in the traditional sense: they are not probabilistically related to their reference. On the other hand, the specification of *presence* calls for more than even the amodal (multimodal or panmodal?) invariants identified by S&B. As James Gibson put it, the fact that one is dealing with a real situation is specified by the very *inexhaustibility* of the information available (Gibson 1979, p. 256).

As we see it, the distinction between the specification of an environmental property and of its *presence* can help us deal with two otherwise awkward problems. The first is that the demonstration, in the laboratory, of the "functional validity" of an invariant – even an amodal invariant – would seem to destroy what it seeks to affirm, the specific relation to the actual environmental event. But, as Gibson emphasized, "The experimenter . . . is not trying to simulate reality. [One] could not create the illusion of looking around and walking through the countryside in any case, *for [one] would have to create the countryside*" (Gibson 1979, p. 305; emphasis added).

The second problem is this. Despite their argument against the very possibility of unimodal invariants, in the Web version of their article S&B not only chose to include photographs of themselves, but photographs that look remarkably *like* them – and (as far as we know) nobody else. Which is *not* to say that we think they are *there* on the page. Plenty about them is, of course, missing from their images, and plenty about their images informs us that it is their images rather than themselves that are there (Polanyi 1970; Thines et al. 1991, pp. 117 et seq.).

## With either separate or integrated arrays of senses, perception may not be direct

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**Abstract:** The information required for perception may be available in the energy arrays that stimulate sensory organs but in a form not directly suitable for the planning and execution of the organism's actions in the environment. The requisite form of information is obtained, with no loss of adequate perception, by representation of sensory stimuli in frames of reference determined by internal control signals producing actions. This process seems evolutionarily advantageous but makes perception essentially non-direct, regardless of the degree of intra- or inter-modal sensory integration.

To plan and control movements of an artificial arm, robotic engineers use "sensors" that directly, and usually separately, measure kinematic variables (the position, velocity, and acceleration of arm segments). As if on purpose, the nervous system avoids direct measurement of kinematic variables. For example, muscle spindle receptors are sensitive to changes in muscle length and, as such, they play a major role in the perception of position of body segments (Matthews 1981). However, in spindle afferents, the positional signals are mixed with those related to the rate of change in muscle length. Moreover, afferent output is influenced by independent efferent signals from gamma-motoneurons, making the relationship between the activity of spindle afferents and position ambiguous, even in static conditions (Fig. 1A).

For example, during tonic isometric contractions, the activity of muscle spindle afferents increases with increasing torque under the influence of gamma-efferents (Valbo 1974) although arm position remains unchanged. On the other hand, during slow isotonic

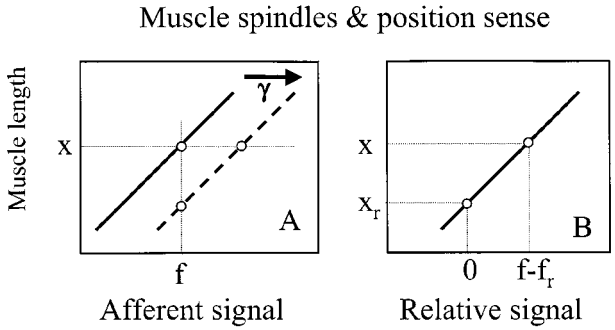



Figure 1 (Feldman & Lestienne). Tonic activity ($f$) of spindle afferents is related to muscle length, $x$. (A) The effect of gamma-efferent influences on the output signal of spindle afferents is measured by the shift of the solid line (arrow). As a result, the same afferent activity may be associated with different muscle lengths (e.g., for the points on a vertical line) and the same muscle length with different afferent outputs (for the points on a horizontal line). The ambiguity disappears (B) if the muscle length is measured based on the changes in the afferent activity ($f$) relative to that ($f_r$) elicited by gamma influences at a referent muscle length ($x_r$) for which $f-f_r = 0$.

movements actively produced by subjects, spindle afferents may fire at the same frequency despite the changes in the arm position (Hulliger et al. 1982). Despite the ambiguity of the relationship between the spindle output and the position of arm segments, the arm is correctly perceived as being motionless in isometric conditions although the activity of spindle afferent changes. In isotonic conditions, the arm is perceived as moving although the spindle activity remains the same.

How is this remarkable ability achieved? Stoffregen & Bardy (S&B) could suggest that adequate position perception (kinesthesia) results from some integration (a "global array") of spindle signals with those of other sensory systems. This would be consistent with the evidence that perception of position is based on signals from muscle, joint, and skin afferents (Gandevia & Burke 1992) and that these signals are integrated at the level of neurons of ascending tracts (Arshavsky et al. 1985; Lundberg 1975; McCrea 1992). However, it has been shown that neurons integrating these afferent signals also receive independent signals from central pattern generators (e.g., Arshavsky et al. 1985). Due to these independent signals, the ambiguity of the relationship between the arm position and sensory output is likely not reduced but rather induced by the nervous system at any level of sensory integration, contrary to the basic idea of the target article.

An answer to the question of how, in principle, adequate position sense can be achieved despite the ambiguity has been given in the framework of the lambda-model for motor control (Feldman & Levin 1995). According to the model, the central nervous system organizes spatial frames of reference for the sensorimotor apparatus and produces active movements by shifting the frames in terms of spatial coordinates. The hypothesis has been supported in several recent studies (Gribble et al. 1998; Feldman et al. 1998; Lestienne et al. 2000). The spatial frames of reference used for actions can also be used in perception (Feldman & Latash 1982; Feldman & Levin 1995). In particular, kinesthetic perception is likely based not on sensory signals per se but on these signals represented in a frame of reference determined by central control signals underlying the motor output. For example, gamma-motoneurons not only influence the sensory output of spindle afferents but also the muscle motor output, via spindle afferent feedback to motoneurons.

To perceive position, some neural systems presumably measure spindle afferent activity relative to its background level ("efferent copy") specified by gamma motoneurons (Fig. 1B). During isometric contractions, the efferent and afferent activity increases in



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parallel so that the relative changes in the spindle activity are about zero, thus signalling that the arm is motionless. On the other hand, during isotonic movements, the decrease in the spindle afferent activity normally resulting from muscle shortening is likely compensated by the increasing activity of gamma efferents so that the spindle activity may remain unchanged despite the changes in the arm position. However, due to changes in the referent signals coming from gamma motoneurons, the arm is perceived as moving. Afferent signals from tendon organs, joint and skin receptors, also measured relative to motor control signals, could contribute to kinesthesia in consonance with muscle spindle afferents (Feldman & Latash 1982).

The hypothesis that position sense involves action-based referents was also used to explain kinesthetic illusions arising during muscle vibration (Feldman & Latash 1982) as well as the phantom limb phenomenon in which a limb continues to be perceived even after it has been amputated (Feldman & Levin 1995; Melzack 1989). The hypothesis that perception is based on sensory signals represented in an action-based frame of reference seems applicable to other senses. For example, in all cases of postural control described in the target article, the requirement of mechanical balance only constrains the set of possible body configurations. Subjects can still choose a desired posture from this set in a way consistent with task demands. Based on experimental data (Feldman et al. 1998; Lestienne et al. 2000), it has been suggested that taken together, action-generating control signals can determine a referent body configuration ("referent body image") so that external forces, including gravity, deflect the system from this configuration until balance between the muscle and external forces is regained at some actual body configuration.

The same referent configuration could be used in the perception of the actual postural configuration to decide whether or not the latter meets task demands. The ability to specify appropriate referent body configurations may be a basic mechanism underlying action and perception, which is preserved even in extreme conditions, such as weightlessness when subjects retain the basic set of body configurations characteristic of terrestrial conditions, despite substantial changes in the tonic activity of muscles (Lestienne & Gurfinkel 1988).

Action-based referent signals also seem necessary for visual processing. For example, while walking in a room or tilting the head, we do not perceive that the room is moving despite the motion of the projection of the visual scene on the retina. This implies that the visual constancy is actively supported by referencing the visual stimuli to control signals producing motor actions, a process reminiscent of the sense of a constant position during isometric contractions. The suggestion that visual and motor systems are interdependent is well supported by experimental observations of different sensorimotor illusions in humans (Lackner & Dizio 1988; Lestienne et al. 1977) and by neurophysiological studies in animals (Deliagina & Fagerstedt 2000).

In conclusion, neither individual nor global array of sensory stimuli is directly suitable for the planning and execution of actions of the organism in the environment. Since actions are most essential for the survival of organisms, an action-based representation of sensory stimuli has been naturally selected, which makes perception essentially non-direct, regardless of the degree of intra or inter-modal sensory integration.

## The global array: Not new to infant researchers

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**Abstract:** We find Stoffregen & Bardy's argument that the senses are united and that specificity exists within the global array compelling. However, this view is not entirely new and research on the development and the origins of perception in infancy, inspired by Gibson's ecological perspective, also supports their claims. The inclusion of this developmental research will strengthen and challenge some of Stoffregen & Bardy's views.

Stoffregen & Bardy (S&B) tackle several of the more thorny issues in the study of perception. In particular, they examine whether the senses operate independently or collectively as a unitary system in the pick-up of information. They also examine the nature of information available for perception and how information can directly specify an organism's opportunities for action. S&B present a compelling and richly elaborated argument, inspired largely by Gibson's theory and contemporary dynamical systems perspectives, for the claim that perception is based on the detection of higher-order relations that exist across different forms of energy in a global (spatiotemporal) array. S&B also argue that this view is new and is incompatible with any view of perception that proposes that the senses work separately, or entails a process of internal comparison across the senses to detect intersensory redundancies.

We are in agreement with S&B on many points. For instance we agree with their assertion that information available in the global array is the fundamental basis for perception and action and that it is not impoverished; rather information specifying the potential for action can be directly perceived. We also agree that there is no clear basis for the assumption that perception is accomplished by separate senses. Finally, we agree with their assertion that perception is never truly unimodal, given that one always perceives the environment in relation to the self. However, we believe that S&B have not fully captured the contribution of current developmental research with respect to amodal specification and infants' perception of the global array. Their claim that most views of amodal perception entail a process of internal comparison is not completely accurate. Finally, S&B have omitted a convincing account of how modality-specific properties and differences across the senses are perceived within their perspective.

Concerning S&B's discussion of amodal specification and the global array, we point out that their view of amodal specification is not new. As highlighted by E. J. Gibson:

> More accurately, amodal specification refers to the fact that information is not specific to one sensory modality. I mean the term to suggest that there is information in stimulation, which is not tied to specific sensations but is rather invariant over them. An amodal property is not an intermodal relationship strictly speaking. I mean by it a higher order relational stimulation which is not specific to a modality. Intensive dimensions might be an example. (Gibson 1969, p. 219)

These assumptions have shaped much of the infant work conducted from the ecological perspective (e.g., Bahrick 1988; 1992; 1994; Bahrick & Lickliter 2000; Bahrick & Pickens 1994; Eppler 1995; Rochat 1995; Schmuckler 1995; Walker-Andrews 1988; 1997). These developmental researchers have similarly described the global array as a spatio-temporal array, and have also emphasized that amodal specification is abstract, higher order, and entails detection of relational information with a unified perceptual system. These conceptualizations of amodal specification do not involve a process of internal comparison in order to detect redundancies across the senses (e.g., see Bahrick & Lickliter 2000). Further, the "intensity hypothesis" (see Turkewitz et al. 1983) also embodies S&B's view of amodal specification and describes early infancy as a period when all stimulation is experienced along an undifferentiated dimension of intensity.



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Given that the study of infants provides a view of the organism in a more basic state, a greater emphasis on infant research, especially that conducted to discover the origins and general principles of perception, would be appropriate for S&B's discussion of the bases of perception. For example, infant research has generated the following insights regarding the nature of perceptual development, relevant to and consistent with S&B's views regarding amodal specification: First, infants are adept perceivers of amodal relations, including temporal synchrony, tempo of action, rhythm, intensity, and spatial location (see Bahrick & Pickens 1994). In fact, temporal synchrony may be the most "global" amodal relation, as it is inherently relational and cannot be perceived in any single modality alone. Second, infants detect intersensory relations in order of increasing specificity. That is, global, amodal relations (e.g., synchrony) are detected developmentally prior to nested amodal relations (e.g., temporal information specifying object composition, tempo, or rhythm), and amodal relations are detected developmentally prior to arbitrary, modality-specific relations (e.g., the red object makes a squeaky sound; the word pen goes with the thin object; Bahrick, 1992; 1994; in press). In fact, there is general agreement that infants detect temporal synchrony early on, if not at birth (Bahrick, in press; Lewkowicz 2000; Slater et al. 1999). Third, the detection of arbitrary, modality-specific relations is guided and constrained by detection of amodal relations. Thus infants learn arbitrary, modality-specific relations in the presence, but not in the absence of amodal relations such as temporal synchrony uniting the visual and acoustic stimulation (Gogate & Bahrick 1998; Hernandez-Reif & Bahrick, in press; Slater et al. 1999). Fourth, intersensory redundancy facilitates perceptual differentiation and leads to more effective processing than the same information presented unimodally (Bahrick & Lickliter 2000). Thus, the answer to S&B's question as to whether infants are sensitive to information in the global array, is a clear "yes," and there is already much evidence on this topic. We are eager to find out how S&B integrate the general principles of development outlined above into their discussion of perception.

Finally, we are in agreement that observers must also detect differences in stimulation that emanate from different energy sources. Detection of amodal invariants requires detecting what is constant across different kinds of stimulation. In fact, redundancy of this sort is a powerful garner of infant attention and infants detect amodal properties (e.g., synchrony, rhythm, tempo) developmentally prior to other properties. Further, according to the intersensory redundancy hypothesis (Bahrick & Lickliter 2000), infants are better able to discriminate an amodal property when it is presented bimodally than unimodaly. Bahrick and Lickliter (2000) demonstrated that 5-month-olds detected a rhythm when it was presented visually and acoustically (a hammer banging in synchrony with its impact sounds), but not when it was presented either visually or acoustically alone. This intersensory facilitation entails detection of the convergence of stimulation (rhythm) across different modalities (a higher order temporal relation) and therefore also implies an appreciation of the differences in stimulation across modalities. Pick up of differences, too, must be accomplished with a unified perceptual system. In fact, we would suggest that the greater the differences in stimulation, the more the redundancies across these differences stand out as higher order invariants. One need not conclude that we have separate senses in order to register the differences in stimulation emanating from different energy sources. Our perceptual system is flexible, unified across the senses, and attention to these different dimensions is a matter of attentional selectivity.

Briefly, S&B have done a wonderful job of making explicit and questioning the basic assumptions underlying current research and theory in perception. This article serves as a call to other researchers to examine these issues, make explicit the assumptions underlying their research programs, and evaluate their internal consistency.

## Goal directed meaning connects perception and specification

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**Abstract:** We believe that the task goal in voluntary movements provides meaning to existing information sources in the environment and determines, in a dynamic way, the use and relative importance of these different sources. This task-centered meaning bridges the apparent controversy between what information is available in principle (i.e., specification), and what information is perceived.

Stoffregen & Bardy (S&B) analyze three hypotheses about relations between ambient arrays and physical reality, arguing that that it is not possible, in principle, for there to be a unique relation between physical motion and the structure of individual energy arrays. S&B argue that physical motion relative to different referents is specified only in the global array. This perspective poses a challenge to traditional, inference-based theories of perception and cognition, as well as work within the ecological approach to perception and action.

While this target article elucidates the differences between specification (i.e., the existence of information), and perception (i.e., information pick-up), and the implications for theories of perception, we would argue that what is missing is the acknowledgment of the meaningfulness of information, namely the primacy of the task-centered goal in these voluntary movements. S&B state,

> sometimes behavior is not controlled relative to the direction of balance even when the direction of balance is present; we sacrifice alignment with the direction of balance to some other goal. Examples include a soccer goal-keeper diving to catch a shot, and a baseball player diving to catch a fly ball. In such cases, once the player has left the ground, the ball may be the sole referent for both perception and control.

What we would argue is that even before leaving the ground the ball is the most meaningful referent because the goal of the task is to catch the ball!

We believe that the task goal determines the dynamic use of different sources of information and the saliency of each informational source during the completion of a task. Recent experiments from our laboratory have shown how the introduction of different types of local sensory information (e.g., haptic or auditory) can both locally and globally stabilize a subject's coordination during conditions where it would normally become unstable (Fink et al. 2000; Jirsa et al. 2000; Kelso et al. 2000). In addition, it has also been shown that the same information (e.g., relative phase) can be important for disparate tasks, such as movement pattern recognition and production (Haken et al. 1990). Furthermore, when a biological system functionally stabilizes a system that is inherently unstable (i.e., an inverted pendulum), the visually specified time-to-balance drives the corrective actions necessary to avoid a catastrophic fall (Foo et al. 2000). However, during non-critical motions of the pole, the same time-to-balance information does not appear to be important.

One extension of this view that the goal determines the meaningfulness of the available information is that learning is a process by which the organism discovers just what information is important to the successful completion of the task. From the authors' own example, "learning a somersault, for example, appears to depend upon the discovery and control of higher-order relations between vestibular, mechanical, and optical patterns of energy (Bardy & Laurent 1998)." This process of discovering the relevant perception/action relationships may also be seen in motor development (e.g., prehension in infants, see Thelen 1990)

In short, the linkage between specification and perception is driven by meaningful (i.e., task specific) informational variables



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and their dynamics, the origins of which likely lie in the co-evolved relationship between the organism and its environment. What could be more meaningful and specific to the goal directed functioning of a system than information that specifies the coordination among its parts? We are not only creatures of perception and action; we are goal-directed creatures. As Sherrington (1906) remarked, a dog not only walks; it walks to greet its master.

## Specification, information, and the loss of receptor systems

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**Abstract:** Claims made in the target article that information-that-specifies is contained in relations among structured energy arrays, considered as wholes, may well be true, but claims that information-that-specifies is only contained in irreducible relations among structured energy arrays, considered as wholes, fail to persuade, at least in the case of the blind.

Stoffregen & Bardy (S&B) find almost all existing theoretical accounts of perception wanting, including both constructivism and direct realism, and their claims are bound to be controversial in a new way. I expect that their arguments will be unacceptable to constructivists for most of the same, noncontroversial reasons that direct realism has always been unacceptable (see Ullman 1980). More controversial are the claims by S&B that the constructivists' insistence on the ambiguity of stimulation at the level of both individual sensory modalities and Gibson's (1966; 1979) higher-level perceptual systems were correct after all. The specificity that Gibson argued for and sought experimentally, they argue, lies only in the higher-order structures that extend across perceptual systems. S&B's claims appear to constitute a simultaneous advocacy of an anti-reductionist holism (the information in the global array is not only more than but is "qualitatively different from" that in any single energy array) and an anti-psychological reductionism: that (only) the physics of (only) ambient global arrays explains specificity and information for perception completely and without residue.

Their arguments for the existence of precise information in the spatiotemporal structure of multiple sensory arrays (taken as a collective) may be more specific than that contained in such arrays considered additively, or within any single sensory array, and that such information ought to be explicitly studied, are entirely reasonable. For the analogous reason that it is not possible to account for less variance by adding another factor in multiple regression, the collective information in $n$ energy arrays will never be less than that contained in $n-1$ energy arrays. However, whether it is qualitatively different information that is contained in the so-called global array and whether there is information-that-specifies only in such global arrays, however, are more contentious issues. In the target article, specificity appears to be identified with information, such that only a perfect correspondence of the structure of the global array with reality constitutes information ("The question is not whether [the global array] exists but, rather whether it contains information"). While I cannot agree with this, my focus here will be on a somewhat different issue.

S&B write as if there is only a single global array, one independent of people or perceptual systems. I am puzzled by this. In section 6.2.3, S&B explicitly address the nature of stimulation and information in those with complete loss of "receptor systems." The notion of the global array's status as the sole specifier of information, as S&B acknowledge, may be questioned because there are situations where the global array is not complete, as in the case of complete darkness. They respond that the lack of energy need not constitute a lack of information; in fact, "the absence of a form of energy *is* information" (emphasis in original). How does one understand the situation confronting a congenitally blind person, for whom there has never been this variety of stimulation? It seems perverse to suggest this person detects the absence of the optic array; he never had access to it, and hence even having the knowledge that he lacks vision would not constitute information. Instead he has access to a global array that has one dimension fewer than that available to his sighted sister. Can this array (maximally global for him, but less global than that of his sister) specify reality?

If the compressed global array cannot specify reality (as seems to be suggested by S&B's reference to "restricted walking" in the blind) one would expect that it would not contain crucial information carried by the optical structures and that, as a result, his performance would be less timely and/or accurate. Since mobility in the blind is indeed often tentative, slow and restricted, it may be assumed that this is indeed the situation that arises. But it hardly seems guaranteed in advance. If the information available to the blind person can specify reality, then S&B 's insistence that only the global array is specific cannot be sustained because two quite different global arrays (with $n-1$ and $n$ dimensions) would both specify the same reality and one would have to conclude that the extra dimension contributes neither additional nor qualitatively different information. Is it conceivable that both brother and sister could perceive certain features (or Gibsonian affordances) of the world with equivalent accuracy, in situations (such as locomotion) that ordinarily depend upon "sensitivity" to patterns that extend across optics? If there were sufficient information in the blind person's $n-1$ dimensions to match the performance of the sighted person's $n$ dimensions, this would seem to imply the complete global array was no more specific than an incomplete one. Either the contents of the optic array contain no measurably greater amount of information (on its own or when incorporated into an existing global array) than are contained in the other arrays, or the $(n-1)$-dimensional global array of the blind is expanded without increasing its dimensionality.

Stoffregen has done as much as anyone to specify the informational basis for some remarkable echolocational abilities of humans (Stoffregen & Pittenger 1995), including the discrimination of the presence and shape of small object shapes based on self-generated sounds that are heard directly and as echoes returning from structured layouts, often within a time frame so that the echoes are available before the original sound has been completed (e.g., Kellogg 1962; Rice 1967). Recently, I have found evidence that naive persons deprived of optical structures can make immediate use of broadband continuous echoes to make decisions about the passability of gaps between walls when they retain active control of the direction in which the (head-mounted) cone of emitted ultrasound is being directed and are free to explore the layout by any head movements that they choose (Hughes 2000; cf. Warren & Whang 1987). Plainly, the echoes heard are not the only information available during such activities; the haptic, inertial, and mechanical arrays are not obliterated. But what becomes of the global array with the introduction of a new acoustic structure and the removal of optical ones? Does such modal substitution bear at all on the notions of information and specificity? I think so. Instances of functionally equivalent perceptual descriptions being secured by different perceptual systems, suggest various hypotheses, including that of amodal specification (Epstein 1985). Such manipulations may not be specific in the sense in which S&B prefer it, but it nonetheless remains theoretically relevant and rich in practical implications for populations such as the blind.

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## Brain science: A more direct way of understanding our senses

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**Abstract:** Stoffregen & Bardy suggest that the senses are not separable. However, they have a philosophical approach rather than using direct evidence that the nervous system analyzes sensory information in a highly flexible manner.

The target article tackles the popular question of how we perceive information; concluding that the existence of separate sensory systems is in doubt. As evidence, Stoffregen & Bardy (S&B) primarily use analogies from physics and examples of convergence and interactions of different senses, but they largely ignore the extensive and relevant data on human physiology, sensory systems, and brain processes in analyzing sensory information.

In this commentary I present some empirical evidence concerning the representations of sensory systems in the brain and their cross modal changes. Scientists have been enthusiastic about cross-modal brain plasticity since the 1970s but it has been studied perhaps even more intensively during recent years. By now there is ample evidence that a brain area which normally processes information primarily from one sensory modality can become responsive to other modalities. For example, in early-onset deafness caused by damage to the peripheral nervous system, brain areas that normally process auditory input become responsive to visual input (Neville et al. 1983; Rebillard et al. 1977). Similarly, in early-onset blindess, areas that normally analyze visual information are taken over by auditory and somatosensory functions (see, for example, Cohen et al. 1997; Kujala et al. 1995a; 1995b; 1997; Rausohecker & Korte 1993; Sadato et al. 1996). However, not just any function spreads to brain areas deprived of their normal input. For example, the occipital cortex of the blind seems to be activated by attended but not by unattended auditory or somatosensory stimuli (Kujala et al. 1995a; 1995b; 2000; Liotti et al. 1998).

These cross-modal activation patterns have a functional role in perception. If the neural functioning of the occipital cortex of an early blind individual is temporarily disrupted, simultaneous Braille reading is hampered (Cohen et al. 1997). This shows that traditionally "visua1" areas of the brain in individuals who have always been totally blind actually process tactile information. Cross-modal reorganization of brain functions may take place even after childhood: Visual brain areas are activated by tactile (Buechel et al. 1998) and auditory (Kujala et al. 1997) tasks in blind subjects who had had normal vision until puberty or adulthood. Whether this activity corresponds functionally to actual perception or information processing remains to be clarified.

The neural substrate for these cross-modal changes might be neurons driven by sensory stimulation other than what is mainly received by a primary sensory brain area. Murata et al. (1965) found that, in the cat visual cortex, 47% of neurons respond to tactile stimulation and 38% to auditory stimulation. The human occipital cortex, which is traditionally thought to primarily analyze features of visual input, has an important role in tactile orientation analysis (Zangaladze et al. 1999): The disruption of occipital function in human subjects interfered with tactile discrimination of grating orientation, but not with tactile discrimination of grating texture or the detection of electrical stimuli applied to the fingerpad.

The flexibility of the nervous system in sensory processing has also been demonstrated by lesions to different brain areas and by various manipulations of the pathways that mediate sensory information. For example, if retinal projections are redirected to the auditory thalamus in neonatal ferrets, these projections not only activate parts of primary auditory cortex via thalamo-cortical connections but also form a retinotopic map (Roe et al. 1990; Sur et al. 1988; see also Frost & Metin 1985 for redirected retinal projections to the somatosensory cortex). These visually driven auditory-cortex neurons have typical properties of neurons in the visual cortex, such as orientation and direction selectivity. Moreover, these visual-auditory connections function in a meaningful manner (von Melchner et al. 2000). The ferrets could discriminate gratings presented to the part of the retina from which the projections had been redirected to the primary auditory cortex. Although visual acuity was lower than normal for the input in the part of retina that was projected to the auditory cortex, the finding is nonetheless critical to the issue discussed in the target article: it indicates that the initial analysis of visual information can take place in the primary auditory cortex.

These findings on sensory representations and their plasticity in the cortex support S&B's main idea that sensory systems are not as separate as previously thought. However, the claim that "there is no clear basis for the assumption that perception is accomplished by a set of distinct perceptual systems" is far too strong. Although there are interactions and synesthesia between the senses, and even though the brain can be very adaptive in how it processes sensory information, the senses are also in many respects distinct. For example, some sensory functions appear to be represented in the modality-specific areas of the brain in a rigid manner. Zangaladze et al. (1999), for example, found that the visual cortex is involved in analyzing orientations received tactually but it does not seem to be processing somatosensory texture analysis.

The research on sensory representation in the brain clearly provides some support for S&B's doubt about the traditional view of separate senses, but S&B seem to take it too far. The flexibility in the processing of sensory input between the modalities is clearly greater than has been thought previously. However, this does not warrant totally abandoning the notion of separate senses, particularly in light of evidence of limits in cross-modal representations.

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## Expanding the theory: Nonverbal determination of referents in a joystick task

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**Abstract:** The arguments of Stoffregen & Bardy for studying perception based on the global array are intriguing. This theory can be examined in nonhuman species using nonverbal tasks. We examine how monkeys master a skill that incorporates a two-dimensional/three-dimensional interface. We feel this provides excellent support for Stoffregen & Bardy's theory.

Stoffregen & Bardy (S & B) present situational examples that demonstrate previous theories' shortcomings in dealing with perceptual illusions, specifically that of motion perception (sect. 6.1), and they propose a new perspective that utilizes specification in the global array. We believe that S&B's ideas on the use of the global array in motion perception, specifically situations involving visual, kinesthetic, and vestibular stimulation, are useful in addressing skill acquisition in humans and nonhuman animals. We present findings from our laboratory that support their theory that individuals work to detect the unique global array while mastering motor skills.

We study how capuchin monkeys (*Cebus apella*) acquire skill in a task incorporating visual, kinesthetic, proprioceptive, and vestibular stimulation. Our capuchins (8 adult males) have mastered using a joystick to move a cursor in a controlled manner on a com-



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puter monitor. The system provides a unique learning situation in that while their movements are made in three dimensions, the monkeys gain visual knowledge of results in two dimensions. To a capuchin, working in two-dimensional space is a novel experience. In addition to providing artificial relations between visual feedback and manual action, this testing system enables us to study mastery of a skill using different kinesthetic feedback than is available when action occurs directly upon the target object. The joystick and cursor are spatially separated and not physically connected. Thus, unlike striking a ball with a bat, there is no direct kinesthetic feedback about the effect of moving the joystick (i.e., no vibration of the joystick from contacting the cursor). This situation affords an interesting experimental context in which to study how perceivers learn about the two-dimensional/three-dimensional interface in "virtual" displays.

S&B suggest that description of motion perception is meaningful only if it is made in terms of referents (sect. 4.5). In the examples presented, identification of these referents is elicited using questions asked of the participants (sect. 5.2). However, perception in skill acquisition can be investigated in nonhuman animals as well. To evaluate perceptual processes in nonverbal individuals, other ways of examining perception must be found. We have used visual tracking of the cursor and an unexpected phenomenon we call "body-tilting" to examine perceptual contributions to learning a perceptuomotor skill in capuchin monkeys. Both of these variables change in a patterned way with increasing mastery of the joystick. We confine our comments here to the body-tilting phenomenon.

We noticed that monkeys skilled at using the joystick demonstrated a pronounced tilt of the torso, shoulders, and head in the direction of joystick movement and resultant displacement of the cursor when they moved the cursor to the left or the right on the computer monitor (Filion & Fragaszy 1997). To determine whether visual stimulation due to the cursor displacement or movement-associated stimulation related to manipulating the joystick was the relevant referent in this task, we assigned four naive capuchins to different learning situations. Two subjects learned to use the joystick in the normal condition in which manipulation of the joystick results in isomorphic movement of the cursor (e.g., a push to the left moves the cursor to the left). The other two animals experienced an inverted relationship in which movement of the joystick and cursor displacement was 180° degrees opposed.

We found that animals in both the isomorphic and inverted groups tilted in the direction of the cursor displacement, whether or not it was the same direction as joystick movement (Leighty & Fragaszy 2000). Individuals in the inverted group were tilting in the direction opposite of their arm movement. After achieving mastery in the inverted condition, these subjects experienced a reversal in the joystick/cursor relationship. They continued to tilt in the direction of cursor displacement under these new conditions. This suggests that the relevant referent in mastering this skill is visual (i.e., the direction of cursor displacement) and not the kinesthetic properties of moving the joystick.

Why would these animals tilt when using a joystick? As Stoffregen & Bardy note, a naive individual must identify and utilize different structures in the global array to acquire new perceptual-motor skills (sect. 7). It may be that tilting alters the structure of the global array in such a way that the animal is better able to detect the relationships embodied in this perceptually novel situation (sect. 6.2.5). It is interesting to highlight the instances of this form of behavior outside of the laboratory in humans. One can see tilting being performed that seems to have no direct impact on the outcome of the prior goal-directed action. For example, when bowling or golfing, individuals often tilt in the direction of desired outcome after releasing or striking the ball. One also sees tilting in children (and adults) playing video games while using a button controller or joystick. It may be postulated that this form of behavior is merely a superstitious act (according to operant definitions) that ultimately serves little function in performance. We believe, however, that these behaviors increase one's ability to detect relevant patterns of the global array, and thus they are incorporated into exploratory activity early in the learning process. In our view, and in accord with S&B's theory, improved detection of the global array contributes to the identification and use of referents in performance of required actions.

S&B note the paucity of research in the area of development of athletic and other motor skills in relation to the global array (sect. 7). We believe that systematic investigations in humans and nonhumans, such as we have conducted with capuchins using nonverbal indices of perceptual processes, can help understand skill development. Similar work will be essential in evaluating S&B's theory of the specification of the global array. Comparative and non-language-based testing of this theory will generate wider acceptance within perceptual psychology, along with better interfacing with other fields (e.g., sports and developmental psychology, behavioral ecology).

Although this theory works well with tasks utilizing visual, kinesthetic, and vestibular stimulation (e.g., joystick tasks), and also with visual and auditory stimulation (e.g., McGurk effect, sect. 6.2.6), we are curious to see how S&B and other investigators would apply the assertion that the senses work as a single system (sect. 7) to gustatory and olfactory stimulation. Expanding the theory to incorporate all forms of stimulation would strengthen S&B's arguments.

## Situating situated multimodal perception: The relevance of global arrays to development

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**Abstract:** Stoffregen & Bardy reject the likelihood that infants are sensitive to the global array, implying that intersensory integration is not possible in early development. We argue that infants are sensitive to unimodal arrays and are able to integrate them through the active participation of their nervous system and that the observed developmental changes are due to experience and brain development.

Stoffregen & Bardy (S&B) propose a bold new view that is a direct descendant of Gibson's ecological psychology. Based on the underlying assumption that perception is thoroughly multimodal, they propose that perception and action are linked by a perceptual system that is responsive to global, modality-independent arrays. The global arrays are detected directly and thus integration of modality-specific information by internal (i.e., neuronal) processes is unnecessary. In this way, they reject Gibson's notion that perception and action are guided by distinct, single-modality arrays. Here we address some of the questions that the concept of global array raises for those interested in the development of perception.

Based on their objection to the notion of separate senses, S&B explicitly reject the possibility that infants and novices are initially sensitive to unimodal arrays and, thus, by implication endorse the idea that infants can perceive global arrays. S&B also reject the possibility that experience might enable the pickup of global arrays, and thus leave the developmentalist with the only obvious option – the pick-up of global arrays either appears magically or is there from birth and, therefore, is innate. The problem with either view is that it does not explain the processes underlying the development of perception. In addition, the overwhelming evidence is that perception does change over development. How, then, can we explain such changes, particularly with regard to intersensory functions? First, the different sensory systems have their functional onset at different times during early development



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and follow different developmental courses (Gottlieb 1971). As a result, the various sensory and perceptual abilities that would be essential for the detection of global arrays each emerge at different times. For example, basic perceptual competencies such as spatial and temporal acuity, depth perception, object perception, sound localization, texture perception, and shape perception, to name a few, each develop at different times and at different rates (Keliman & Arterberry 1998). Moreover, motor abilities, which in S&B's view are critical to the detection of global arrays, lag considerably behind. Thus, whereas by six months of age a number of basic sensory/perceptual abilities are already fairly well developed, crawling does not emerge until around eight months and walking not until even later.

Given that (1) self-generated perception-action coupling is essential to the perception of global arrays, (2) different perceptual capacities develop asynchronously in the first months of life, and (3) perceptual and motor development is dissociated, serious doubts about pre-motor infants' ability to perceive global arrays can be raised. Therefore, what is needed to substantiate S&B's hypothesis in human development is either a demonstration that babies can, in fact, perceive global arrays, or a suggestion as to how they would develop this capability other than from integrating modality-specific information. Moreover, if infants do not respond to global arrays (and thus must somehow learn to do so), the question is what exactly do they perceive?

Interesting to note, evidence shows that infants can perceive various types of intersensory relations (Lewkowicz & Lickliter 1994). If this evidence does not signify detection of global arrays then what does it signify? Our view is that infants are, in fact, sensitive to unimodal arrays and that they can integrate them based on equivalent and redundant features through the active participation of the nervous system. The various developmental changes observed in intersensory abilities are, in turn, likely to be due to experience, as well as brain growth, development, and reorganization (Lewkowicz 2000; von Melchner et al. 2000; Wallace & Stein 1997). S&B would likely reject the specifics of our view by stating, as they do, that it is not consistent with the ecological approach; unfortunately, they offer no alternatives. For those interested in development, however, the principal challenge is to determine how a dynamic system that is constantly organizing and reorganizing (Gottlieb 1991; Thelen & Smith 1994) is capable of perceiving intersensory relations despite the fact that it may not be able to perceive global arrays.

Our view is that the nervous system (i.e., internal processes) plays an essential and critical role in the development of intersensory perception. Indeed, one could argue that this is completely consistent with ecological thinking. Specifically, if we extend the evolutionary argument that Gibson used to motivate his ecological psychology (and one that S&B would likely not find objectionable) that organisms evolved to respond directly to perceptual structure then it is equally likely that nervous systems also evolved to do so. Given that no behavior is possible without the brain, why ascribe all behavioral control to external input and reject internal processes? How can one speak of organism-environment mutuality, and not acknowledge the organism's internal machinery and its attendant internal processes? Recent neurophysiological findings show that, at least in the case of spatial multimodal cues, the nervous system does not automatically pick up the relations across modalities but, instead, actively synthesizes them. Stein and his colleagues (Stein 1998) have shown that the deep layers of the mammalian superior colliculus contain multimodal cells. These cells exhibit a marked enhancement in activity when near-threshold auditory and visual stimuli are presented. In other words, there is a strong dissociation between the information in the global array, the corresponding neuronal activity, and behavioral responsiveness. Moreover, these cells are not present at birth but appear later in development and when they do they still do not exhibit mature functional properties. While we do not know how these cells develop in human infants, the absence of multimodal responses in the developing colliculus of the cat casts serious doubt on the assumption that the perception of global arrays is innate. Even more troubling for the ecological direct perception view is the finding that when the association cortex is inactivated the collicular cells cease to perform intersensory integration. This, in turn, results in a failure to produce appropriate behavioral responses. In other words, perception is also in the head, not just "out there"!

## Amodal specifying information: Where is occlusion?

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**Abstract:** James Gibson's theory of information, as specific to (but not necessarily "like") its sources, is especially indebted to the study of occlusion for its core examples. In occlusion, one is "amodally" aware of hidden surfaces. Is this still too related to one modality to count as a good case for Stoffregen & Bardy?

Stoffregen & Bardy (S&B) argue that researchers should examine information defined across energy fields but not defined within any one. I do not think that it is clear how to flesh out their sketch with relevant data and more detailed theory. To make their position clear, the authors will need to review a much larger body of data, some of which surely exists and much that will have to be generated. I take it that a major goal of their target article is to stimulate work on both of these. It seems clear that their paradigm case is the specification of ground slope that they mention in section 6.1, drawn from Gibson 1966, pp. 62–63. I hope that S&B's response will recommend a variety of avenues of research but one set that I think would be especially helpful concerns occlusion.

Occlusion emerges as a topic in the term "amodal." The position that S&B attribute to James Gibson with the label "amodal" is a position Gibson did endorse in 1966, but he did not call it "amodal." Moreover, he recognized the problems the authors warn about. "If stimulus information is *equivalent* across sense modalities, as I argue, then a new problem arises of the consistency and *discrepancy* of information, either *within* a perceptual system or between perceptual systems (*cross*-modal, *supra-intermodal,* amodal, the 'cooperation' of the senses, 'unity' of the senses, etc. (Gibson 1966)."

Eleanor Gibson, as cited by S&B, used "amodal" in the authors' sense, but James Gibson did not. Taken by itself, this is a minor point, but considering it leads naturally to core concepts of ecological psychology, specification, and information. These words are used frequently in the target article, but without elaboration (allowing S&B to stick closely to their main points). Because "specification" and "information" are common enough words in English, there is little in the target article that would mark them as carefully chosen theoretical terms, yet what they indicate are precisely the qualities of the ecological position that make the authors' argument plausible. Therefore I think it is worthwhile underscoring their meaning for James Gibson.

The usage of the word "amodal" that James Gibson cited was from Michotte et al. (1964). In what some have called the "rabbit hole effect," which forms half of the well-known "tunnel effect," Michotte showed that changes of shape of a circle caused by progressively removing segments, when shown as an animated film or its equivalent, did not look like something changing shape at all, but rather looked like a constant shaped circular form being hidden. Michotte referred to the awareness of the hidden parts as amodal because there was no visual sensation coming from them, what Gibson (1966, p. 205) liked to call a "sensationless perception." This usage of "amodal" is common in the work of Kanizsa and Gerbino (1982) and the framing of the issue is similar to that coming from the Grossberg group under the heading "filling in" (Pessoa et al. 1998).

Gibson argued that what was crucial here was the specifying



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power of the optical change itself. He maintained that the optical changes caused by something's going out of sight were different from the changes caused by something's going out of existence. He reasoned that if going out of sight (with no change in existence) and going out of existence are optically distinct transitions (for starters, the first is reversible, the second is not), and an animal can see that distinction, then there is a basis for perceiving the continued existence of what is temporarily out of sight (Gibson et al. 1969). There is a real sense in which one can be said to be perceiving the hidden, and for Gibson that is based on the detection of information (the specific type of change).

Studying the details of something going out of sight is, of course, the all important (for Gibson) topic of occlusion. The optical conditions for occlusion are specific to going out of sight as compared to going out of existence. Both are more specific than referring to them as equal cases of "disappearance" of texture. Gibson counted the optical changes specific to each as information, that is, the changes would be informative about some state of the environment (its permanence or impermanence) relative to an observer/actor. What is important to emphasize here is that the language of specificity was adopted as a contrast to terms that would presuppose some kind of similarity or resemblance. It was not a paradox for Gibson to assert that something (occluded surfaces) could be perceived without being "present to the senses (Gibson 1986, p. 189)." He delighted in formulations like "the perception of persistence is not based on the persistence of the percept."

No doubt, S&B understand these points full well. However, because so much that is central to Gibson's ideas about information as specifying its sources is packed into the study of occlusion and its kind of "amodality," I would welcome their making an explicit connection between their ideas and occlusion. I would add that occlusion need not be studied only visually. One can imagine that the sound heard suddenly by someone in the street from a door or window opening on a noisy party would not sound like the beginning of the party, but a "window" on to the sound of an ongoing party. The sense of the party's existence would be "amodal" in the Michotte sense. How would that compare with turning a radio on and off? In touch, one rarely touches all the connected surfaces at once, but can discover what is connected to what. Is occlusion, either from vision or this more generic sense, related to informative cases in the Stoffregen & Bardy scheme? Is there multimodal occlusion? Or is this "amodality" beside the point?

## Toward a strategy for demonstrating the perceptual independence of the global array from individual sensory arrays

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**Abstract:** This commentary discusses a strategy by which investigators can examine whether observers perceive properties of the global array independently of properties in individual sensory arrays. Research showing that perception of complex relationships appears to be independent of the perception of individual components is considered. Ashby and Townsend's (1986) methods for identifying perceptual independence are important tools for studying the global array.

Stoffregen & Bardy (S&B) argue that prospective actors detect properties of the global array independently of properties in individual sensory arrays. One challenge is to develop research strategies and tools that could demonstrate whether prospective actors are able to detect this information directly, that is, without having to compute global properties from the detection of independent properties contained in each source of energy. I am skeptical about the possibility of proving that a computational approach will not work because one could resort to a different set of computational procedures (Mark 1987). However, research can identify constraints on the nature of such computations so as to render implausible approaches based on cognitive computations.

One strategy is to develop tasks in which the resulting behavior or perception appears to be grounded in the detection complex relationships among components of single arrays, so that the complex relationship is detected independently of one or more of its elementary components. Todd's (1981) study of visual information about moving objects showed that observers of a depiction of a moving object were able to detect information about time to arrival or where a free falling object would contact the ground. Todd's analysis of the relationships available in these depictions indicated that observers were detecting a relationship among variables that included the object's acceleration. Yet Todd demonstrated that observers were relatively poor in judging whether an object was accelerating or decelerating.

Apparently, Todd's observers were detecting the complex relationship independent of their perception of individual components. Whereas Todd's analysis was restricted to the visual array, Mark's (1987) examination of the perceived maximum surface height on which an observer could either climb on bipedally or sit on may well have involved relationships in the global array. When observers' capabilities were manipulated by having them wear 10-cm high blocks on their feet, judgments of their action capabilities initially overestimated their stair climbing capabilities and underestimated their maximum sitting capabilities. However, when given the opportunity to engage in exploratory movements (Mark et al. 1990), observers were able to discover their new capabilities in the absence of any opportunity to practice the relevant goal-directed action. Throughout the experiment, Mark (1987) also asked observers to estimate the height of the blocks on which they were standing. Participants consistently overestimated the actual height of the blocks by an amount greater than the error in their judgments of their sitting or stair climbing capabilities.

This finding places a severe constraint on any computational procedure for determining a prospective actor's sitting or stair climbing capabilities – a viable algorithm cannot involve perceived block height in recalibrating the actor's capabilities. Alternately, prospective actors may be detecting affordances (complex relationships between the environment and the prospective actor that have implications for action) directly. The analyses devised by Ashby and Townsend (1986) for distinguishing perceptual independence of individual perceptions go to the heart of this matter. Amazeen (1999) has used this tool effectively to demonstrate that haptically perceived heaviness is independent of haptically perceived size. The experimental goal, then, for implementing S&B's approach, is to devise experiments that show complex relationships in the global array are perceived independently of properties of individual arrays.

## Functional separation of the senses is a requirement of perception/action research

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**Abstract:** Stoffregen & Bardy's arguments against separation of the senses fail to consider the functional differences between the kinds of information potentially available in the structured energy arrays that correspond to the traditional senses. Since most perception/action research pursues a strategy of information perturbation presupposing differential contributions from the various ambient arrays, the global array hypothesis can only be extended and tested by analyses that consider the functional aspects along which the senses can, in fact, be separated.

Stoffregen & Bardy's (S&B's) argument concerning the global array is intriguing hut potentially disturbing because it entails a re-



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jection of the traditional separation of the senses. A bold claim in its own right, this rejection ultimately calls into question the reality of separable ambient energy arrays and consequently denies that specification can exist within such separate arrays. We argue, however, that analysis of the informative character of the various modalities is essential to understand the informative stability of the hypothesized global array under conditions that perturb the functioning of the various senses. S&B present the global array as a logically necessary conclusion from their rejection of separation of the senses. However, the global array hypothesis can stand independent of this rejection and must do so if it is to stand at all.

If we accept that specification is only possible within the global array then perception/action must then rely exclusively on the global array. The authors, however, did not describe many particulars of specification in the global array. We note that there must be multiple ways for the global array to be configured or for information to get into the global array from the various modalities. This follows, for instance, from the successful visually guided locomotion of John Hale (Cole 1995), who lacked proprioceptive information below the neck or from the capable activity exhibited by blind and deaf individuals like Helen Keller. In these cases, a functionally adequate global array must be realizable via a subset of the normally functional sensory organs. Clearly, however, not just any subset of the sensory organs will do. Were we to combine the sensory deficits of both Hale and Keller in the same unfortunate perceiver, it is unclear how the olfactory, taste, and vestibular systems could acquire information about distal layout or limb position.

S&B have neglected to include an account of differential effects of specific sensory deficits on the structure of the global array presumably because they reject the notion of separable senses. Nevertheless, testable predictions concerning the effects of specific sensory attenuation or absence on the structure of the global array would constitute an important empirical aspect of the author's hypothesis, particularly because temporary loss of certain modalities is a regular aspect of our natural ecology. Ultimately, we must inquire how the global array evolves over time and changes when, for example, we turn off the lights before bed. Do we lose altogether the specification of evolving limb posture and body position in the surrounding layout when one or more modalities are attenuated? If specification persists, then how are we to understand it without independent analysis of the contributions of the modality (that is, the sense) that has been temporarily lost?

S&B are critical of efforts to delineate separate sensory systems using any anatomical or neurophysiological basis – but a lack of differentiation between anatomically defined senses is not the same as a lack of differentiation between sensory systems. Gibson (1966) focused on the role of perception in behavior such as maintaining orientation with respect to the surroundings. His functional, rather than anatomical, approach to an analysis of the senses did yield systems that spanned the traditional anatomically defined senses. Nevertheless, Gibson described vision and audition as among these perceptual systems and in his analysis, vision could be used to achieve different goals in different tasks, for example to look at pictures or to guide locomotion. Thus, for Gibson, the notion of separate senses was not simply an obsolete Aristotelian relic but a reality of the functional requirements of perceptual behavior.

To understand how vision can be applied to such disparate tasks requires analysis of the kinds of information available via the structured arrays corresponding to the traditional senses. The optic array cannot, by itself, provide information about absolute spatial scale because it consists of only angular and temporal patterns. Nevertheless, as described by Gibson, optical structure alone does provide information about the ordinal structure of surrounding layout and the observer's spatio-temporal relation to it – enough information to allow the control of steering, for instance, in remote teleoperation. Obviously the human perception/action system did not evolve to guide remote locomotion via a video display, but the ability of humans to succeed at this task under such sensory-deficient conditions indicates that sufficient specification does exist in the optic array alone.

S&B reject analysis of sources of information specific to the individual senses, but such analysis is required for any perturbation study of perception/action. This is extremely significant because, as discussed by Bingham and Pagano (1998), most investigations study perception via perturbation methods wherein the information in particular sensory arrays is removed or attenuated. Bingham and Pagano suggested that investigations should proceed by observing the changes in performance when information is removed as compared to an unperturbed performance standard. This requires an analysis of the information provided via particular senses to predict perturbation effects.

The need to evaluate the effect of perturbation is important because the apparatus used to control and manipulate information is itself perturbing aside from the intended experimental manipulation. Virtual reality (VR), for instance, has excited much interest because it allows optical information to be controlled via computer graphics while retaining an active observer. But VR requires a user to look at a computer graphics display which entails perturbing visual accommodation and vergence. These perturbation effects must be evaluated if VR is to be used to study perception/action. In our own VR research, we have referred to results from previous studies in which either accommodation or vergence had been isolated and manipulated to test their role in distance perception. We used these results to predict the potential effect of the VR displays on performance in reaching tasks. We found that VR produced the predicted effects (Bingham 2000a; Bingham et al., submitted). This research required analysis and study of the visual system both independent of and as part of a system for the coordination and control of reaching.

Because we must ultimately probe the nature of perception/action systems by means of perturbations like these, functional analysis of the senses is essential. Because Stoffregen & Bardy failed to address the role of such perturbations in the study of perception/action, it is difficult to access the theoretical or explanatory potential of the global array and its requisite unity of the senses. Discussion of methodology is essential to the enterprise.

## A different way to combine direct perception with intersensory interaction

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**Abstract:** There is a discrepancy between Stoffregen & Bardy's concept with experimental work on human self-motion perception. We suggest an alternative: (1) higher brain centers are informed by a given sensory cue in a direct and rapid way (direct perception), and (2) this information is then used to prime and shape a more complex mechanism that usually involves several cues and processing steps (inferential).

We welcome the Stoffregen & Bardy's (S&B's) attempt to broaden the basis for ecological psychology or, more specifically, the direct perception concept. As sensory physiologists dealing with inferential explanations of human perception of self-motion, we are repeatedly confronted with the limitations of our "bottom-up" approach and therefore take notice with great interest of the "top-down" views offered by psychologists. We think that the issue of directly perceiving a Gestalt-like "global stimulus array" versus an intersensory interaction in terms of sensor fusion (Mergner & Rosemeier 1998) may revive and deepen the interdisciplinary discussion. We agree with the authors that perception mostly builds upon more than one sensory cue; however, based on experimental evidence concerning perceptual control of dynamic behavior in space, we feel that multisensory processing mainly



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takes place in the inferential elaboration of perception, whereas direct mechanisms (not necessarily multisensory ones) mostly would have priming functions. In particular, we shall argue that: (1) an "inferential" concept of perception can largely be in line with the ecological view, that (2) there may be a coexistens of a direct and an inferential information pick-up in one and the same perception, and (3) that the former actually may prime or shape the latter.

***Concepts of ecological psychology as part of an inferential theory.*** Referring to the example of the "global array" resolving the ambiguity of an isolated consideration of the optokinetic signal (sect. 6.1), we note that a simple neural network with one vestibular and one optokinetic neuron in the input layer, and one "self" and one "pattern" neuron in the output layer could, in principle, determine whether the observer or the pattern was stopped. Inasmuch as the activities of the two input neurons are viewed as a unique pattern propagating through the network, one may talk of a global, direct perception. However, one can as well interpret the network as an inferential processor which, using appropriate input-to-output coupling weights, derives the correct answer from two different afferents; yet, in spite of this inferential approach we would still classify the answer as a holistic Gestalt perception. This is to say that there is often no sharp division between the concepts of direct and inferential perception.

From our own work on the role of visual-vestibular interaction for human self-motion perception (Mergner et al. 2000b) – experiments in which observers and their visual surround were rotated independently of each other using various combinations – we conclude that a rule-based ecological view is largely compatible with the inferential approach of biocybernetical models. In fact, the 1atter reflect the evolutionary experience that the visual world as a whole is fixed in space and, hence, self-motion perception is foremost dependent on the visual cue. The vestibular cue would be, for one thing, a "technical embellishment" that takes over when the dynamical limits of the visual system are being exceeded (at frequencies >0.8 Hz). A different rule is invoked in situations where large parts of our visual fields are covered by coherently moving stimuli (a situation which usually occurs only transiently). Self-motion perception then must rely on the vestibular cue in order to avoid or to minimize visual self-motion illusions (vection, e.g., circular vection, CV. Contrary to S&B, we stick to the notion of an "illusion" because, from an ecological point of view, "true" motion is primarily a way to get from one point on the earth to another). Finally, because low frequency horizontal self-rotations only give rise to optokinetic signals (the vestibular system in this plane has high-pass characteristics), a third rule specifies that low frequency optokinetic signals are to be interpreted as indicating self-motion (with the risk of creating an illusion). These rules can be seen as features of the "global array" that determines the Gestalt of the resulting perception.

Interesting to note, with sinusoidal rotations of 0.4 Hz (at this frequency both the visual and the vestibular cues provide reliable motion information), perceived self-motion perception was observed to rather faithfully reflect the actual body rotation, independent of the rotation of the optokinetic stimulus (OKS). This observation apparently contradicts the first rule and would seem to indicate that subjects relied solely on the vestibular cue for their self-motion perception. However, the analysis of a model which successfully simulated this and other observations (Mergner et al. 2000b) suggests that during rotation in a stationary visual environment, self-motion perception is determined by a visual contribution; this contribution would originate from a "direct pathway" representing "head-to-visual reference" motion. The role of vestibular signal in this scheme is to define the kinematic state of the visual reference (after fusion with a processed version of the visual cue). According to this view one tends to perceive self-motion primarily with respect to a visual reference frame. This frame, in turn, is experienced as moving if its movements with respect to the gravito-inertial reference frame exceed a vestibularty defined threshold (example: movement experienced inside an illuminated funicular cabin, which is swaying in darkness). Likewise, during vestibular-somatosensory interaction self-motion can be viewed as being primarily based on somatosensory afferents and being referenced to the body support, while the vestibular information would be used to monitor and evaluate the kinematic state of the support (Mergner et al. 1997).

***Direct and inferential perception may coexist.*** Investigations into the conditions favoring the occurrence of CV lead us to believe that direct and inferential perceptions can coexist and actually may collaborate. Point of departure was the observation that CV is facilitated in conditions with a brightly illuminated OKS, as compared to an OKS that is so dimly illuminated that the visual field shrinks to the point where the observer can no longer see his orbital rim boundaries (Mergner et al. 2000a). These observations led us to investigate CV in conditions with an artificial orbital rim that could be rotated independently of the eyes (which fixated a stationary or moving target) and of the OKS (stationary of moving). The stimuli were applied at very low frequency (0.05 Hz) where, in case of a real self-rotation, vestibular afferents would no longer contribute much to its perception. The results of these experiments led to a describing model which, among other facts, explains why background motions across the retina do not elicit a CV if they are caused by eye movements. The model postulates two independent internal notions of head motion relative to OKS. One would be based on the visual afferents signaling the relative motion of the orbital rims (and hence of the head) with respect to the OKS. The second would be a visual signal obtained by the summation of OKS retinal slip with an eye movement related efference copy (assuming a stationary head). Noticeably, each of these two cues alone is able to evoke CV; however, under normal circumstances (i.e., in the presence of a structured background) where they tend to arise in combination, they neutralize each other. The purely visually derived signal can be viewed as providing a direct perception, while the coordinate transformation giving rise to the second signal is an example of inferential processing. Thus, direct and inferential cues appear to coexist and to cooperate.

***Could direct perception prime and shape inferential perception?*** We hold that the direct perception concept refers mainly to everyday situations in which individuals interact with their environment and receive a wealth of mostly congruent sensory information. If one conceives of the brain as a learning neuronal network (ignoring its anatomical and developmental "prewiring"), one would assume that it is overtrained with regard to everyday situations and may have learned to handle these mostly on the basis of direct perception. Yet, also in these situations, inferential perception still may be required to adequately direct motor output to the various joints of the body. Indeed, inferential models such as our model of vestibulo-somatosensory interaction (Mergner et al. 1997) specify the kinematic state of each part of the body (head, torso, hips, etc.). By directing an observer's attention to these states, these notions become conscious perceptions and can be probed experimentally. Using appropriate transformation laws, they can be processed to elaborate a behaviorally adequate motor innervation. In contrast, a logical extension of the "global array" view to motor reactions would seem to require the combination of an already huge sensory parameter space with a similarly large space encompassing all possible configurations of the observer's own states, a notion that is difficult to accept, even in view of the immense information storage capabilities of the brain. However, we nonetheless see a role here for direct perception (not necessarily for a global one, though): The operations required for inferential processing and for the transformation into motor output are likely to be quite complex because they have to take into account the rules of spherical kinematics (unlike in most laboratory experiments, natural motions of the body and its parts are not restricted to coplanar rotations). We speculate, therefore, that in standard situations direct perception could provide higher brain centers with a first and rapid information on external events, which would help these centers to rapidly select the correct calculation path for the detailed inferential analysis of the given sit-



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uation; in other words, a combination of direct and inferential processes might yield an optimal trade-off between speed and reliability. However, in complex and rare situations (e.g., observer and visual background or body support moving simultaneously and independently of each other), direct perception is unlikely to provide us with an adequate "first guess" of the ongoing external events so that, for the sake of reliability, the brain would have to rely foremost on its inferential capabilities.

There may be a relation between the hypothesized priming function of direct perception and the role of cognition in perceptual processes. Cognition can, within wide limits, modulate and predetermine the perceptual interpretation of a given set of sensory signals. For example, observers who expect a constant velocity rotation frequently will perceive such a rotation even if they are passively turned in darkness although their only source of information, the vestibular system, will indicate an exponentially decaying velocity. Likewise, the priming function of direct perception may be one of setting the stage for an inferential interpretation in agreement with the initial impression conveyed by the direct perception. Conceivably this occurs by the intermediate of a cognitive level where first the sensory Gestalt of the current situation is recognized. Stoffregen & Bardy do not address the role of cognition for perception, continuing a tradition of classical sensory physiology which virtually ignored cognition. In our view, cognition is inextricably interwoven with perception, and instead of trying to eliminate its role by artificial experimental paradigms, it can be used to elucidate the mechanisms underlying inferential processing (see Mergner et al. 2000b).

## Energy, information, detection, and action

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**Abstracts:** Before one can talk about global arrays and multimodal detection, one must be clear about the concept of information: How is it different from energy and how is it detected? And can it come to specify a needed movement? We consider these issues in our commentary.

Stoffregen & Bardy (S & B) present the concept of a global array – invariants that span more than one individual energy type (and its associated sensory system). What distinguishes such invariants from the usual variables studied by ecological psychologists is that they comprise variants at the level of the energy type or sensory system; variants are, by definition, not specific to their sources. We agree with S&B that such invariants exist and that it is a worthwhile enterprise to consider their possible role in perceiving and in acting. We disagree with many of the rest of their claims – particularly, the impossibility of specification in a single-energy array, their underestimation of Gibson's (1966) claim that the senses be considered as perceptual systems, and their inattention to the problem of what is specified, especially regarding action. In our commentary we make two points; one concerns the relations between energy, information, and detection and the second claims that sometimes actions, rather than environmental facts, are specified by information.

**Point 1:** Energy is not information and information is not picked up by receptors. Electromagnetic radiation is structured by refraction, diffraction, and reflection. The patterns so created can specify some of the properties of the media and surfaces. If these are specific (ecologically, rather than mathematically or logically; see the commentary of Runeson et al. in this issue), living things might evolve, develop, or build devices that can pick them up. It is not light, however, that is detected, but information.

In the course of trying to track down the optical variable(s) that fielders use to guide their locomotion to catch balls hit in the sagittal plane, we asked people to attempt to run and catch luminous balls in the pitch dark and to do so monocularly (Oudejans et al. 1999). We found that people were successful. Given that to-be-caught balls are followed with pursuit eye movements (Oudejans et al. 1999, Expt. 1), one would expect that the image of the ball to be more or less stationary on the retina. The retina could not, therefore, be registering optical variables necessary to guide movement (e.g., Chapman's, 1968, optical acceleration). We concluded that ultimately this unmistakably optical information was registered by non-retinal mechanisms. That is, the eye and head movements created by tracking transformed an optical pattern into eye or eye-and-head rotations, which would be picked up by "vestibular and proprioceptive" mechanisms. Thus, while light is necessarily detected by rods and cones, the information in light is not necessarily detected by a retina. This counters S&B's implicit assumption that once information is described that the nature of its detection is obvious.

**Point 2:** What is specified? By entering into the debate of whether "physical reality" is or is not specified, S&B ignore the intimacy of information and action. A discussion of "specificity" quickly gets spooky in the absence of a serious consideration of what is specified. We do not believe that S&B's answer, physical reality, is sufficient. A key idea of the ecological approach is that affordances can be specified by information and more generally that information can provide a basis for controlling movement.

Recently we have argued that variables of stimulation can be specific to action without their being specific to some environmental fact or characteristic. This means that one should not always expect a 1:1 relation between an information source and a property of the environment. We present two examples. First, in our study of the timing of elbow extensions in the punching of falling balls (Michaels et al., in press), we found that the onset and rate of elbow flexion were controlled by optical expansion – the rate of change of optical size of a ball as it approaches. Expansion rate, however, does not specify properties of the approach of the ball; it varies with ball size, approach velocity, and distance. Nevertheless, it appears that, over the course of practice in the task, expansion rate comes to specify when and how fast to flex the elbow. As a second example, we recently demonstrated (Oudejans et al. 2000) that errors in judging offside in soccer appear to be the result of assistant referees' using an optical variable that does not specify who is closer to the goal (attacker or defender). The offside judgment is based on the optical angle between defender and attacker. This angle would specify who is closer to the defender's goal line only if the line judge were always on the offside line. Oudejans et al. (2000) showed, however, that the line judge is frequently off that line when judging offside. As a result, the line judge sometimes puts the flag up even though the attacker is not offside, or keeps the flag down even though the attacker is offside (depending on the side at which the attacker passes the defender). As in the ball-punching case, flagging appears to be lawfully related to an optical variable that does not specify the environmental facts. Instead, the arrow of specificity points toward the unfolding movement. One should look both ways, therefore, before declaring that arrays are non-specifying.

The settings in which animals act have characteristics that are important for actions and may be useful in their control. There is a sea of structure and changing structure available that is potential information. Some of these structures and transformations must "get into muscles," to borrow Turvey's phrase. For potential information to be actual, a variety of media must be transparent to it; these can include energy distributions, chemical distributions, skin deformations, and neural firing patterns, to name a few. To make sweeping arguments about inherent limitations of single types of energy, single organs, and which organs are detecting what energy diverts attention from action and information and revives the energy-based distinctions that Gibson had purged in 1966, or so we thought.



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## Fragmentation, coherence, and the perception/action divide

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**Abstract:** I discuss Stoffregen & Bardy's theory from the perspective of the complementary aspect of input conflict, namely, input coherence – the unity of perception. In a classical approach this leads to the famous "binding problem." The conceptual framework the authors construct leaves no space for a binding problem to arise. A remaining problem of perceptual conflict, arising in cases of inversion of the visual field can be handled by the theory the authors propose.

Sensory conflict plays an important role in the target article. In this commentary, I will look at the paper with a complementary theme in mind: sensory coherence, or the unity of perceptual consciousness.

According to the classical view, perceptual input information is not only ambiguous, therefore requiring inference, but it is also fragmented. Fragmentation applies at a variety of levels. First, the input information is shattered to pieces as it is spread out over thousands or even millions of receptor cells. At a higher level, fragmentation occurs because of the separateness of the senses: separate modules in the various modalities deal with the shattered pieces of input to build modality-specific higher-level representations. These higher level representations are supposed at least partially to solve both the ambiguity problem and the fragmentation problem. Ambiguity has been solved because knowledge not present (such as Marr's rigidity constraint, 1982, pp. 209–10) in the stimulus itself has been brought to bear upon it. Fragmentation is partially undone because from the receptor mosaic emerge sense-specific representations, perhaps in a "canonical" format. Yet fragmentation remains a problem. Now how do all these outputs from these separate modules get glued together? The situation is aggravated by the fact that it is widely assumed that there is intermediate level fragmentation within the modules: within the visual module there are submodules for color, form, movement, and so on (Zeki 1993). So the traditional view creates for itself the famous "binding problem": How do all these separate representations get together so as to lead to the unified perceptual consciousness we normally enjoy? The favourite solution within the tradition is well-known: it is neural synchronisation that is doing the job (Crick & Koch 1990).

Whatever the merits of the synchronisation idea, it is still unable to deal with still higher levels of fragmentation. What, for example, binds lower level sensory representations (as outputs from perceptual modules) to their conceptual representations? Even after the color of the bucket, its shape and its cold feel have been bound, it still needs to be bound to how I conceive it: as the bucket I used to scare the attacking dog on aunt Margaret's farm, for example. And there is yet a further level of fragmentation; how does the passively received input representation, even when fully bound with each other and with conceptual representations, becomes something I can act upon? How is the perception-action divide crossed? Does it need to be bound with plans, or with goal-representations? Clearly, we're on the verge of a combinatorial explosion, or worse, conceptual impossibility (cf. Shanon 1993).

One of the many nice aspects of this paper is that it shows conclusively that these problems of fragmentation and binding, as the side coin of problems of input conflict, arise not only within the traditional view, but also within all forms of Gibsonian theories that assume separate senses. With hindsight, one sees that it could not be otherwise: fragmentation at separate senses (accepted by many Gibsonians) is just a higher-level version of fragmentation at sensory receptors (criticised by all Gibsonians). It is only with S&B's proposal of unifying the senses ab initio, that the conceptual space closes so as not even to leave room for the problem of perceptual unity to emerge.

From the various remarks in the target article concerning the dependence on the goals of action as the functional basis of the interaction with the global array (e.g., end of sect. 4.5, also sect. 6.2.5), one sees how the theory also contains the ingredients to cross the last gap created by fragmentation: the gap between perception and action. A consequence of this is that the distinction S&B make between perception and action can only be heuristic. Just as they characterise their view as one in which perception is not seen as the parallel action of a group of systems, but as the unitary action of a system with parts, they, it seems to me, would have to apply this to action and perception and see these as aspects of one global thing: the organism in its interaction with the environment (as I think they would certainly be willing to do).

More interesting, bridging the perception/action gap in this way allows for a real form of fragmentation: erroneous or disunited perception when either the organism's perceptual situation is problematic when viewing conditions are suboptimal or the perceptual apparatus is damaged (cf. sect. 6.2.3) or when its action possibilities are suboptimal. An interesting situation occurs when both are suboptimal, as in the well known case of people wearing goggles that invert the retinal image.

It has been well documented that once behavioral adaptation to the goggles occurs, and once people learn to act in the "normal" way again, their perception returns to normal. However, perceptual adaptation does not occur in an "all at once," but in a fragmented way. Perceptual adaptation seems to depend on which behavioral capacities have adapted, and they do not all adapt at the same pace (for discussion, see Hurley 1998, p. 347–48, and O'Regan & Noë, in press). What this suggests is that just like perceptual unity, perceptual fragmentation is not an internal affair. Rather it is a matter of behavioral "disunity." At last, we have a real case of fragmentation, but one that perfectly fits within the framework Stoffregen & Bardy sketch.

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## Act globally, think locally

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**Abstract:** The authors attempt to prove that single energy arrays cannot specify reality. We offer contrary evidence that motion structures the acoustic array to specify fundamental attributes of the source. Against direct detection in general, we cite evidence that humans weight acoustic inputs differentially when making perceptual judgments of auditory motion.

Stoffregen & Bardy (S&B) attempt to prove the inadequacy of perceiving reality via single energy arrays through the following syllogism: perception in general is largely the perception of motion; motion is relative and often indicated divergently among energy arrays; hence, reliable perception of the environment is not possible via single arrays. We agree that motion is vital to successful perception. But in addition, dynamics can impose sufficient constraints that allow even single sensory arrays to specify other distal properties relevant to an animal's behavior beyond motion per se.

For example, analytical demonstrations exist showing that auditory motion can structure the dynamic acoustic array to specify fundamental attributes of the sound source, such as its position, velocity, and time-to-contact (TTC) (Jenison 1997). These higher order variables are inversely determined from the forward equations describing the physical mapping of intensity, frequency, and interaural time delay (ITD) from source to observer. Such inverse solutions are evidence that single energy arrays can specify reality provided that sufficient input dimensions within the modality exist.

We believe there is a more general inquiry into S&B's hypoth-



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esis concerning the adequacy of individual arrays for perception. Namely, how many sources of sensory input does it take to specify a distal property? In our view, this is a simple question of algebra. Specification of a higher order property implies the existence of an inverse solution from the proximal inputs to the distal variable. If there are not enough "knowns" (input) to "unknowns" (distal variable), then the property may not be identifiable. Hence, increasing the number of inputs should generally increase specification. This is the root of the S&B's argument for the necessity of multimodal ("global") information. Again, we would generalize this position by saying what is needed to specify the world is simply enough proper input information, independent of whether that information is conveyed within ("multiple specification") or across modalities ("amodal specification"). By "proper" we mean that there is a lawful physical relationship between the distal property and the input.

While this approach explicates the physical journey from environment to receptor, we also believe in a corresponding journey from receptor to percept. The achievement of perception is "harder" than just saying a variable has or has not been detected, as most ecological theorists seem satisfied to claim (Marr 1982). Typical in such arguments, there is no description by the authors of how higher order information is in fact directly detected by the animal (e.g., are there transducers for global variables [Fodor & Pylyshyn 1981])? Rather than appealing to direct detection, we formally question: (1) how are input sources or physical dimensions combined when detecting properties specified by multiple inputs? and (2) how may perception be achieved through a form of statistical estimation, given the stochastic nature of neural transduction and transmission?

To investigate these questions, we have simulated the estimation of higher order auditory variables (e.g., auditory TTC) using two models of input fusion. The first employs a Kalman filter which can successfully estimate higher order terms using as input the noise-corrupted observed intensity, frequency and ITD of a simulated moving sound source (Jenison 1996). In theory, one could extend the Kalman filter to integrate information from different modalities, obviating any debate over a qualitative versus quantitative difference between uni- and multimodal input. What is required are representations of the forward equations mapping distal states to physical input dimensions across modalities. These equations allow the filter to dynamically adapt the fusion of input information in order to improve its estimate of source states.

It may be the case that the Kalman algorithm does not strictly represent neurophysiological mechanisms. However, it has been proven equivalent to a form of dynamic Bayesian estimation (Meinhold & Singpurwalla 1983), a process which we believe better describes how neural systems may extract information from sensory input. As a model embodying fewer assumptions, we have also trained a recurrent neural network to estimate TTC from the same acoustic dimensions (Neelon & Jenison 2000). Performance of both models degrades as a function of reducing either the number of inputs or their signal-to-noise ratio (e.g., increase sensor noise or virtual distance of the source). This again illustrates that perceptual estimation is likely to be a continuous (though nonlinear) function of the quantity and fidelity of lower order inputs.

Ecological theorists may remain unconvinced that real observers combine sensory inputs to perceive higher order information. There is evidence, however, that human subjects differentially weight acoustic inputs when making judgments about moving sources. First, we have tested listeners in tasks requiring them to discriminate between the intrinsic frequency and TTC of two moving sound sources (Neelon & Jenison 1997; 2000). Subjects show a pattern of results similar to that of model simulations as sensory input is degraded. Further evidence is provided by Lutfi & Wang (1999), who indirectly measured the weights human observers place on the acoustic inputs of level, frequency and ITD when discriminating between moving sources. They correlated listener response with experimentally controlled input variation to estimate how much influence each input had on performance. They discovered that as task and source parameters changed, so did the weighting schemes.

To conclude, we agree in principle with S&B's arguments that multiple, dynamic inputs should provide better specification of the external world than single or static inputs. However, they offer no evidence that global energy arrays are necessary for identifying every environmental property; on the contrary, we cite analyses which show the sufficiency of the dynamic acoustic array to specify several attributes of moving sound sources. The degree to which the world is inversely determined by sensory inputs (i.e., perception) is a product of the lawful relationship of energy propagation between them and the statistical reliability of the neural representations of that input.

## Input-driven behavior: One extreme of the multisensory perceptual continuum

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**Abstract:** The propositions that the senses are separate and that the global array may be sufficient for adequate perception are questioned. There is evidence that certain tasks may be primarily "input-driven," but these are a special case along the behavioral continuum. Many tasks involve sensory information that is ambiguous, and other sources of information may be required for adequate perception.

Despite the long scientific tradition of separating perception into separate sensory systems, it has long been recognized that different sensory systems interact in ways that remain poorly understood. Our present understanding of multisensory interactions sits at the level of phenomena such as the McGurk effect, rather than with organizational principles of how senses interact.

Stoffregen & Bardy (S&B) address the problem of multisensory interaction from the perspective that separate senses do not exist. Unfortunately, their arguments against separate senses are not compelling. S&B reject an anatomical basis for separate senses due to interactions of structures only within a sense (two eyes/two ears that work together), not between. There is little doubt that anatomical substructures have developed to be sensitive to particular forms of energy. With eyes closed, how well could one determine the intensity of a light source directed at the pinnae? Moreover, the fact that animals with different receptors interpret the same form of energy in different ways does not argue against separate senses, but against the unique meaning of a stimulus to a perceiver.

More problematic is the question of whether structured energy fields provide "sufficient/insufficient" information for accurate perception. The problem may be in the proposition itself. The ecological view suggests that information for behavior is specified uniquely in the ambient array, individual or global, and any non-1:1 mapping negates specification. But, why is specification an either/or concept? Why not view the specification of behaviorally relevant information along a continuum? Under certain task conditions, the stimulus array dominates the response, which one might call "input-driven" behavior or perception. Time-to-contact ($\tau$) (Lee 1981) is a classical example of such input-driven perception. Change the parameters of the task conditions, however, and the same sensory information may now be ambiguous, requiring other processes and sources of information to be recruited for adequate perception (e.g., memory). This view is more in line with current thinking about cognition, which stresses the dynamic nature of processing inputs from multiple sources (cf. Beer 2000).

In the search for specification, S&B appeal to the concept of the global array; essentially a higher-dimensional version of the ambi-



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ent sensory array originally introduced by Gibson (1979). Their formulation is vague and the arbitrary three-dimensional plots intended as abstract representations of the global array are not particularly informative. Examples of higher-dimensional variables are provided, however, that lend credence to the existence of the global array. S&B misstep, as discussed above, when the global array is viewed as eliminating the need for internal processing. There may be situations in which the global array resolves ambiguities provided by single-sensory information. It does not follow that internal processes are no longer necessary. Again, the solution may be task specific, with "input-driven" responses representing one end of a multidimensional continuum. This view is consistent with the engineering literature, which considers multisensory integration as a subproblem of "data fusion," in which any number of inputs, not just sensory, are combined to form a percept of an environment object or event (Hall & Llinas 1997).

There is no argument here that structured energy arrays exist and that they may specify behaviorally relevant information under certain task conditions, in the ecological sense. The question is whether such behavior represents all perceptual processing or merely one extreme of the perceptual continuum. Responses to other task conditions may "weight" internal processes such as memory/experience/instruction more heavily to form an adequate percept. Recent studies support the existence of internal models in sensorimotor integration (Kawato 1999) and multisensory integration (Merfeld et al. 1999). There is growing support that the extraction of information is a process of estimation, which may be based upon the statistical properties of multiple sources of input over time (e.g., Oie et al. 2000; van der Kooij 1999).

A more precise formulation of the global array than that offered by the target article raises interesting questions of how to distinguish processes of direct perception from processes considered more internal. For example, autonomous robots that process sensory information from multiple sources for obstacle avoidance dynamically display what is deemed cognitive behavior in the form of decision-making (Schöner et al. 1995). The general scheme involves fusing two sensory sources that are spatially nearby to erect a repellor, which the robot travels around, or to erect two separate repellors when sensory sources are spatially distant, which the robot may travel between. The decision to go around or between two obstacles arises from the fusion of sensory sources that vary parametrically. That this behavioral solution may be construed as a classically internal process, decision-making, without any obvious internal representation indicates that dynamic aspects of multisensory processing may redefine what is considered internal.

Our view is that Stoffregen & Bardy's stance may contribute to understanding the problem of multisensory perception if it is conceived as a special solution at one extreme of the perceptual continuum. The dichotomous nature of the direct perception/internal processing discussion may follow the evolution of the nature/nurture debate. It is not a question of one or the other, but of how each are blended to solve the task at hand.

## Is the brain specified?

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**Abstract:** How to conceive the place of the brain in the specification of the animal environment relation? Reality is a continuum between external physical energies and brain energy. The global array concept linked to the physical world and its physical energies could be transposed to the brain as a physical object and a dynamical system.

We are largely in agreement with Stoffregen & Bardy (S&B), particularly with the epistemological and theoretical point of view about the nonexistence of separate senses. Their article clarifies the functional role of sensory information. Today, the separate-senses view still remains in researchers' heads especially because of the computer analogy and semantic segregation of object properties characteristic in humans. Many studies dealing with the dominance of one sensory channel during a sensory conflict can still be found in the literature. But the results of these studies are highly contradictory. Indeed, the dominance of one sensory channel depends on age, learning (Misceo et al. 1999), task or form of cognitive type. It would be interesting to reinterpret these differences in sensitivity to one form of sensory information amodally.

Our contribution, but also our objection, deals with the place of the brain in the specification of the animal-environment (A-E) relation. According to S&B the A-E relation is specified by information picked-up in the global array, but *"before the stimulation of sensory receptors."* The global array concept linked to the physical world and to its physical energies can be transposed to the brain as both a physical object and a dynamical system. The physically different external energies (air vibration for audition, light for vision) activate different sensory cortices with energy exchanges of a similar nature (chemoelectrical current is the common energy propagated along the axon and though the synapses). Moreover, neurons are structurally interconnected and work in parallel. By distinguishing a physical exterior and a biological interior, the brain is excluded from the physical world. However, experiments have shown that during ontogeny, brain structure *is specified* through the A-E interaction, that is, by epigenetic factors. The studies of Von Melchner et al. (2000) and Sharma et al. (2000) in ferrets and the studies of Kujala et al. (2000) in humans asked the following question: Are neural connections genetically pre-cabled? In this case, each cortical sensory area would be activated only by one specific physical energy. Or, in the opposite way, is the cerebral architecture specified by the activation of the sensory pathways? The studies in ferrets have demonstrated that when a modality-specific brain area such as the primary auditory cortex is totally deprived of its normal sensory input (the stimulating effect of air vibration is suppressed), it becomes responsive to stimulation from other modalities such as the visual input. Thus, the rewired auditory cortex has the same characteristics as the visual cortex. Sharma et al. (2000) showed that in ferrets in which retinal projections are routed into auditory pathways, visually responsive neurons in the rewired primary auditory cortex are also organized into pinwheels, as observed in V1. In humans, some studies have shown that in the blind the occipital cortex are activated by sound changes (see Kujala et al. 2000, for a review). The neurophysiology of plasticity (i.e., the structural and functional modifications of the nervous system by the properties of its activation) informs us about the amodal functioning of the brain. The specification of an auditory area by visual input (or the reverse) shows that a given part of the brain is not genetically predestined to process a given type of information.

Just as a change in one environmental property modifies the global pattern of external energy, a change in one environmental property modifies the neural connections between different sensory cortices (primary or associative). There are contamination phenomena in all the sensory cortices when one input is modified (Pailhous et al. 1990; Schöner et al. 1998). Our opinion is that this unique combination of neural activation, specified univocally by the properties of physical reality, modifies amodal perception. So, the processing of the global array is not localized in associative areas as thought by the authors, but rather achieved through a unique spatio-temporal activation pattern of the brain: perception is more univocal than direct. The mysterious concept of direct perception is involved in this context. Speaking about a neurophysiology of direct perception makes sense only if the univocal characteristic of network activation is taken into account. Then, we are in agreement with the authors that the A-E relation is globally specified by the physical world. But our opinion is that the physical world includes the brain and more generally the whole organism (in another commentary, we would say that we cannot



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understand the functioning of the nervous system isolated from its more immediate environment – the rest of the body – we cannot do neuroscience without doing physiology!). The perception of reality is not mediated by the brain because the brain is included in reality. It is clear that "direct perception" does not signify "without working of the nervous system." Reality is a continuum between external physical energics and physical (because chemoelectrical) brain energy. By excluding the brain and its energy from the physical world in order not to separate the senses, inanimate matter is separated from the living matter. If biology is separated from physics, there is no longer continuity between brain and environment, just coupling. Though we are totally in agreement with S&B on the non-separation of senses and on the concept of global array, their demonstration would nevertheless, be easier if it integrated the brain. Indeed, there are neither channels nor boxes in the brain, only networks, massively interconnected and working in parallel. Even when the stimulation is unimodal, its treatment is always global, as rightly underscored by the authors.

With regard to this continuity between the physical world and the brain (which does not exclude its singularities), how is it possible to have a discontinuity between environment and behavior at a macroscopic level? We will not be surprised that this discontinuity is marked by the laws of adaptation: "the behavior of an animal is adapted to its environment." And why is the behavior adapted ? Because the species which are not adapted to the environment do not survive (Darwin 1958). The perception-action coupling is the result of an adaptive change of our central nervous system to environmental properties. In separating the nervous system and its adaptive properties out of the physical world, the perception-action coupling is masked. That is the reason the neurophysiology of plasticity has to have its place in the ecological approach.

## Cortical specification makes sense

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**Abstract:** Overwhelming evidence points to the existence of separate sensory channels in the nervous system. The power of this type of parallel organization is that information is first processed in neurons specialized to code it most efficiently. However, sensory pathways are convergent and divergent at each level as well, as is necessary to interpret multimodal and conflicting information.

The prospect of commenting on a review that extends from the theory of relativity to cognitive psychology is somewhat daunting to a non-psychologist, non-physicist, and thus I will attempt to provide a perspective from a sensory neurophysiologist's and neuroanatomist's point of view, filtered through our work on brain development and evolution. From that perspective, it seems Stoffregen & Bardy (S&B) do not rigorously incorporate existing knowledge about the anatomy and physiology of both unimodal and multimodal sensory pathways into their theory. However, their target article is certainly thought-provoking, and many of their ideas and examples are of considerable value in clarifying possible future approaches to the questions they delineate.

S&B's conceptualization of an animal being "directly sensitive" to the "global array" could be interpreted in several ways. It is difficult to see how a parameter such as the hand velocity necessary to intercept a moving object could be "detected directly" since multiple information sources are necessary to calculate it. If their argument is that information does not access the brain through unimodal channels to be later combined in multimodal areas, the evidence does not support them.

If, on the other hand, their argument is that multimodal areas are of critical importance to an animal's ability to understand its world, that most environmental stimuli have a multimodal component, and that animals have neurons that are sensitive to multimodal stimuli, then this is not only an obvious point but has a great deal of experimental support, and does not require proposing at this point. Gibson and others, including Charles Darwin, suggested long ago that sensory systems are shaped by evolution to decipher those signals that are of greatest importance to the organism (Gibson 1979), and such signals often contain energy across different modalities.

Or perhaps by "directly sensitive" they mean that there are modules or arrays that are constructed developmentally and/or evolutionarily that are inherently capable of interpreting aspects of the global array relevant to survival. The authors are right in that it is probably the case that such modules have not been properly searched for in many cases, given that most physiologists restrict themselves to one sense. But this notion of "combination-sensitive" neurons is a very old one (e.g., Lettvin et al. 1959) and has been applied to multimodal inputs by numerous investigators (e.g., Stein & Wallace 1996).

Work by sensory physiologists over the past few decades has made it clear that the brain contains a series of tuned input channels (sensory organs) that are sensitive to a particular range or type of energy with minimal overlap, and that these classes are segregated by modality in the early stages of processing. Indeed, this parallel organization is essential for optimum processing efficiency, as different neurons and pathways are specialized for processing certain aspects of a stimulus. Examples of this are the channels coding form and motion in the mammalian visual pathway (Livingstone & Hubel 1988), the time and intensity channels of the auditory pathway (Feldman & Knudsen 1997), or the amplitude and phase channels in the electrosensory pathway (Kawasaki & Guo 1998). In these cases, the neurons and synapses in each pathway are designed optimally for the task at hand. Another crucial advantage of parallel organization is that the separate lines can be brought together in multiple different ways; if they were joined at the outset this combination and recombination process would not be possible. In that sense, arguing that perception is not organized via different channels, while perhaps heuristically useful, seems out of tune (pun intended) with the evidence. Researchers have not "assumed that the patterns in the global array are not sensed directly," rather there is excellent evidence that sensory information is decomposed at the receptor surface and then recombined in an internal, multimodal representation of the environment, with attention to the position of the eyes, head and body through reafference or efference copy.

How does an animal define one sensation as auditory and another as visual, rather than as combined auditory/visual stimuli? The evidence suggests that the assignment is historical; visual cortex becomes visual during its development in large part because it is usually hooked up to the photoreceptors. If one hooks up visual cortex to auditory receptors, or vice versa, the perceptual assignment of the tissue is transformed (Gao & Pallas 1999; Heil et al. 1991; Pallas, in press, for review; Pallas et al. 1999; von Melchner et a1. 2000). Anima1s with early visual inputs to the auditory pathway, when asked to categorize a wide variety of visual and auditory stimuli, will define visual stimulation of the auditory pathway as visual (von Melchner et al. 2000) In other words, auditory cortex can be taught to process and perceive visual stimuli through experience.

The biggest drawback of S&B's theory is that the authors do not report or propose any concrete experiments to test their theory or to refute the well-established current view. Their argument, that multinodal patterns of information are sensed directly and that senses function as a single unit, is of limited value if not backed up by experimental evidence. Hopefully it will at least serve as an impetus to greater care in experimental design by the various disciplines engaged in the study of perception.



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## Direct perception of global invariants is not a fruitful notion

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**Abstract:** The epistemological premises and scientific viability of Stoffregen & Bardy's ecological perspective are evaluated by analyzing the concept of direct perception of global invariants vis-à-vis (1) behavioral evidence that perception is based on the integration of modal sources of information and (2) neurophysiological aspects of the integration of sensory signals.

Stoffregen & Bardy (S&B) aim at internal consistency within the theoretical framework of ecological psychology. Starting from the epistemological premises of (unique) specification and direct perception, it is concluded that the senses cannot be separated. This radical conclusion calls for an evaluation of the premises and viability of S&B's ecological perspective. In doing so, we concentrate on considerations and behavioral findings regarding illusions, informational conflicts, flexibility, and learning, as well as neurophysiological aspects of the integration of sensory signals.

***Illusions and informational conflicts.*** It follows from S&B's analysis that an event is only fully specified in the global array. However, this is not to say that modal arrays do not specify anything. Optic flow, for instance, specifies relative motion with regard to the visual environment. Experiments involving informational incongruencies, resulting in illusory or real self-motion, indicate that such modal sources of information are used and that their relative importance may differ. This is underscored by graded degrees of illusion that scale with presentational aspects of the manipulated information. For instance, the visually-induced illusion of self-tilt increases with the field of view (Allison et al. 1999). It is unclear how such a graded effect can be understood in terms of the direct perception of a global invariant. Moreover, the correspondence between postural sway patterns and modality-specific information (generated by, e.g., an oscillating visual scene [Dijkstra et al. 1994] or touch bar [Jeka et al. 1997]) seems more readily understandable on the basis of modality-specific information sources rather than nondecomposable global invariants.

Only if perception is based on multiple sources of information can the occurrence of informational conflicts be explained. A convincing demonstration of such a conflict involves the observation that a deafferented patient could easily draw a five-point star while watching her hand in a mirror, whereas this was rather difficult for normal control subjects. As the relation between movement direction and visual scene (mirror image) was manipulated in both groups, the most logical explanation is that the control subjects experienced a conflict between visual and proprioceptive information, whereas the patient did not because propriocepsis was unavailable (Lajoie et al. 1992).

***Flexibility and learning.*** The qualitative differences between global arrays of different dimensions imply that global invariants used in an array with dimensions X and Y are of limited use in an XYZ-array. As such, the system is incapable of flexible adaptation to situations that involve global arrays of different dimensions: A global invariant is specific for a particular array and does not transfer to other (e.g., higher or lower dimensional) arrays. A system combining multiple (modal) sources of information would be more flexible in this regard.

Similar considerations pertain to the attunement to global invariants during perceptual-motor learning. How can extensive practice involving full vision result in the ability to juggle with eyes closed? After all, practice in a particular global array does not allow for simultaneous attunement to an invariant in a qualitatively different (lower dimensional) array that is not actually present. Likewise, shifts in dependence on particular modalities during a learning process (Fleishman & Rich 1963) are difficult to understand within S&B's framework, whereas this phenomenon is readily explained from the perspective of multiple modal sources of information.

***Integration of sensory signals.*** If perception is based on multiple modal sources of information, the process of integration may be viewed as the result of computations and weightings performed by some intelligent homunculus. However, recent findings regarding MST (medial superior temporal) cells in monkeys may illustrate a less spooky mechanism of integration of relevant "information." Many of these neurons respond to both optic flow and vestibular information (with some cells showing enhanced activity when the two are congruent and others when they are incongruent), while other neurons are sensitive to only one of the two modalities (Bremmer et al. 1999; Duffy 1998). Thus, MST cells play a role in the detection of relative motion and self-motion. Whether such sensitivity to modality-transcending information is to be interpreted as integration over different modalities or as direct perception is a theoretical rather than empirical question.

***Conclusion.*** S&B attempted to carry the epistemological premises of ecological psychology (specification and direct perception) to their logical extremes. However, many observations and considerations cast doubts on the fruitfulness of the proposed direct pick up of global invariants. Although one option is to abandon the concept of specification altogether (e.g., nonspecifying quantities that correlate highly with relevant properties may be used instead, cf. Michaels & De Vries 1998), an epistemology based on modality-specific specification may still provide an adequate framework for examining how animals know (their relation to) the environment. Because the ecological approach rests heavily on its epistemological premises, the question whether such a view qualifies as "ecological" depends on whether integration of modal sources of information is considered as "direct perception." Whatever one's predilection in this regard, the road proposed by S&B does not seem to be the one to follow.

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## How important is specificity?

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**Abstract:** There is good neuropsychological evidence for an amodal, relational basis for perception and action. Using this idea, it may be possible to define more accurately what is meant by specificity, in the Gibsonian sense of the term. However, for complex organisms, and most especially for creative, open-ended perceivers and actors such as human beings, specification may not be relevant.

Approaches to perception and action might be said to have direct and indirect poles. The direct approach claims that the information available to active perceivers, or at least some portion of it, is both necessary and sufficient to enable action towards the real world, without error or distortion. Indirect or constructive approaches hold that sensory information is necessary, but not sufficient. Memory, inference, and other cognitive operations must occur before we can make sense of sensation and hence use it to guide our actions.

The former pole we might identify with the ethos of physics, with its search for law-like generalisations. The latter pole we might identify with psychology, an altogether more pluralistic discipline, within which law-like generalisations are merely a part of a far more heterogeneous and negotiable body of findings.

While at different points in their article the authors deal with both these poles, the underlying concern seems to be strongly with the former, physics-like project. For example, in the introduction



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they note that investigating how sensory arrays might specify the properties of reality is a problem for physicists, not psychologists. They nonetheless pursue this issue and conclude that the arrays of ambient energy reaching any particular sensory system are actually ambiguous with respect to the dynamics of the physical world from which they come. The arrays cannot, they claim, unambiguously specify real-world properties.

*Prima facie*, this seems like a significant challenge to the direct approach as it presently stands. That approach, based on the work of James Gibson, has always rested on the assumption that the dynamic structure of an ambient array is rich enough to be the basis for adaptive, accurate action. If it can be shown that it is not, then this seriously weakens the whole approach.

But Stoffregen & Bardy (S&B) do not give up on specification. In fact, they offer a new conceptual basis for it and one which, being broader, may actually be more stable and general. The novel aspect of their proposal is that specification does indeed exist, but within a global, that is, multi-sensory array of higher-order relations between arrays of energy picked up by the different senses.

This proposal has a great deal to commend it. The notion that specification was tied to a particular sensory system seems unlikely *a priori*. Animals, after all, use their senses together, not separately, and seldom rely on a single sense to coordinate complex patterns of activity. Moreover, there is a great deal of evidence that points the other way. That there is cross-talk between sensory pathways is well known, but what recent neuropsychological findings indicate is that sometimes there may also be cross talk between the sensory and motor pathways (e.g., Rizzolatti & Arbib 1998). Recent moves towards a more embodied, enactive view of perception and action likewise support the idea that we should treat the sensory-motor pathways as mutually constraining or defining (Hurley 1998).

However, S&B are still pursuing a conventional ecological line, namely, to demonstrate specificity as a challenge to inferential theories. The task of ecological psychology is to show that specification exists and rests in discoverable, law-like relations. But since these relations are now treated in a rather more complex way than before, the challenge is perhaps not as strong or distinctive as it was. The notion of "higher-order" relations is a significant step away from the simplicity and clarity of the original Gibsonian programme.

Perhaps a more radical challenge, to both direct and indirect approaches, would be to contest the notion of specification itself. This is not to reject it. Clearly, under some circumstances and for some perceivers, especially simpler ones, specification is important. For example, organisms like reptiles, who, while active and skillful are nonetheless bound to rather fixed patterns of action within relatively limited niches, probably rely on specific patterns of energy which are not too difficult to discover. Such organisms, in Popper's terms, are in closed rather than open ecological and evolutionary niches. What they need to know in order to do what they need to do may indeed be quite specific and hence specifiable.

But for organisms living in more open niches, and especially for creative perceivers like human beings, specification may be irrelevant. Their actions are more adventitious and unpredictable; they perceive and act under uncertainty. Here, precise specification may not be a realistic objective for psychological research. Complex organisms, especially human beings, are not like that. The world is imperfectly known and actions are seldom perfectly adapted to circumstances. More often they are provisional, exploratory, and, being subject to inaccuracy, are continually recalibrated.

The proposal that there exists a higher-order, multi-modal, relational basis for perception and action is an exciting one. The challenge, or opportunity, is to use this idea to investigate the flexibility, not the fixity, of higher-order perception and action. The sensory systems of higher organisms are tolerant. That is, they are able to operate under uncertainty and intermittent interruption. Indeed, under most circumstances, specification may only exist momentarily. In which case, a multi-modal array of relations might have the role of maintaining the spatio-temporal consistency of action.

It seems a rather limited use of this powerful idea, merely to pursue an old agenda of formally accounting for specification. Sensory systems, and the amodal patterns of neural activity to which they contribute, are tuned by on-going activity. For all that S&B acknowledge the importance of action, the emphasis remains, in true Gibsonian style, on perception, on what is there to be perceived. They note Berkeley's scepticism about how the different types of sensory experience could ever cohere into unified percepts. In response, they propose higher order relations.

But Berkeley is more easily defeated. Perception and action are unified by an effort after meaning. Sensory systems exist and are used in order to discern objects and situations fit for action. For simpler organisms, this may well be achieved primarily on the basis of a specific, and hence specifiable, set of relations between the world and the information reaching the senses. For more complex ones, and most especially for human beings, the open, creative, and adventitious nature of their actions makes specification, at whatever level, a secondary matter. It is not a central aspect of perception and hence need not have such a primary role in psychological inquiry.

## Three consequences of believing that information lies in global arrays and that perceptual systems use this information

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**Abstract:** Stoffregen & Bardy provide grounds to suppose that specification requires global arrays and that this information is used by perceptual systems. Three conclusions follow from this supposition; (1) global specification will be taken seriously only if additional examples are discovered; (2) research into single-sense information must take global information into account, and (3) ecological psychologists must account for perceptions based upon non-specific information.

Stoffregen & Bardy (S&B) make many claims about information in what they call "global arrays." Rather than attempt to evaluate all those claims, I will assume that the authors are at least partly right and examine the consequences of that assumption. Specifically, I will suppose that the following "limited global hypothesis" is true: (1) some aspects of the environment are completely specified only by information in a global array, and (2) when such global array information is available, it is detected and used by perceptual systems on some, but perhaps not all, occasions.

Even if the limited hypothesis becomes widely accepted, I will be very surprised if many perceptual researchers go on to make major changes in their theoretical or empirical work. Two classes of demonstrations must be developed before global arrays will have a broad impact on research practice. First, more analyses of information are needed, ones which clearly document the existence of information that is available in the global array but not in any "single sense" array. Second, researchers must be convinced that perceivers make use of global information. In other words, we need empirical demonstrations showing that perceptual performance based on global information is measurably different (faster, more accurate, less variable) than that based on single-sense information. Until a reasonable number of both types of demonstrations are available, global information can be treated as a rare special case rather than as a central fact about perception. In summary, while S&B provide a first glimpse of what may eventually constitute a major challenge to perceptual theory and research, a good deal of work remains to be done to make that challenge fully credible.



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My second group of comments concerns the appropriate conduct of research. The ultimate goal of most perceptual researchers is, or at least should be, to provide an account for perception as it occurs in everyday life. Researchers who both have this goal and accept the limited global array hypothesis must include consideration of global array information in their work. First, it would be risky to limit analyses of information to single-sense arrays: If the information needed to perceive the environment is sometimes available only in a global array, then the researcher cannot know in advance whether or not the information relevant to the aspect of the environment he or she is studying lies in a local or a global array. Second, when global array information is known to be available for the phenomenon under study, it is surely important to know whether or not that information is used by perceivers. While the researcher might well demonstrate that local information does influence perception, we would still not know whether or not global information is utilized in everyday perception.[1] In summary, the target article presents a challenge to all perceptual researchers: We can no longer be certain that our research into perception based on single-sense information will contribute to the understanding of perception as it occurs in everyday life.

Finally, the target article has important implications for followers, including myself, of the ecological approach to psychology. Ecologists believe that it is rarely useful to study perception using displays from which the researcher has removed some of the information available in naturally-occurring arrays. The logic behind this belief is straightforward: Since perception in everyday life is based upon the detection of information which specifies the environment, studies using arrays which do not specify the environment will not tell us how the perceptual system operates in everyday life. Ecologists believe that the results of research in which the experimenter has, by artifice, removed information from arrays (e.g., by requiring monocular viewing, preventing head motion, showing displays for fractions of a second, etc.) have no clear interpretation. However, if the limited hypothesis is correct, then ecological psychologists will need to pay more attention to perception in circumstances where the environment is not uniquely specified.

It seems to me clear that circumstances arise both naturally and frequently which force perceivers to interact with the environment with less-than-optimal information available. Moreover, such interactions often achieve the perceiver's goals. Note, for example, how effectively the blind walk and how much the sighted can do in the dark, when they are looking in the "wrong direction," and so on. Similarly, the deaf function well in everyday life, as do the hearing when noise masks informative sounds. A systematic account of perceptually-guided actions which are frequent, successful, and occur in natural situations must be included in any theory of perception.

The target article rightly criticizes researchers for assuming, on ill-examined grounds, that an adequate theory of perception can be based on information carried only in single types of energy and detected only by the traditional senses. The question of whether or not global information actually exists and is used by perceptual systems matters very much to both theory and research. The target article does not answer this question. It does, however, show us that we need to stop assuming that the answer is self-evident and start doing the difficult work that will provide the facts which will lead to the answer.

NOTE

**1.** It is worth noting that we do not know very much about the accuracy of perception in everyday life. Most of our research concerns the effect of some stimulus variable on perception: that variable is manipulated in various ways and the perceptual consequences tracked. We rarely establish the accuracy of perception in everyday life (i.e., when full information is available and the perceiver's actions are unconstrained) and then ask how much of the variance in everyday perception can be accounted for by our pet stimulus variable.

## Movement dynamics and the environment to be perceived

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**Abstract:** In perception science, an alternative to focusing on individual sensory systems is to describe the environment to be perceived. We focus on the emergent dynamics of human-environment interactions as an important category of the environment to be perceived. We argue that information about such dynamics is available in subtle patterns of movement variability that, of necessity, stimulate multiple sensory systems.

Stoffregen & Bardy (S&B) argue that specification exists only in patterns that extend across different forms of ambient energy. They emphasize that this is a fundamental problem for the vast majority of experiments that seek to arbitrate between theories of direct and indirect perception by manipulating "single-energy arrays." Their arguments suggest further that such experiments are, at best, misleading with respect to the behavior of real animals in real environments.

We are in basic agreement with S&B about the centrality of the "global array" in understanding animate behavior. Our research, however, is not concerned with comparisons between theories of direct and indirect perception. Instead, direct perception is a first principle of ecological psychology that guides our research on the interdependence of perception and movement. Direct perception motivates an interest in mappings between the world and the stimulation of an animal's sensory systems. We are interested in how such mappings allow one to observe and, thus, to control one's movement in an environment. At the same time, we examine how movement instantiates such mappings and how a tacit understanding of our own movement dynamics reveals momentary task-specific domains over which 1:1 mappings exist (Riccio 1995; Riccio & McDonald 1998b).

Our approach to understanding perception in the context of real interactions between an individual and an environment is based on Gibson (1979/1986). Although this last work of James Gibson focused on visual perception, we believe it provides the best blueprint for studying specificity in the "global array." The reason is that Gibson made a clear scientific distinction between "the environment to be perceived" and "information in stimulation," and he gave logical precedence to the former. Put simply, a scientist must understand what can and should be perceived before questions about specificity can be addressed (Riccio 1993; 1995; Riccio & McDonald 1998b). This starting point would not necessarily lead to mappings between the environment to be perceived and patterns of stimulation (i.e., information in stimulation) of a single sensory modality. In fact, as S&B point out, we cannot determine how this could ever be the case when human movement is involved (Riccio 1995; Riccio & McDonald 1988a). Furthermore, we are sympathetic to their argument that it may be impossible or meaningless to study perception only in the absence of movement. The scientific study of perception must be broader than what it has been throughout most of twentieth century.

Most of our work on human posture and movement has focused on the environment to be perceived. A fundamental assumption of such "ecological physics" is that the environment cannot be described independently of the animal and the animal cannot be described independently of the environment (Gibson 1979/1986; Riccio 1993; 1995; Riccio & McDonald 1998b; Riccio & Stoffregen 1991; Stoffregen & Riccio 1980; 1991). Any biomechanical model of posture or movement, for example, makes specific assumptions about the surroundings of the body (e.g., the surface of support) even if they are not explicitly included as parameters of the model. Descriptions of the human body and its surroundings



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can be unified with respect to conventional mechanical properties or dynamical constraints that are due to momentary couplings between perception and movement (Riccio 1995; Riccio & McDonald 1998b). We have been working to characterize such emergent dynamics, which impose constraints on human posture and movement (Riccio 1993; Riccio & McDonald 1998a).

Our working hypothesis is that the dynamics of the animal-environment interaction can be perceived and that this capacity is essential to human adaptability. This requires that information about such dynamics is available in the stimulation of sensory systems. We have argued that pick-up of dynamical information is facilitated by obtaining stimulation through the exploratory activity of perceptual systems (Riccio 1993; Riccio & McDonald 1998a). Perceptual systems include sensory systems and all the movement systems of the body that act essentially as accessory structures for sensory systems (Gibson 1979/1986) . We have provided evidence that the dynamics of animal-environment interactions are revealed in subtle, albeit ubiquitous, patterns of movement variability that, of necessity, stimulate multiple sensory systems (Riccio 1993; Riccio & McDonald 1998a). An important implication of our findings is that perception and movement will be compromised by conditions that suppress or obscure the informative patterns of movement variability. We have argued that body restraint is one method of suppressing such patterns (Riccio et al. 1992; Stoffregen & Riccio 1988; 1991). We also have argued that pathological movement may result from obscured patterns of movement variability (i.e., impaired observability), rather than from impaired musculoskeletal dynamics *per se* (Riccio & Stoffregen 1991).

Our research on movement coordination problems in Parkinson's disease has focused on the consequences of reduced variability for movement coordination and perception. The classic Parkinsonian symptoms are tremor, rigidity, and slowness or absence of movement. Functional implications are that individuals with Parkinson's disease experience increased instability during postural and movement tasks, an associated higher incidence of falls, and reduced ability to make transition to another movement pattern. A common assumption in many studies on movement disorders is that increased variability (e.g., stride length or stride frequency) is associated with instability during locomotion. However, based on theoretical considerations and empirical work from a dynamical systems perspective (e.g., Diedrich & Warren 1990; Haken et al. 1985; van Emmerik et al. 1999), variability in coordination dynamics has been shown to be essential in pattern change. In addition relatively high frequency variability can play a role in exploratory behavior (Riccio 1993; Riccio & McDonald 1998a). In addition, noise added to a weak signal can improve detectability in muscle spindle or cutaneous receptors ("aperiodic stochastic resonance"; Collins et al. 1996).

In our work on gait in Parkinson's disease we have shown a systematic reduction in variability of relative phase between pelvic and thoracic rotations compared to age-matched control subjects. This reduced variability is associated with a reduced capacity or inability to change movement patterns (van Emmerik et al. 1999). The relative phase variability is considered a functional measure of rigidity in Parkinson's disease. In a similar fashion, the classical 4–6 Hz tremor in Parkinson's disease has been shown to affect the coordination dynamics during gait and manual movements (van Emmerik & Wagenaar 1996).

The inability to change coordination dynamics in the trunk is linked to reduced variability in couplings and has expected consequences for gait stability in patients with Parkinson's disease. It is our contention, however, that the observed reduction in variability of segment couplings as well as the steady 4–6 Hz tremor not only have consequences for stability, but also affect the patient's capacity to detect relevant dynamics for the task at hand. In this regard, we claim that the observed symptoms of rigidity and tremor in Parkinson's disease patients have consequences for the pick up or availability of information by perceptual systems. We are currently investigating the consequences of head, neck, and trunk rigidity in these patients for the availability of information in stimulation. Recent work from our laboratory suggests that the coordination and timing of the eyes, head, and trunk when shifting gaze is influenced by gait cycle dynamics (Peters et al. 2000). The proposition here is that increased rigidity or decreased variability in segmental couplings could limit the degrees of freedom in this eye-head-trunk coupling and possibly obscure movement dynamics that are important for perception.

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## Inadequate information and deficient perception

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**Abstract:** Stoffregen & Bardy's primary motivation for rejecting current views on specification in favor of the global array is that current forms of specification in single-energy arrays allow the ambiguous or inadequate specification of reality. I show that this motivation is not justified, and that the global array concept still falls prey to inadequate specification.

In certain situations that Stoffregen & Bardy (S&B) describe, single-energy stimulus arrays are discrepant, resulting in "input conflict, with its attendant lack of specificity, and . . . the need for inferential processing" (sect. 3.3.3). I do not question the existence or formal structure of the global array, or even the possibility that animals might use the global array to guide behavior. Instead, I question the assumption that insufficiencies of single-energy arrays require an appeal to a global stimulus array. A theory of direct perception does not require that reality always be adequately specified in stimulus arrays, because perceptual errors may often be traced to inadequacies of information. Furthermore, it is illogical to dismiss current formulations of specification in favor of the global array on the basis that information in single energy arrays does not adequately specify reality, because the global array may also inadequately specify reality.

When reality structures two or more arrays differently, then according to S&B (sect. 3.2), "at least one of the structures must be wrong, in other words, not specific to reality." From their perspective, any position that allows for structure in energy arrays to inadequately or incorrectly specify reality (i.e., that allows for input conflict) is fundamentally flawed. The motivation for their position seems to revolve around one implicit assumption: The only satisfactory account of specification is one that eliminates the potential for inadequate information. S&B seem to imply, furthermore, that because direct perception (Gibson 1966; 1979/1986) depends upon specification, then in order for perception to be direct, stimulus information cannot be inadequate or deficient.

Neither of those positions is necessary for a direct account of perception. There are numerous instances where the information contained in energy that reaches a perceptual system is somehow insufficient (i.e., does not specify reality). When this occurs, perceptual error may result. Consider the classic "bent stick illusion" – a straight stick partially submerged in water appears to be bent, because the light that reaches the eyes contains inadequate information (due to refraction). The information that specifies a bent stick is inadequate because it specifies a false state of affairs (Gibson 1966). From a direct perception perspective, the illusory perception is not problematic, because perception can only be as accurate as the information that is detected (cf. Kennedy et al. 1992).

S&B argue that a theory of specification is unsatisfactory if it allows inadequate specification. Because of their interest in intermodal perception, the example of inadequate specification that they focus upon is input conflict. However, input conflict is but one ex-



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ample of inadequate information; many other forms exist (Gibson 1966). The concept of the global array avoids input conflict, but it does not avoid other forms of inadequate information. For instance, there is nothing about the global array that would predict an observer to perceive a partially submerged stick as being straight rather than bent. The global array is not immune to some forms of inadequate specification, and therefore is potentially ambiguous with respect to reality. By their own criterion – the elimination of ambiguity with respect to reality – S&B's global array is just as unsatisfactory as other specificational accounts. In my opinion, the possibility of inadequate specification is not a problem with the global array (for the same reasons it is not a problem for single arrays), but it demonstrates faulty logic in S&B's motivation for rejecting current accounts of specification in favor of the global array.

S&B state that perceptual errors might imply a need for perceptual learning rather than a lack of specificity. While this may be true in many circumstances, it does not, in general, rule out the possibility that some perceptual errors are due to a lack of specificity. For instance, it is not clear how any amount of improvement in the ability to discriminate structure in a stimulus array would prevent the bent stick illusion. Surely, one may come to know that the stick looks bent because of refraction, but no amount of perceptual learning could cause the stick to appear straight, rather than bent, because the light that reaches the eyes specifies a bent stick.

An additional issue related to inadequate information and perceptual learning deserves brief mention. It has been empirically demonstrated that over the course of perceptual learning, people may base their initial responses on nonspecific stimulus variables, but eventually shift to basing their responses on variables that specify the object or event being perceived (Jacobs et al. 1999; Michaels & de Vries 1998). S&B (sect. 7) concluded that such a pattern of responses would be "contrary to and unnecessary in ecological theory," presumably because it would involve a reliance on inadequate (nonspecific) information. I disagree, and instead suggest that this result supports the ecological perspective by demonstrating that the acquisition of accurate perceptions is closely tied to the discovery and utilization of relevant, macroscopic stimulus variables. When responses are not based on these variables, they are typically inaccurate and/or unreliable.

In sum, I question the logic of S&B's motivation for and development of the global array concept, rather than the concept itself. Sensitivity to a global array is a plausible idea and the construct might have explanatory power. One suspects that ultimately the matter will become an empirical one. With respect to that possibility, I raise a final concern. The novel methodologies that S&B propose in order to test for sensitivity to the global array may not be compatible with the study of phenomena that have driven a substantial portion of research on intermodal perception – adaptation to transformed stimulus arrays and intermodal discrepancies (e.g., prism adaptation). Adaptation and global array methodologies seem to place incompatible demands on experimental protocols. Can empirical and theoretical connections between the global array and adaptation to intermodal discrepancies be made?

## The generality of specificity: Some lessons from audiovisual speech

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**Abstract:** The global array might prove to be an important and even necessary concept for explaining some multi-modal phenomena from the specificational perspective. However, we suspect that specification exists in energy arrays detectable by single or multiple sensory systems. We argue for a more general modality-neutral perspective and review results from recent research on audiovisual speech perception.

Kudos to Stoffregen & Bardy (S&B) for addressing the problem of multi-modal integration from a specificational perspective. Many Gibsonian-based explanations of multi-modal effects – including our own (e.g., Rosenbium & Saldaña 1996; Rosenblum et al. 2000) – have provided only a rough sketch of how specification might be instantiated cross-modally. S&B's thoughtful examination of these issues provides an invaluable step toward solving the problem. Regarding their solution, we suspect that the global array does exist and that it can provide specificational information to guide behavior. However, we are doubtful that specificity exists only at the level of the global array, and take issue with S&B's arguments for this claim. We suspect that specificity for behaviorally-relevant environmental properties exists in energy arrays that can be apprehended by single or multiple perceptual systems.

S&B build a strong case for the ubiquity of multi-modal perception in even the most seemingly unimodal tasks (e.g., change in visual fixation). We are also generally supportive of the global array concept, and believe it might prove a useful tool for the specificational perspective in explaining some cross-modal effects. We suspect that there are properties of the environment that are only specified in higher-order relations across energy arrays. However, it is the proposed universality of these properties where we begin to take issue with S&B's proposal.

S&B argue that the global array is the only level at which specification can exist. They motivate this argument with examples that ostensibly show conflictual cross-modal specificity. However, we are not likely the only readers to note that many of S&B's examples are based on laboratory contrivances (moving rooms, rotating drums, flight simulators, McGurk effects), or recent human invention (cars, airplanes, elevators, weightless environments). It is unlikely that the evolution of human perceptual systems could have anticipated these scenarios. While theories should ultimately be able to explain how perception occurs in these artifactual settings, it would seem erroneous to build a theory of specification around these examples.

In other examples, S&B enlist global array properties in lieu of thorough descriptions of single-energy arrays. Consider the traffic scenario in which a thorough description of the acoustic array (including ambient and reflected sound), could reveal structure that is specific to the (relatively) stationary environment as well as to moving cars. With this fuller description, the acoustic array could be considered sufficient for specification. Similar criticisms could be applied to S&B's global array explanations of (kinesthetically) detecting upright stance on an inclined board, and (visually) detecting Tau for both target distance and head movements.

Finally, while not all aspects of an event scenario might be available unimodally (e.g., concurrently perceiving self-movement and having the awareness that it is driven by a simulated display), informational properties most relevant to any single action might be available to a single sensory system. Consider the case of driving a car and apprehending one's position relative to both the car and outside world. This example highlights the importance of construing events, and their perception, as nested. We suspect that for many situations, each nested event is specified unimodally, while the nesting relationship itself might be specified in the global array (thought it need not). Construing events as nested could relieve the problem of conflictual specification occurring in more natural settings.

From this analysis we can summarize our own perspective, a perspective similar to Gibson's. Information itself is modality-neutral. It can be instantiated in specificational structure that is available to a single sense, available to multiple senses simultaneously (and redundantly), or available only across senses (non-redundantly). Fortunately for animals, the second case is the most common: redundant information across modalities allows for a graceful degradation from sensory impairment and diminished ambient arrays (fog, noisy rooms). The latter case – global array specification – is more rare, less relied-upon, and may be idiosyncratic to particularly higher-order stimulus properties (e.g., aesthetic) and relations between tasks (e.g., in artifactual situations).



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A modality-neutral[1] perspective could account for multimodal perception without requiring internal mediation across modalities. A type of information (e.g., inverse rate of change information for time-to-arrival, time-varying kinematic pattern information for speech articulation) can be instantiated as structure in multiple arrays (visual; auditory), but perceiving is concerned with the information, not the energy array in which it is available. In this sense, "cross-modal" integration is not something that occurs in the animal, but occur in – and as a property of – the information itself. This would be true whether the specifying structure exists within a range of energy detectable by a single sensory system, or across a range of energy detectable only by multiple sensory systems. Specificity is general.

We feel that much of the neurophysiological and behavioral evidence cited by S&B are also supportive of a modality-neutral account (e.g., Fitzpatrick et al. 1994; Stein & Meredith 1993). The same seems true of recent neuropsychological and behavioral findings on audiovisual speech perception. Recent brain imaging research shows that visual speech can change auditory cortex activity during audiovisual integration and even silent lipreading (Calvert et al. 1997; Sams et al. 1991). Also, mounting perceptual research suggests that the audiovisual streams are integrated very early, possibly at the level of information extraction (see Green 1998, for a review). The sensitivity to modality-neutral information also seems to occur at a very young age. Infants detect audiovisual correspondences in phonemic properties (Kuhl & Meltzoff 1984), and portray McGurk-effect-like behavior (Rosenblum et al. 1997). These latter findings should also be encouraging to S&B: they suggest that sensitivity to the specificity existent across modalities is a fundamental perceptual ability.

But what of the McGurk effect itself? Would not the global array concept explain how a /d/ can be perceived from the concurrent visual specification of /g/ and auditory specification of /b/? In fact, here we must tip our hats to S&B: it is likely that the resultant perceived /g/ is specified in the structure existent across optic and acoustic arrays. For an ecological explanation of the McGurk effect, the global array could save the day. However, contrary to S&B, we do not think that the global array can provide information about the experimental manipulation itself. It is unclear what type of perceptual exploration might reveal the audiovisual discrepancy, short of seeing the audiovisual dubbing procedure. Furthermore, research shows that it makes little difference whether subjects are asked to report "what was said" or "what you heard": audiovisual influences still occur (e.g., Massaro 1987). We find the inability of the global array to specify the McGurk manipulation encouraging: Perceptual encapsulation evidences the lawful nature of specificational information.

In conclusion, we think S&B have posed an important challenge to specificational approaches. A specificational account must explain how multiple sensory systems simultaneously extract structure from energy. However, we will put our money on modality neutral information existent in all forms of specificity: whether detectable by single or multiple sensory systems.

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NOTE

**1.** We prefer the term modality-neutral over "amodal": while perceptual information is not modality-specific, it cannot exist without instantiation in some energy array (excepting ESP).

## Specificity is always contingent on constraints: Global versus individual arrays is not the issue

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**Abstract:** Stoffregen & Bardy's proposal that perceptual systems can use information defined across two or more sensory domains is valuable and urgent in its own right. However, their claim of exclusive validity for global-array information is superfluous and perpetuated for incorrect reasons. The seeming ambiguities of individual arrays emanate from failures to consider relevant ecological constraints and higher-order variables.

James Gibson's (1950; 1966; 1979/1986) demonstrations of specificity and the associated refutation of the ambiguity dogma were made possible by two brave intellectual advances: Gibson recognized that useful information could reside in higher-order properties of the ambient arrays (a breakaway from elementarism) and, furthermore, that by restricting analyses to natural conditions a wealth of meaningful and reliable information could be brought in evidence. The latter amounts to an invocation of ecological constraints, in addition to the laws of nature.

Stoffregen & Bardy's (S&B's) proposal that relevant information can reside in a global array extending across energy array borders falls well within Gibson's approach in the first respect. If useful specifying variables can consist of relational properties across a single array and over time, it follows naturally that they could also extend over two or more types of energy arrays. Thus, S&B's proposal of a search for global invariants is laudable as such, as is their claim that properties specified by such invariants could be directly perceived. This enterprise gains urgency from the recognition that the senses operate simultaneously and that information from different arrays is often necessary for the control of action.

However, S&B not only proffer global invariants, they also make extensive claims that specificity occurs exclusively with such invariants. We disagree, and argue that S&B's failure to find specification in individual arrays follows from their failure to apply Gibson's insights concerning ecological constraints and nonelementarism. The groundbreaking contributions by Gibson and others concerning information in individual arrays should remain a valid basis for perception research.

***Ecological constraints.*** All specificity is contingent on constraints ("constraints as grantors of information," Runeson 1988; 1989; cf. Barwise & Perry 1983). Moreover, the specificity they engender pertains to properties, not the structures or media as such (cf. Bingham 2000b; Turvey 1992). Potentially, constraints can be any lawfulness or regularity, ranging from laws of nature, via ecological universals such as textured environmental surfaces to, say, local conventions. Thus, relations of informative specificity vary in degree of universality depending on the scope and stability of the constraints that grant them.

It follows that specificity can not be meaningfully investigated without acknowledging the questions: specification of what properties, under what conditions? Without restricting analyses to particular properties and conditions, specificity will be hard to find. We question the relevance of universal, unconstrained deliberations on specificity for the understanding of perception and action.

Apparently, S&B do not consider the role of constraints in their discussion of specificity. Thus, we are not impressed when they take the hypothetical existence of perfect virtual-reality devices to prove optic array ambiguity. To be consistent, they should also have considered the possibility of slightly more complicated devices as proof against specificity in the global array. What if light



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would not propagate linearly? What if an evil genius were distorting arrays? If one allows such arguments there will always be reasons to reject specificity (cf. Dretske 1981).

An ecological stance does not proffer specificity because injection of yet higher order variables can outweigh such arguments, but because it dismisses non-ecological circumstances as irrelevant. Constraints at the ecological level grant specificity to informative variables, whether single- or multi-array. It is biologically irrelevant whether a variable that specifies a useful property of the organism-environment system is granted by ecological constraints or by physical laws alone.

Culture and technology add and break constraints. Traffic lights add specification of safe street crossing. Conversely, virtual-reality gear and swinging rooms deliberately break a basic ecological constraint by decoupling the visible environment from the earth and thus makes the optic array lose some of its specificity. Inadvertent cases also occur, as in elevators. This presents new possibilities and challenges to perceivers. Will they be able to educate their attention to detect other information – in the global array – that specifies the new situation? Interestingly, the success of virtual-reality technology will rely on people's failure to do so.

***Non-elementarism.*** S&B's failure take advantage of Gibson's nonelementaristic approach is evident in their dismissal of somatosensory specificity concerning body sway versus tilting of the surface of support: Ankle rotation can be due to either of them. However, in many other somatosensory variables, the two events have distinct effects. For instance, standing on a slanted board produces force components parallel to the surface with corresponding shearing skin deformations, varying in proportion to the angle of tilt. Conversely, sway produces alternating shifts between heels and toes in the perpendicular skin pressure component. Amplitudes and directions of ankle joint load forces will also differ distinctly. Somatosensory ambiguity has certainly not been demonstrated.[1]

S&B's claim that the acoustic array can only specify relative motion between other cars and one's own is similarly vacant. One can hear quite a bit about how one's own car is moving, in particular whether it is moving or not. The acoustic array is structured by reflection and occlusion of sounds among cars on the road and among terrain features. These multitudinous effects are a potential source of informative variables in the acoustic structure, which S&B have dismissed offhand.

We do not claim that we have shown or can show that specificity exists in those cases. Our point is that S&B have not provided any proof for the claimed ambiguities. In principle, ambiguity in natural arrays is not the kind of thing that can be proved, because there is no way to ensure that all possible higher-order variables have been tried and all relevant constraints have been considered for their information-granting potential (Runeson 1988). Ambiguity could become a tenable claim only after long and hard attempts to prove specificity have failed.

Finally, we notice that S&B's reasoning is remarkably congruous with that of the classical, no-specification tradition. The possibility of specification is brushed very lightly, often by letting a single variable (mis-)represent the informative potential of a whole energy field. With non-specificity seemingly proved, a case is made for the standard remedy: invocation of something more. Traditionally, the recourse has been to memory and constructive inference – S&B instead bring in additional sensory domains as remedial necessities.

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NOTE

**1.** It would be tempting to call this reasoning of S&B's "pre-Gibsonian," however, also Gibson (1966, pp. 62f) failed to consider the shearing force component. When related to the perpendicular component it specifies slant of the surface of support without recourse to gravito-inertial information.

## Perceptual systems: Five+, one, or many?

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**Abstract:** The target article's value lies not in its defence of specification, or the "global array" concept, but in its challenge to the paradigm of 5+ senses, and its examples of multiple receptor types cooperatively participating in specific pick-up tasks. Rather than analysing our perceptual endowment into 5+ senses, it is more revealing to type perceptual systems according to task.

Stoffregen & Bardy (S&B) can and should not hope to persuade us that the traditional five senses (plus, presumably, a few more, like vestibular sense, proprioception, etc.) just do not exist. Clearly for many purposes it is valid and useful to think of the senses in this way. The circularities they point to, arising from defining the senses in terms of receptor types or energies transduced, do not seem to be vicious.

However, their argument opens up a very important pragmatic and heuristic question that has received almost no previous attention: Is thinking of our sensory endowment as consisting of 5+ independent perceptual systems the most useful and perspicuous way to view the mechanisms of ecological perception? Here S&B make a good case for a negative answer, challenging deeply entrenched and, up to now, virtually unexamined assumptions. They show that certain important, real-world perceptual tasks require the coordinated deployment of more than one type of receptor. If we think of the senses as 5+ channels, our attention is diverted from such cases (which may well be the rule rather than the exception), and even if we do notice them, the separate senses framework leads us to posit unnecessarily complex and conceptually suspect inferential or computational theoretical accounts of them.

But if 5+ senses is not the most useful picture of things, does it follow that the heuristic alternative is to think of the perceptual environment as a single global array, presumably to be perceived by a single global perceptual system? S&B apparently think that if the ambient energies available to our perceptual system do not unambiguously specify what is really out there then we must be doomed to perceive the world only "indirectly," our experience mediated through representations and inferential processes. They are thus led to the notion of the global array in the hope of finding an information source sufficiently rich to ensure specification. But unless we understand "direct perception" to mean "invariably veridical perception" (in which case perception certainly is not direct) it simply does not follow that directness requires unambiguous specification. In fact, we do not ultimately rely on mere perception to tell us what is really out there, we rely on science, which certainly involves inferential processes. Specification is a red herring, and the theory of the global array is a (probably inadequate) solution to a non-problem.

Of course, the global array undoubtedly exists, and our sensory endowment as a whole undoubtedly exists too. Thus, (granting the general framework of Gibsonian direct perception theory) it will inevitably be true to describe any perceptual episode as the pick-up of an invariant of the global array by the global perceptual system. But this is not to say very much. In fact, it is surely the case that many instances of perceptual information pick up do make use of only one receptor type, and even the examples given by S&B each involve only a small subset of the receptor types we have. To insist on treating ambient arrays and perceptual systems only as "global" wholes would be to obscure this point, and threat-



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ens to be just as misleading as the paradigm of 5+ independent channels.

A more revealing analysis might be to type perceptual systems in terms of the specific sorts of environmental information that they gather. The target article's examples suggest that, instead of saying "this is an instance of vision, this of audition," and so on, we might do better to say things like "this is an instance of perceiving that your conveyance has come to a stop," "this is an instance of perceiving that a surface affords sitting," and so on. In this vein, we can think of our sensory endowment as comprised of a number – probably quite a large number – of perceptual instruments, each specialized for the pick up of particular sorts of environmental information, and actively deployed as and when that information is needed for the guidance of behavior. A perceptual instrument (alternatively a "smart perceptual mechanism" [Runeson 1977] , or "smart sensor" [Burt 1988] ) is a complex of anatomical and cognitive structures that is capable of actively testing for the presence or amplitude of some specific type of environmental property. It consists not only of receptors, but also of efferent systems that "tune" them, the musculature that orients them and moves them so as to sample the ambient energy arrays appropriately, and the neural structures and algorithms that control these "tunings" and movements and orchestrate appropriate responses to the receptor outputs (Thomas 1999). I take it that by switching neural algorithms, and thus the way in which receptors are deployed, our fairly limited array of receptor types can be recruited to do a large number of different perceptual jobs, or putting it another way, to form parts of a large number of perceptual instruments (cf. Ballard 1991 on "sensor fission"). We do not so much have 5+ general purpose senses as a large array of anatomically overlapping, specialized perceptual instruments, a capacious "box of tricks" (Ramachandran 1990).

From the entrenched standpoint of the orthodox paradigm of 5+ senses, this theoretical perspective must seem strange and counterintuitive, but S&B throw that paradigm into deep question. Furthermore, they direct our attention toward the significant but previously under-explored possibility that many perceptual instruments may cooperatively employ more than one receptor type. The considerable value of the target article lies, I think, in these challenges to entrenched orthodoxy, rather than in the unnecessary and heuristically rather unhelpful notion of the "global array."

## "The assumption of separate senses": Pervasive? Perhaps – Persuasive? Hardly!

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**Abstract:** We show that Stoffregen & Bardy's arguments against the assumption of separately functioning senses have more historical antecedents than they give credit for, and that multimodal functioning – primitive in perceptual and brain development – does not require this assumption. What is needed is evidence that biological organisms are indeed detecting and acting upon information in a multimodal (or global) array.

The fact that the various senses have, since the turn of the century, been *described* and *investigated* separately hardly reflects a "pervasive" underlying assumption that the senses also *function* independently as Stoffregen & Bardy (S&B) suggest. Furthermore, S&B's attempt to overcome the difficulty by redefining perception in a manner that fits their proposition – that is, "as the pick-up of information that exists in irreducible patterns across different forms of energy" (sect. 1) – is both circular and unpersuasive. Perception and action also tend to be studied and described separately, although most scholars would not want to claim that either could function independently of the other.

Drawing on random examples from the history of psychology, we will first show that there has been more explicit awareness that the senses do not function separately than S&B give credit for, whether the umbrella be amodal, cross-modal, or multimodal functioning. Subsequently, we will show that there is ample evidence that cross- or multimodal functioning is primitive in perceptual development in infants, and that modern theories of brain development build heavily on multimodal sensory input to the nervous system as the foundation for the establishment of functional neuronal groups.

***Historical antecedents of multimodal functioning.*** That S&B's position – and their postulation of a global array – may not be particularly novel is attested to by Titchener (1901) in his classic text on experimental psychology, in which he takes an even more radical view. To his mind, "perception is not simply an aggregate or group of sensations; it is an aggregate or group of sensations put together under certain conditions, arranged or harmonised upon certain patterns. The conditions are found in the physical world about us and the arranger or harmoniser is Nature herself" (p. 128). Sensations, he argued, are joined together by our physical environment, *not* by "anything psychological [that] has intervened between the sensation and the perception" (p. 129). He further suggested that the psychologies, "by the mere fact that they treat of perceptions one by one, in separate paragraphs" (p. 127), have contributed to the popular misbelief of separate senses.

Earlier, Stumpf (1890), in his theory of tonal fusion, went even further both in criticising existing positions and in attempting to provide neural justification for his ideas. He introduced the notion of synergies of the cerebral cortex – "determinate modes of cooperation of two nervous structures having its ground in the structure of the brain, of such a kind that whenever the two structures give rise to their corresponding sensations there arises at the same time a determinate degree of fusion of these sensations" (p. 214). He discusses the way in which such synergies might have been built up over evolution so that what were once separate sensations became, over time, synergies – an issue to which we will return below in a development context.

***Sensory functioning in early development.*** S&B argue that the concept of amodal specification "implies a comparison between information obtained via different perceptual systems" that must have been "independently generated," and that "the postulation of such a cross-modal comparison requires a prior assumption that the senses work separately in such a way that their outputs can be compared" (sect. 3.3.3). This is a misrepresentation both of the developmental work to which they refer and of other work in this domain that makes no explicit assumption that the senses function separately. On the contrary, E.J. Gibson has argued *against* such breaking down of the world and then inventing "processing mechanisms" to put the world together again (Gibson 1977). Her work on perceptual development emphasises time and again the multimodal character of perceptual events, the multisensory consequences of behaviour, and that there exists no learning or development that is strictly within modality (Gibson 1988; 1992; Gibson & Walker 1984).

Reviewing empirical work on perceptual development provides compelling evidence that multimodal functioning is primitive in infancy, illustrating "a kind of unity of the senses in the newborn" (Thelen & Smith 1994, p. 191). Finding evidence of cross-modal functioning at such young ages argues against the necessity – or even likelihood – of inferential cognitive processing in order for cross-modal matching to occur, as S&B would have it. By way of example, newborns match visual with auditory information (Spelke1976), they orient visually towards a heard sound (Mendelson & Haith 1976), and both visual and auditory stimulation summate to produce neonate arousal (Lewkowicz & Turkewitz 1980). Furthermore, newborns match oral and visual information with respect to textured pacifiers (Meltzoff & Borton



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1979) and with respect to rigid versus elastic cylinders (Gibson & Walker1984). In contrast, there is evidence that *modality-specific* attributes of objects begin to be differentiated only later in infancy (e.g., Walker-Andrews & Gibson 1986). The results of these studies shed light on an issue that S&B raise in the last section of their article: Are infants initially sensitive to structure in single-energy arrays, with experience leading to the pick-up of structure in the global array? Although the developmental work cited here uses the concepts of multimodal, cross-modal, and intermodal functioning rather interchangeably, they do attest to development proceeding in the opposite direction, that is from multimodal to modality-specific functioning. Ontogeny, from Stumpf's (1890) perspective, thus seems to proceed in the opposite direction to phylogeny. Following S&B's own argument, the direction of this developmental trend leads to a conclusion opposite to theirs, namely that "the assumption of separate senses" (sect. 7) is *not* necessary for cross-modal functioning to occur.

***Multimodal input as the basis for brain development.*** S&B make a convincing case that the assumption of separate senses is incompatible with physical reality and the notions of specification and direct perception. However, as argued above, the postulation of cross- or multimodal functioning does not rest on this assumption. Furthermore, with their definition of the global array, the authors provide an example of how multimodal functioning can exist without requiring inferential processing that would make perception mediated rather than direct. Support for the latter notion has been provided by Edelman (1987; 1992) in his concept of reentrant mapping – the anatomical interrelating of several simultaneous perceptual and motor representations – which provides a neural mechanism for brain development that has an explicit foundation in multimodal input to the neural network in order for further development of the brain and its functions to occur.

In Edelman's theory of neuronal group selection, perceptual categorisation is the most fundamental psychological task of development that forms the basis for further development of human cognition and action. As all perceptual events have a multimodal character and all behaviour has multisensory consequences (cf. Gibson 1988; 1992), the nervous system is continuously bombarded with multisensory stimulation that is temporally correlated. This time-locked nature of multimodal input, together with the reciprocal activation of neuronal groups by reentrant mapping of motor activity along with sensory information from many modalities, lies at the heart of category formation (see also Thelen & Smith 1994). In early development of the brain, movement and sensory signals are completely coupled and act together to form the global maps that are the basis of further development. Neuronal groups thus get strengthened through their association in the real-world, which forms the basis for experience-driven perceptual categorisation. In other words, the perfect temporal association of multimodal information is the primary link between the mind and the world, thereby providing a neural mechanism for (the development of) specification and direct perception.

In conclusion, in their rejection of the assumption of separate senses, S&B have, historically, a number of bedfellows; their thesis has more empirical support than they are prepared to give credit for, particularly in the field of perceptual development.

What remains to be demonstrated, as the authors are fully aware, is the tenability of the second main idea in the target article, namely, that biological systems are directly sensitive to, and make use of, structure in the global array.

## Abolition of the senses

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**Abstract:** In advocating an extreme form of specification requiring the abolition of separate senses, Stoffregen & Bardy run the risk of diverting attention from the multisensory integration of perception and action they wish to champion.

Science progresses by building on and then making breaks with the past. The emphasis is placed on the latter in the target article by Stoffregen & Bardy (S&B). They stake a bold claim for a single perceptual system that utilizes global arrays of energy. In order to support their position, they need to dismantle the sensory edifice built up over more than two thousand years. This is a tall order: you have to be very sure of your ground if you are to argue that everybody has got it wrong until now. If the theoretical position advocated is considered wanting in regard to singular sensory specification, then the force of the theoretical integration that follows is irremedially flawed.

The arguments against the separation of the senses address three aspects of function – the physics of the stimulus (energy), the structure of the receptor system (anatomy), and the responses to stimulation (neurophysiology). S&B state that they have been unable to find an explicit justification of the assumption of separate senses, and then they cite Aristotle's deliberations, which are directed specifically to this point. S&B seem to be presenting a theory of Aristotle's "common sensibles" rather than of perception generally. They do not refute Aristotle's statements about the special objects of sense.

It is surprising that the authors did not cite the work of the "common sense" philosopher, Thomas Reid (1710–1796). He made the distinction that S&B are trying to sustain – that perception is distinct from sensation, and that the former does not involve cognition. However, Reid does maintain that there are representational stages in perception:

> Although there is no reasoning in perception, yet there are certain means and instruments, which, by the appointment of nature, must intervene between the object and our perception of it; and by these our perceptions are limited and regulated. First, if the object is not in contact with the organ of sense, there must be some medium which passes between them. Thus, in vision, the rays of light; in hearing, the vibrations of elastic air; in smelling, the effluvia of the body smelt, must pass from the object to the organ; otherwise we have no perception. Second, there must be some action or impression upon the organ of sense, either by the immediate application of the object, or by the medium that goes between them. Third, the nerves which go from the brain to the organ, must receive some impression by means of that which was made upon the organ; and probably, by means of the nerves, some impression must be made upon the brain. Fourth, the impression made upon the organ, nerves, and brain, is followed by a sensation. And, last of all, this sensation is followed by the perception of the object. (Reid 1764, pp. 424–25)

Advocating the unity of perception and action need not involve the abolition of the senses.

It is difficult, in an historical sense, to imagine originating a classification of the senses that did not depend on anatomical and perceptual distinctions. Such a classification would have preceded others based on energy because the characteristics of perception were described long before there was an adequate understanding of energy sources in the environment. These categories were later reinforced by evidence from neuroanatomy and neurophysiology: specialized receptors respond to features of the stimulus and these are analysed in discrete regions of the brain. Subsequent cortical and subcortical analysis certainly integrates signals from different sources, but this does not call for denying the specificity of the senses. The examples of binaural localization and binocular stere-



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opsis functioning "in a unitary manner" are not surprising, but they are unlikely to be treated as evidence against separation of the senses. In the context of neurophysiology, concern should be given to receptor systems and their cortical projections rather than higher cortical functions which integrate signals from the sensory projection areas. The arguments for unitary perception are more forceful than those for a unitary sense.

Most detailed examples of perception given in support of S&B's approach understandably derive from their own research, although they are from a narrow range of visual-vestibular interactions. Moreover, many are artificial in a real sense since they mostly involve vehicular motion. Any theory that is based on the global array and its use should restrict the phenomena to those that occur in the natural environment rather than incorporate dimensions that are unique to one species. Since an evolutionary perspective is implied by the authors, they should confine their analyses of perception and action to those which do not incorporate artificial devices.

The vestibular system provides a telling example of the manner in which our understanding of perception has been advanced by the specification of sense. It was the first increment in two millennia to Aristotle's five senses. The anatomy of the vestibular labyrinth was described long before its function was appreciated; between these two events the visual consequences of vestibular stimulation were subjected to observation and experiment (see Wade 2000). Rotating the body to induce vertigo resulted in postrotary nystagmus and apparent visual motion, the directions of which were dependent upon head orientation during rotation. These responses to body rotation could be interpreted when the hydrodynamic theory of semicircular canal function was advanced in the 1870s. Would such understanding have been achieved without the specification of a separate vestibular sense? It is the case that Stoffregen and Riccio (1988) have denied the link between vestibular stimulation and perceived orientation, but there are those inclined to dispute their claims (see Curthoys & Wade 1990).

## Infants, too, are global perceivers

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**Abstract:** Infants are global perceivers. They detect patterns in stimulation that allow detection of many affordances of the environment. Pick-up of structural patterns across forms of ambient energy awaits maturation of sensory systems and improvements in motor skill, but development proceeds rapidly during the first year. Researchers in perceptual development must devise and refine existing tools to examine infants' abilities.

When I first examined infants' emotion perception using an intermodal task (Walker 1982), I was asked why I compared an infant's looking time to a happy facial expression projected alongside a sad facial expression and accompanied by a happy vocal expression to that shown in the opposite setup. That is, the comparison was with the infant's looking time to the happy expression when it was projected alongside the sad expression, but accompanied by a sad vocal expression. The expectation instead had been that I should use, as baseline, looking at a facial expression when it was presented as one of a silent pair. I have struggled to answer this question, never able to furnish an argument that convinced although I was certain of my choice. I have argued that (1) two facial expressions and one soundtrack and (2) two facial expressions – comprise only two very different events. Stoffregen & Bardy (S&B) provide the rationale I have been seeking: the whole is not only greater than but is qualitatively different from the sum of its parts. The integrated action of seeing and hearing leads to the perception of an "irreducible" product, in the present example an emotional expression that affords opportunities for action.

The target article is the paper I almost wish I had written. S&B present a logical, well-supported argument for specification. They point out how many of us have been unable to escape the assumption that the senses are separate channels even as we claimed we were rejecting that accepted wisdom. They clarify for me why it has been so difficult to maintain precision with such terms as "intermodal," "crossmodal," "amodal," and "multimodal." I have tried, for example, to reserve "crossmodal" for situations in which an observer viewed something and subsequently heard or felt it, a situation that may require the kind of inference that most theories assume.

S&B make additional points that speak to the common fallacy that infants will be unable to "process" information when they encounter in the lab a stimulus event such as a moving, computer-generated disk punctuated by a beep at the lowest point in its trajectory, flanked by another disk that is not. The usual assumption is that infants must compare information obtained via vision to that obtained via audition to determine which icon is consistent with the sounds, and that this will tax their abilities (Bahrick 1992; Lewkowicz 1993). Infants at a specific age may indeed fail a specific intermodal task, but not because they cannot deal with simultaneous presentations of separate optic and acoustic arrays. Sensitivity to a higher-order pattern is required, not internal comparisons of information derived from single-energy arrays.

Two aspects of S&B's paper could be improved. First, although they acknowledge that James Gibson (1966) provided the original example for information in the global array, they do not describe the scope of his contribution. This may represent misinterpretation, ambiguities in the theory, or evidence for the growth of Gibson's own thinking. Congruent with the latter, Gibson (1979) himself described the theory of information pick-up as in an "undeveloped state." But he went on to say: "Information is not specific to the banks of photoreceptors, mechanoreceptors, and chemoreceptors that lie within the sense organs. Sensations are specific to receptors and thus, normally, to the kinds of stimulus energy that touch them off. But information is not energy-specific" (p. 243). He asserted that we directly perceive the qualities of things in the world, especially their affordances. S&B take up these ideas and propel them much farther along the path Gibson had begun to clear.

Second, S&B little attend to developmental research. Consider results from Walker-Andrews and Lennon (1985) and Pickens (1994). In the earlier study, 5-month-olds observed videotapes of a Volkswagen (VW) moving toward or away from them accompanied by a noise that increased or decreased in amplitude. Infants looked preferentially at the videotape consistent with the engine noise – the approaching VW when the noise grew louder, the receding VW when it softened. Note that the rate of change in amplitude was correlated with movements of both vehicles, but infants responded to directional information as well. Pickens (1994) introduced critical refinements – a condition in which a toy train changed in size only (rather than moving in depth), another in which each film's brightness varied, and one in which the trains moved up and down. Infants looked appropriately for motion in depth and, less so, for size changes. They did not show preferences related to brightness changes or vertical movement. Five-month-olds were sensitive to ecological relations specifying approach versus retreat and did not generalize to intensity or metaphorical relations.

Although S&B fail to capitalize on the wealth of infant data, they simultaneously present a challenge to developmental researchers. The authors proffer but dismiss the possibility that infants are initially sensitive to structure in single-energy arrays and develop sensitivity to the global array because this assertion demands the corollary that there are separate senses. In fact, infants appear to be sensitive to the global array. They detect some invariant patterns in the first few weeks of life (e.g., Gibson & Walker 1984; Meltzoff & Borton 1979). Months later they can detect arbitrary relations such as those contrived between the color and taste of a substance (Reardon & Bushnell 1988) or a label and a moving ob-



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ject (Gogate & Bahrick 1998). There is continued debate about the role, if any, of modality-specific information during infancy (c.f. Bahrick & Lickliter 2000) as well as the acknowledgment that although all sensory systems are potentially functional prenatally, they mature at different rates. Taking a lead from the present paper, however, those of us who study infants should consider more carefully how we present perceptual problems. It may no longer suffice to construct multimodal displays and test whether infants appreciate invariant relations. S&B suggest some alternatives, but designing such studies given infants' limited behavioral repertoires will be difficult.

In closing, S&B have contributed an important essay in the debate about the nature and origins of perception. They make a convincing case for specification and for an active perceiver, one not hobbled by the imposition of energy-specific stimulation but free to sample the global array and detect affordances.

## Motion, frames of reference, dead horses, and metaphysics

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**Abstract:** Various annoyingly incorrect statements of Stoffregen & Bardy are corrected, for example, that perception researchers commonly use the term "absolute motion" to denote motion without any frame of reference, confuse earth-relative and gravity-relative motion, err with respect to the frame of reference implied by their subject is motion responses, believe in sense specific motion percepts, and do not investigate sensory interactions at neurophysiological levels. In addition, much of the target article seems to concern metaphysics rather than empirical science.

Stoffregen & Bardy (S&B) state that "a common concept . . . among many researchers, including myself, is . . . the idea of absolute motion" not defined in terms of any frame of reference (S&B use the term referent). But neither I nor anyone else that I know has ever embraced such a peculiar idea. The relativity of motion has always been my explicit point of departure (Wertheim 1981) and I have argued that a theory must he flawed if it yields a concept of motion that is not definable in terms of a frame of reference (see e.g., my discussion of the "hidden reciprocity assumption" in Wertheim 1994, sect. R2). S&B call on researchers always to mention the particular frame of reference in terms of which they define motion. But this is what everybody has been doing all along (see e.g., Swanston & Wade 1988, Wertheim 1994, and many of its accompanying *BBS* commentaries, also sects. R5 and R6). In the literature (e.g., Kinchla 1971; Wertheim 1994, p. 302) the term "absolute motion" denotes motion defined in terms of the three-dimensional (3D) frame of reference dimensioned by the earth's surface and the direction of gravity. Other names might have served just as well: for example, "motion relative to absolute space," "Newtonian motion," "exocentric motion," or "earth-relative motion." This is perfectly in line with Einstein's claim that the idea of frameless motion has no meaning. When S&B defend Einstein's views vis-à-vis those of perception researchers (see also Stoffregen 1994), they beat a dead horse.

The same can be said about S&B's elaborate argument that there can be motion relative to the earth without it being relative to the direction of gravity (i.e., when perpendicular to the direction of gravity). To my knowledge nobody has ever equated earth-relative motion with motion relative to the earth's gravity.

S&B also criticize many researchers, including me, for stating that the perception of visually induced self-motion is often illusory. What those authors mean is that in the presence of a large optic flow field, one often experiences a perception of self-motion relative to the earth's surface, while, physically speaking, one remains stationary relative to that surface. The most common example of this illusion occurs when an earth-stationary observer is seated inside a rotating optokinetic drum. S&B claim that this is not an illusion, because the relative motion between the drum and the observer is correctly perceived. It is, but that is not the illusion which concerns a different percept, namely, perceiving self-motion relative to the earth's surface. S&B seem to believe that this is not really perceived inside the drum, although experimenters believe it is. They claim that there is no illusion; only a misunderstanding between observer and experimenter as to the frame of reference relevant to the observer's percept, a misunderstanding which should disappear when the frame of reference is explicitly stated in the perceiver's verbal report.

However, whether S&B like it or not, earth-relative self-motion really is experienced by observers inside an optokinetic drum: they believe that they are moving relative to the floor of the experimental room in which the drum is located (and perceive the drum as stationary relative to that floor). Since this is not physically the case, the term illusion is correct.

Contrary to what S&B suggest, researchers in the field of visual-vestibular interactions and self-motion (including myself) are always careful to correctly ascertain the frame of reference in which subjects report self-motion percepts. They either specifically ask about it, or use non-verbal methods (e.g., by asking the subjects to continuously keep a joystick pointed toward where they believe the door of the experimental room is located). In fact, these researchers were the first to recognize the dangers of verbal ambiguities about frames of reference; terms such as "exocentric" and "egocentric" originated from their work. S&B's accusation that researchers "routinely exclude correct responses from their analysis . . . because of verbal ambiguities in their subjects' reports," reveals a shocking lack of knowledge. This is not even kicking a dead horse, but kicking a nonexistent one.

Another problem is S&B's claim that my analysis of percepts of "absolute motion" is sense-specific (see also Stoffregen 1994), that is, requires only one sensory system. This is incorrect. In my model (Wertheim 1994) the retinal coordinates of image motion are recalibrated into the 3D coordinates of the frame of reference defined by the earth's surface and gravity. This is brought about with what I termed "reference signals." These are compound signals constructed from sensory afferents generated by various sensory systems (somatosensory, vestibular, and visual). In addition, retinal and reference signals themselves have no perceptual meaning. It is their interaction which yields percepts of motion.

Consequently, on the perceptual level, one cannot speak of separate senses. This is also implied by other inferential theories, which use the theoretical forerunners of reference signals ("extra-retinal signals," "corollary discharges," "efference copy signals"). Hence, no inferential theorist assumes that motion perception is sense-specific (see Wertheim 1999, for a more detailed analysis of this issue). Nor do vestibular researchers – who, for decades now, are trying to unravel the way how retinal, somatosensory, and vestibular afferents interact to bring about particular percepts of self-motion – assume that motion perception (of any kind) is sensory-specific (see e.g., Sauvan 1999). On the contrary, these sensory interactions are their core business, both on the perceptual and on the neurophysiological level.

Hence, it is not at all surprising that S&B have been unable to locate an explicit justification of the assumption of separate senses in the philosophical, behavioral, or neurophysiological literatures. Who would want to justify a false assumption? S&B's call to search "for neural units that respond to patterns of activity that extend across different kinds of receptors, such as the retinae and the vestibule," again is out of touch with the literature. Here too the authors beat a dead horse.

Finally, it is difficult to make sense of S&B's discussion of various possible relations between an energy array and (aspects of) reality – a relation which is "prior to and independent of . . . psychological processes." The point is that, reality *per se* is unknown. This is metaphysics, not empirical science. Reality can only be assumed: we assume that what we perceive is reality. For all practi-



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cal purposes, the array itself is reality (or as close as one can get to it). What else can S&B's mean when they say that the array is "not a hypothesis but a fact"? For empirical ecological psychology, an array's relation to reality (whatever this means) is irrelevant.

Instead, it takes the concept of an energy array as its point of departure, and then tries to investigate what sort of information (e.g., motions, frames of reference, etc.) can be recognized in its structure and how it might be picked up by a perceiver. For inferential theorists, who do not shun cognitive evaluations of incoming sensory signals, the issue is different: How do percepts of the various kinds of object- or self-motion arise from the neurophysiological and cognitive processes that operate in association with our sensory systems? As I have shown (Wertheim 1994), the answers offered by these two approaches are not mutually exclusive, for they refer to different percepts: relative motion between objects may be perceived from retinal information only, but percepts of "absolute motion" (as defined above) require non-retinal information as well. To describe these kinds of information in terms of many energy arrays or a global multidimensional one is merely an exercise in semantics.

# Authors' Response

## Specification in the global array

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**Abstract:** We discuss issues raised by the commentators, such as specification in single-energy arrays, task-specific pickup of information, general principles of the ecological approach to perception and action, and how specification may be constrained by the facts of physical relativity. While the commentaries raise many important issues we conclude that they do not undermine our argument that specification exists solely in the global array.

### R1. A general theory of perception and action

We seek a theory of perception and action that is internally consistent and general. General, in the sense that it applies to all perception and action, across situations, across individuals, and across species. Internally consistent, in the sense that concepts used to explain one aspect of perception and action must be compatible with concepts used to explain other aspects (e.g., Shaw et al. 1982).

Although many of the commentators work toward general theories of behavior, some seek to understand perception and action primarily in humans (e.g., **Ahrens; Pallas; Wade**), while others focus their explanations of perception in "natural" circumstances (**Runeson et al.**). Perception and action are known to be adaptive in a great variety of species that exhibit an astonishing diversity of perceptual, motor, and neural anatomy, and in a great variety of situations, such as teleoperation (**McMichael & Bingham**) and orbital flight, which do not seem to fit any credible definition of *natural.* It is our belief (cf. Gibson 1966; Shaw et al. 1982), that a single theory of perception and action can and should apply to all of these.

Commentators who appeal to human perception or to the nervous system do not appear to be moving toward a theory of perception and action that is general across species (contra **Wade,** we seek a theory of perception and action that is general across species). For example, **Ahrens** defines sensation as the "transduction of ambient energy into a spatiotemporal pattern of neural activity," which seems to imply that sensation is limited to species that have neurons. This would seem to require that we develop separate theories to explain perception in species that have neurons and those that do not. This is problematic in the simple sense of not being general. It also raises the question of the evolutionary development of perception, since species with nervous systems evolved from predecessors that did not have nervous systems (Reed 1996). Similarly, **Lewkowicz & Scheier** assert that "no behavior is possible without the brain." While this may be true for humans and other chordates, it is not true for behavior in general (Berg 2000; Pittenger & Dent 1988). The development of a central nervous system is one way in which living things have achieved adaptive control over the animal-environment interaction, but it is not the only way and, most importantly, it is not a *sine qua non* for the adaptive success of species (Reed 1996). Adaptive behavior requires perception and control of the animal-environment interaction. Given this, and given the fact that many successful species do not have central nervous systems, a theory of perception and action that is general must be based on principles that are not limited to the properties or activity of any particular neural apparatus (Gibson 1966; Reed 1996).

It is important also to consider the fact that the nervous system is an effect of behavior, at least as much as it is a cause (Berthoz 1997; **Pailhous et al.**). This is true at the ontogenetic level: As Reed (1966, p.69) argued, "it is not the animal's brain that organized its world, but the evolutionary ecology of the animal that organized its brain." This is also true at the phylogenetic level, that is, in terms of individuals, as is illustrated in the examples provided by **Kujala** and **Pailhous et al.**[1] We do not suggest that the nervous system is wholly plastic; that this is not true is again shown by **Kujala.** However, together with **Pailhous et al.,** we reject the very widespread assumption that the nervous system is primary. Perception and action (including adaptive learning) occur in species that have very different nervous systems from ours and, indeed, in species that have no nervous system at all (Berg 2000; Pittenger & Dent 1988; Reed 1966). For this reason, a general theory of perception and action cannot be rooted in the nervous system.

Several commentators (e.g., **Kujala; Vereijken & Whiting**) suggest that existing neurophysiological research supports our arguments about the global array. We agree that such research may be consistent with the pickup of information from the global array. However, existing neurophysiological research is not likely to be suitable for theory testing with respect to the global array. Much of the existing neurophysiological research is consistent with a wide variety of divergent theoretical positions (as pointed out by **Mergner & Becker**). An example is the research on blind people cited by **Kujala.** While this work impressively illustrates the flexibility of the nervous system and the role of experience in CNS organization (**Pailhous et al.; Vereijken & Whiting**), it provides no information about the parameters of sensory stimulation to which the nervous system is sensitive. There is, however, existing neurophysio-



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logical and neuroethological research that supports the general premises of the ecological approach to perception and action, adopting an *a priori* decision to focus on natural (i.e., nonlaboratory) perception-action in response to natural (i.e., nonreductionist) stimuli. This research has demonstrated the existence of neurons (for example) that react to high-order, low-dimensional patterns in ambient energy (e.g., Camhi 1984; Saito et al. 1986; Tanaka & Saito 1989). This research has been conducted in the context of single-energy arrays. As stated briefly in the target article (sect. 6.2.4) and in several commentaries (**Wade; Kujala,** and others), new research of this kind is needed that is specifically designed to permit empirical contrasts between neurophysiological sensitivity to structures in the global array, as opposed to sensitivity to structures in single-energy arrays.

## R2. Ecological psychology: General issues

Several commentators raise questions that are relevant to the ecological approach to perception and action, in general, rather than to our analysis of the global array, in particular (e.g., **Ahrens; Feldman & Lestienne; Oie & Jeka; Pallas**). As noted in section 1 of the target article, the ecological approach is an established theory with a well-developed set of principles (see e.g., Goldfield 1995; Michaels & Carello 1981). These often differ in fundamental ways from the principles that guide more traditional theories of perception.

A common misconception is that the ecological approach rejects the possibility that perception may be influenced by or dependent upon mental activity. Internal, experience-dependent influences on perception and action are an essential fact of life, even in single-celled animals (Pittenger & Dent 1988), and any theory of perception and action must take these into account at a fundamental level (contra **Pickering**). The ecological approach does this, mainly through the theory of differentiation (Gibson 1969; 1988). The question is not whether mental activity exists, or whether mental activity is essential (**Oie & Jeka**). The question is about the nature of mental activity, and this is intimately related to the issue of specificity. If specificity does not exist, that is, if potential sensory stimulation is ambiguous with respect to reality, then mental activity must be inferential (e.g., associative). However, if specification exists then mental activity need not be inferential, that is, it may not be necessary to "process" information in order that perception be accurate. This is the essential distinction. We agree with **Oie & Jeka** that behavior is not always "dominated" by perceptual information, but this is not directly relevant to the issue of whether reality is specified; the existence of specification is not a psychological issue (sect. 1), and cannot be confirmed or rejected on the basis of behavioral experiments. Similarly, specification cannot exist or be created in neural activity (**Mergner & Becker; Peper & Beek**); this would be equivalent to indirect perception on the basis of ambiguous stimuli.

Dynamical systems theory is useful for describing perception-action phenomena, but it is not helpful in resolving the theoretical debate between direct and indirect perception (cf. **Ahrens; Oie & Jeka**). This is because dynamical systems theory is neutral with respect to the directness or indirectness of perception; dynamical descriptions are compatible with either position (e.g., Bardy et al. 1999; Jeka et al. 1998; Kelso 1995).

Researchers have sometimes suggested that it may be possible to integrate ecological and Helmholtzian theories of perception (e.g., **Mergner & Becker;** Wertheim 1994; cf. **Oie & Jeka; Pickering**). We disagree, and believe, along with James Gibson (1966), that the basic premises of the two theories are not reconcilable. The ecological approach to perception and action is incompatible with inferential (i.e., Helmholtzian) approaches. A major reason for this is that specification and non-specification motivate separate and incommensurate theories of perception. If specification exists, then there is not a clear theoretical motivation for the existence of inferential processes (e.g., association) in mentation (**Myin**). Students of neurophysiology often assume that perception begins when energy is transduced at receptors. That this assumption is not only controversial but flatly unnecessary has been argued by ecological psychologists for decades (e.g., E. J. Gibson 1969; J. J. Gibson 1966; Michaels & Carello 1981; Reed 1996).

The division of information pickup into sensation and perception, which is often taken for granted (e.g., **Ahrens**), is in fact a controversial assumption (Gibson 1966; Reed 1996). The fact that stimulation of receptor surfaces gives rise to neural activity does not necessarily mean that the activity is "entirely mechanistic," or that "no meaning is conveyed" (**Ahrens**). The existence and operation of the nervous system does not imply that neurological function and mentation are mechanistic. Similarly, the ecological approach to perception and action explicitly rejects the assumption that knowledge about reality is calculated (**Pallas**).

**Neelon & Jenison** review a common argument that the existence of specification does not explain "the achievement of perception," and we agree. Specification (in the global array or elsewhere) is not a theory of perception but, rather, a fact that has implications for theories of perception (e.g., Runeson & Frykholm 1983). As we noted in section 6.2, if specification exists, then there is no theoretical motivation for invoking "statistical estimation" in order to perceive the world. Similarly, if specification exists in the global array, then there is no theoretical motivation for combining "multiple inputs."

In the target article, we considered the possibilities that specification exists always, or never. **Oie & Jeka** and **Pickering** (see also **Michaels & Oudejans; Runeson et al.**) take a contrasting position, suggesting that specification may exist in some circumstances, but that it is not a general phenomenon (what **Cabe** refers to as "non-absolutist" specification). This may seem tempting, but it is not without problems. As we noted in the target article (sect. 1), the question of specification in ambient arrays is not a psychological question but, rather, a question of ecological physics. Ecological physics is a branch of physics that deals with phenomena on the scale of, and with reference to, actual or potential perceiver-actors. With regard to specification, the question is whether there is a unique relation between aspects of reality and the structure of ambient arrays, as a consequence of the physical laws that govern the generation, propagation, and reflection of energy. Because ambient arrays are part of physics, the hypothesis that ambient arrays are "partially," or "occasionally" specific to reality is equivalent to a claim that the laws of the generation, propagation, and reflection of ambient energy are sometimes in effect,



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but at other times not in effect. More generally, the hypothesis of partial or occasional specification requires some principle that can predict when specification exists, and when it does not. We know of no principled basis for such a claim; **Pickering** and **Oie & Jeka** offer none, and do not cite any. Note that our position does not require that everything be specified at every instant, or at every point of observation. The consequences of this for perception are discussed in section R6.

## R3. Specification in the global array

With respect to specification, the thread of our argument has been nicely summarized (with one exception) by **Cabe:**

> Stoffregen & Bardy discredit all existing perceptual theories, because each allows input conflict (input ambiguity) and therefore implies cognitive (indirect) processes. The syllogism is: If array structures (AS) conflict, then perceivers must choose between alternative world structure (WS) interpretations; choice implies cognitive processing; therefore, input conflict implies cognitive processing. The main focus is intersensory conflict, but any AS ambiguity yields the same conclusion. Because all existing perceptual theories entail such ambiguities, they all entail cognitive processes.

We endorse this summary, with the exception of **Cabe**'s reference to cognitive processes. As we will argue below, the ecological approach to perception and action does not reject the reality of cognitive activity. Rather, the ecological approach rejects the assumption that cognitive activity must be associative, inferential, or computational. This assumption is based, both logically and historically, on the prior assumption that in Cabe's terms, there is ambiguity between world structures and array structures. If, as we argued (sect. 6.2.1), the animal-environment system is specified by structures in the global array, then there would be no theoretical motivation for postulating that mental activity is inferential, associative, or computational.

## R4. Constraints on specification

**Runeson et al.** claim that specification may exist in single-energy arrays, basing their argument on the idea that specification occurs under the influence of different types of constraints. We endorse the general concept of constraints, and agree fully that they are critical to specification. However, their argument ignores our discussion of the independence of physical referents (sect. 4). The independence of different physical referents is a profound constraint on specification. Other types of constraints must be posterior to this, as we argued in section 5. We assume that any evil genius must obey the laws of physics; if not, then the "laws" are not laws, and we must either re-open the search for the actual laws of physics, or abandon the idea that physics is lawful. Runeson et al. ask about nonlinear propagation of light, as if this were hypothetical, when it is known as a fact: The bending of light by strong gravitational fields is a major confirmation of Einstein's theory of relativity. Nevertheless, light, like an evil genius, obeys the laws of physics.

**Runeson et al.** (cf. Shaw et al. 1982, p. 218) place strong emphasis on "natural" constraints. We regard this as a problem, because of the difficulty of defining *natural.* As one example, consider cinema. In the movies, recorded samples of the optic array are reproduced on a screen. One common feature of films is an instantaneous cut between images recorded by cameras in different positions, or by a single camera at different times (Anderson 1996). A cut produces an instantaneous change in the optic array. This type of change is physically impossible outside the cinema, due to the fact that living things have inertia, and so cannot achieve an instantaneous shift from one point of observation to another (Stoffregen 1997). In an evolutionary sense, cuts in film must be grossly unnatural. Yet for millions of contemporary humans, optical shifts of this kind are a commonplace of daily life, and have been essentially from birth, in film, television, home video, computer graphics, and so on. For individuals, cuts in film can be classified as unnatural only if *natural* can exclude *typical,* or *ordinary.* We know of no basis for such an exclusion. More generally, Runeson et al.'s argument is viable only if they can develop a rigorous definition of *natural.*[2]

**Runeson et al.** (see also **Costall et al.;** Michaels & Beck 1995, p. 274), suggest that virtual reality devices, moving rooms, rotating drums, and other such devices cause the optic array to "lose some of its specificity,"[3] and suggest that in such devices perception is illusory or erroneous (this argument appears to apply to the cinema, as well). Each of these assertions can be questioned. We have argued that in these devices reality is specified (i.e., the nature of the devices as simulators, and the content of the simulation) and that this specification exists in the global array (Stoffregen et al. 2000b). We have also argued that this information is picked up; this would account for the ability of users of sophisticated flight simulators (for example) to differentiate the simulation from the actual vehicle (Stoffregen et al. 2000a). We would also argue that success at teleoperation (**McMichael & Bingham**) is possible in part because the fact of teleoperation is specified in the global array. Differentiation of the fact of teleoperation (cf. sect. R6) would allow the user simultaneously to control different parts of the body relative to the distal teleoperation environment and the local gravito-inertial environment (cf. Patterson et al. 1997; Smith et al. 1997). Are people in moving rooms, patrons of the cinema, and users of virtual reality devices really fooled? Can they distinguish motion relative to the illuminated environment from motion relative to the gravito-inertial force environment? In many cases the relevant data have not yet been collected (Stoffregen 1997; Stoffregen et al. 2000a).

## R5. Constraints on the detection of information

Several commentators (e.g., **Brenner & Smeets; Coello & Rossetti; Foo & Kelso; Runeson et al.**), point out that perception is selective, and that ambient arrays are sampled for information that is relevant to particular perceptual-motor goals. We cannot agree more and, as **Myin** notes, we made several references to this in the target article. Our own research has emphasized the task or goal-dependent nature of perception and action (e.g., Bardy et al. 1999; Marin et al. 1999; Stoffregen et al. 1999; 2000b). However, the pickup of information is posterior to the existence of information. As noted in the target article (sect. 1), our argument about the global array is an argument about the information that is available for perception. It is not an argument about the psychology of perception (e.g., when information is picked up by perceivers, or the basis for the



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selective pickup of information). The ecological approach of perception and action has already provided, in varying degrees of detail, explanations and theories of information pickup, including the fact that perception is selective and that selection is based on task-specific criteria (e.g., Gibson 1988). These explanations can be applied to the pickup of information from the global array.

Classically in the ecological approach, what is specified and what is picked up are two different questions, and the second cannot be asked before the first is answered. Similarly, what is picked up and how it is picked up are different questions, but again, the first should be asked before the second. Our contribution deals primarily with the "what": what is specified, and thus, what is picked up.

We also agree with **Coello & Rossetti** that perception and action are inherently related, and that people (and other animals) perceive meaningful properties of the animal-environment system (i.e., affordances, Stoffregen 2000a; 2000b, cf. **Michaels & Oudejans; Walker-Andrews**). The failure to perceive accurately arbitrarily chosen properties of the physical world, such as velocity (Runeson 1974), or brightness (**Oie & Jeka**), may result not from any absence of specification *per se*, but from the experimenter's assumption that these are proper objects of perception (cf. Shaw et al. 1982).

This brings us to the issue of what is specified. We can detect only the information that is available, that is, the information that exists. Thus, ecological theory predicts that we can perceive only those things that are specified. Those things will be specified which structure ambient energy arrays in lawful ways. It may not be the case that this is true of all possible states of the universe (e.g., Runeson 1974; Shaw et al. 1982). This point leads to predictions for perception. It should be impossible to perceive directly things that are not specified. We argued that the global array is structured by aspects of the animal-environment system (sect. 6.1). This statement was deliberately vague, in part because we regard the issue as being beyond the scope of the target article, and in part because it has been addressed elsewhere (e.g., Shaw et al. 1982; Stoffregen 2000a; 2000b). We agree, however, that the issue of what is specified is of fundamental importance (**McMichaels & Oudejans; Riccio et al.**).

## R6. Learning, exploration, and perceptual-motor errors

It is noted by **Cabe** (see also **Pickering** and **Riley**), that some error in perception and action is tolerable. Errors in perception and action exist at all developmental levels (**Adolph et al.**). But the existence of error does not imply a lack of specificity in ambient arrays (contra **Pickering, Riley,** and **Thomas,** inadequate detection does not imply inadequate specificity), and it does not imply what **Cabe** refers to as "non-absolutist specification." As we noted in section 7, errors in perception and action can (and do) arise from failures in the pickup of information. An essential requirement in perceptual motor learning is the differentiation of information that is task-relevant from information that is irrelevant to the task at hand (e.g., **Foo & Kelso; Leighty et al.**). For two reasons, this differentiation takes time.

First, and most important, specification exists in space-time, rather that at any given instant or moment (**Adolph et al.**). Instantaneous or arbitrarily brief structures in ambient arrays may be ambiguous with respect to particular aspects of the animal-environment interaction (**Riccio et al.;** cf. Runeson 1988). Similarly, not everything is specified to any given point of observation. One reason that perception is active is that activity on the part of the perceiver is often necessary in order to generate the information that specifies task-relevant aspects of the animal-environment interaction (e.g., Schmuckler & Tsang-Tong 2000). Second, information pickup takes place in spacetime, and both time and movement are required (e.g., Gibson et al. 1987; Oudejans et al. 1996; Pittenger & Dent 1988; Riccio 1993; Riley et al, 1997; cf. Mark et al. 1990). Thus, the shape of the back of an object may not be specified in the global array that is available to an observer standing in front of it. Similarly, the dynamics of an automobile may not be specified when it is not in operation, regardless of the point of observation adopted by an observer (this is why potential purchasers insist on test-driving a car, rather than merely examining it in the showroom). Perceptual-motor error may result from a failure to pick up accurate information that is available, or from a failure (or inability) to engage in exploratory actions that will generate or reveal the relevant information (**Riccio et al.**). These examples are consistent with the well-documented fact that the accuracy of perception is greatly improved when observers are permitted to engage in exploratory activity. For example, circular vection (the experience of earth-relative egorotation when presented with a rotating optical display) is a frail phenomenon that is dependent upon restraint of the head (cf. sect. R7). Similarly, illusory experiences associated with the Ames distorted room depend almost entirely upon severe restrictions of perceptual exploration (Runeson 1988).

The most general examples are provided by **Adolph et al.,** who describe relations between perceptual-motor error and the growth of differentiation. Their examples are general in at least two senses. First, the situations, perceptions, and actions involved are all characteristic of daily life outside the laboratory. Second, every able-bodied person learns to perceive and control locomotion across a variety of surfaces (as do the young of many other species). Adolph et al. also underline the importance of exploratory behavior (see also the classic study of Held & Hein 1963). How would the perception and control of locomotion develop if infants were restrained?

Perception and action need not be perfect, as noted by **Cabe,** and by **Brenner & Smeets** (cf. **Pickering** and **Riley**). In a Darwinian context, it is necessary only that perception and action be accurate enough to ensure survival. We agree with this, but it is not directly relevant to the issue of specification. Specification is part of the environment in which life evolved. Life came into existence in the context of certain pre-existing aspects of reality, such as rocks, water, and the laws of physics that govern the generation, propagation, and absorption of ambient energy. The existence of specification does not require that perception and action be flawless. Specification guarantees the availability of accurate information, but does not guarantee that the information will be picked up or that, if picked up, it will be used accurately. The example of the "bent stick illusion" proposed by **Riley** is appropriate. In contradiction with his interpretation of the illusion, we do not believe that the light reaching the eye contains "inadequate" information.



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This is because information, as we defined it (i.e., as an objective property of the animal-environment system) cannot be inadequate. As acknowledged by **Riley,** the light reaching the observer's eye contains information about a stick being in water. In this context, what is inadequate is not the information, but the detection of the information (e.g., Michaels & Carello 1981).

## R7. Relative motion

A large portion of the target article concerns relative motion; indeed, it is the fulcrum of our argument against the existence of specification in single-energy arrays (sects. 4 and 5). For this reason, we were surprised that motion relative to different physical referents was not addressed by commentators who argue that specification exists in single-energy arrays (e.g., **Michaels & Oudejans; Peper & Beek; Rosenblum & Gordon; Runeson et al.**). Thus, our argument for the absence of specification in single-energy arrays remains unanswered. The formulation of a response to our arguments about relative motion is a serious challenge for scientists who argue that specification exists in single-energy arrays. In particular, it would be necessary to indicate how structures in, for example, the optic array, could provide information sufficient for the control of action relative to referents that do not structure that array (e.g., motion relative to the acoustic environment, or relative to the direction of balance).

Among all the commentaries only one is concerned with issues relating to relative motion, and for this reason **Wertheim**'s contribution is especially welcome. We acknowledge that many researchers, including Wertheim, try to take into account some of the facts of relativity (Wertheim cites some of the same ones that we cited in the target article). However, in terms of the information available for perception, these researchers generally consider motion relative to a single class of referents, the hypothetical sensory reference frames (e.g., Soechting & Flanders 1992; Wade & Swanston 1991; Wertheim 1994). For example, Wertheim (1981, p. 106) concludes that motion is perceived "relative to the magnitude of . . . extraretinal signals," and he distinguishes between the "perception of motion" relative to sensory reference frames and the "physical determination of motion of an object" (p. 107). Wertheim (1981; 1994), does not discuss or consider the possibility that motion might be perceived directly relative to physical referents. To be sure, motion can be measured relative to the retina, the eardrum, and so on. However, as we noted in the target article, if specification exists, then sensory reference frames can be irrelevant to perception of motion relative to physical referents. This is because specification would allow motion relative to physical referents to be perceived directly, so that sensory reference frames would be unnecessary. This reprises James Gibson's (1966) argument that sensations, while real, are irrelevant to perception (see **Mace,** for an historical treatment).

In the target article (sect. 4.2) we pointed out that the surface of the earth and the earth's gravitational field are distinct physical referents for motion and that, consequently, it is possible to move relative to one while being stationary relative to the other. For this reason, we argued, motion relative to these two referents cannot be equated. We are encouraged that **Wertheim** appears to appreciate these facts of physics, and by his confidence that "no one has ever equated earth relative motion with motion relative to the earth's gravity." However, he did not respond to our quotations from behavioral scientists that appear to reflect just this confusion. Dichgans and Brandt (1978, p.758) equated "orientation with respect to . . . gravity," with "position of object and the observer on the earth surface," and Wertheim himself defined absolute motion as "motion relative to external space [i.e., 3D, Newtonian space, as defined by the horizontal surface of the earth and its gravitational field" (Wertheim 1994, p. 302)]. Moreover, in his commentary he defines a reference frame "dimensioned by the earth's surface and the direction of gravity." We are at a loss as to how Wertheim's statements can be reconciled.

As a matter of empirical practice, experimenters rarely define for the experimental subject the frame of reference to be used in making judgments about motion (e.g., Brandt et al. 1973; Ohmi et al. 1987; Wong & Frost 1978). For example, in Wertheim (1981, p. 102), subjects were asked to rotate a potentiometer to indicate that they perceived a stimulus to be moving or stationary, but there is no indication that subjects were given any instructions as to the referents for these judgments (i.e., moving and stationary relative to what?).

**Wertheim** points out that when exposed to optical flow rotating around an axis parallel to earth gravity, experimental participants experience an illusion that they are rotating relative to the earth. We acknowledge the existence of this illusion. However, our interpretation of it differs from Wertheim's. He treats it as a basic perceptual phenomenon, and used it as a building block for a general theory of the perception of object motion (Wertheim 1994). In our view (cf. sect. 7), this illusion is a superficial experience that results from the participant's inability to engage in normal perceptual-motor exploration (that is, to engage in movements that will create the relevant specificational structures in the global array). The illusion is possible because of a highly conditional ambiguity in potential sensory stimulation (cf. sect. R6). As we indicated in the target article (sect. 4; cf. Dichgans & Brandt 1978; Stoffregen & Riccio 1988), potential sensory stimulation is identical during constant velocity motion of the self relative to the gravito-inertial force environment and relative to the illuminated environment. For this reason, these situations are fundamentally indistinguishable. However, potential sensory stimulation during motion relative to these two referents is not the same when there is acceleration. This explains the fact that the illusion of bodily rotation relative to the earth is robust only when acceleration is prevented, for example, when the head is subjected to passive restraint (e.g., Brandt et al. 1973; Ohmi et al. 1987; Wertheim 1987). The illusion is eliminated by head movements, and is often suppressed even by eye movements (e.g., DiZio & Lackner 1986). Similarly, it is largely because subjects in moving rooms are not restrained that we suggested that their perceptions may be veridical (sect. 5.2).

In the target article we argued for the independence of different physical referents for motion, and we proposed that different aspects of behavior might be perceived and controlled simultaneously, relative to different physical referents. Recent research has demonstrated simultaneous differential control of the head and body with respect to independent, referents (Patterson et al. 1997; Smith et al. 1997). During simulated visual flight maneuvers (i.e., turns when the aircraft was controlled by looking out the win-



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dows), pilots tilted their heads (relative to the torso), so that the head remained aligned with the horizon, while simultaneously they controlled the torso so that it remained aligned with the aircraft as the latter rotated relative to the horizon. In each case, the referent chosen for the control of orientation was task-specific: Aligning the head relative to the horizon made it easier to monitor aircraft altitude relative to the ground, while aligning the body relative to the aircraft minimized the effort required to control bodily orientation. Changes in the task yielded changes in the referents for control (cf. **Coello & Rossetti; Foo & Kelso; Runeson et al.**): Under instrument flight conditions, pilots maintained head alignment with the vertical axis of the aircraft (i.e., with the vertical axis of the instruments that they were reading).

## R8. Specification in single-energy arrays

Several commentators (mainly, students of the ecological approach to perception and action) argue for the existence of specification in single-energy arrays (e.g., **McMichael & Bingham; Michaels & Oudejans; Peper & Beek; Rosenblum & Gordon; Runeson et al.**). James Gibson (1966) endorsed two positions, as noted in our sections 3.3.2 and 6.1. On the one hand, he argued for amodal specification, while on the other, he described a structure in the global array. We have argued that these positions are mutually exclusive. Ecological theory must either accept our conclusion, or explain how the two positions presented by Gibson can be reconciled. The ecologically-oriented commentators did not directly address this (though **Runeson el al.** appear to reject Gibson's claim that somatosensory stimulation, taken in isolation, is ambiguous with respect to body sway).

In addition, these commentators (together with **Thomas**) present arguments that do not acknowledge or take into account the fact of the constant, simultaneous stimulation of multiple perceptual systems (sect. 1). Much of this multimodal stimulation is critical for the perception and control of the body and its parts (e.g., head, hand). This stimulation is not ignored, that is, it is easy to demonstrate that it influences the control of the body (e.g., Berthoz 1993; 1997). One implication of this is that any given parameter existing within a single type of ambient energy is never either the sole stimulus, or the sole information that is picked up. If specification did exist in single-energy arrays (a point which we continue to dispute), this would still leave open the issue of how the animal deals with the fact of constant, simultaneous stimulation of (and pickup of information from) multiple perceptual systems. We have argued that this can be accommodated in an ecological theory only within the concept of the global array (i.e., cooperative pickup of global structures); anything else implies internal, inferential "integration," or comparison (e.g., **Feldman & Lestienne**). Defenders of specification in single-energy arrays did not address this issue.

Generally, commentators who defend the hypothesis of specification within single-energy arrays do not address our arguments about the assumption of separate senses (e.g., **Runeson et al.; Neelon & Jenison**), that is, they offered no argument why this assumption should be retained (cf. **Thomas**). In the target article, we provided mathematical examples of structures in the global array that provide information which is not available in the structure of the constituent single-energy arrays. One of these (Eq. 1) was taken from the work of Peper et al. (1994), while another (Eq. 2) was taken from the work of Bingham and Stassen (1994). In arguing for the existence of specification in single-energy arrays, neither **Peper & Beek** nor **McMichael & Bingham** refer to these examples, which nevertheless appear to support our position.

## R9. Falsifiability of specification and ambiguity

**Cabe** (see also **Runeson et al.**) raises the question of whether specification is a falsifiable concept. At the level of individual parameters the concept of specification is not falsifiable; it is always possible to argue that some other, unidentified parameter has the specificational relation. Runeson (1988) made essentially this argument. Similarly, any claim of specification can be voided by a single exception (for instance, the claim of **Burton,** and **Costall et al.,** that pheromones are specific to particular insects is voided by the fact that pheromones can be presented in the absence of the insects, as in pesticides or perfumes). This argument applies to any version of the concept of specification; it is not peculiar to the possibility of specification in the global array. However, the disproving of an instance does not disprove the general concept, because a thing that is not specified by one parameter might be specified by some other one. When one candidate fails, it may be incumbent for researchers to look for another candidate, rather than to conclude that specification does not exist. The problem with this is that no matter how many candidate parameters are falsified, it is always possible that some other, as yet unknown candidate will do the job (Runeson 1988). This is similar to the problem, in inferential theories, with the claim that perception and/or cognition are based on mental calculations or any other inferential process. Whenever it is demonstrated that a given calculation or inference is either unnecessary or counterproductive (e.g., **Mark**), it is always possible to claim that, rather than being direct, some other inferential calculation is being executed. We acknowledge that, at this level, this is a problem for the concept of specification and, thus, for any theory of direct perception. However, scientists who do not accept direct perception theories should be equally rigorous in acknowledging that the same problem applies to the falsifyability of theories of indirect perception.

While specification and ambiguity appear to be unfalsifiable at the level of individual parameters of ambient energy, we believe that the issue of falsifiability extends beyond this level. The concept of specification may be falsifiable at the larger level of general principles. If the laws of physics are general and are in fact laws, then it may be possible to argue that specification, which is a consequence of these laws is as real and valid as the laws themselves. Specification, then, would be falsifiable in the same sense that laws of physics are falsifiable. The concepts of inferential calculation, association, or other processing are wholly psychological, making no appeal to physical reality and thus may be fundamentally resistant to falsification.

Several commentators (**Brenner & Smeets; Michaels & Oudejans; Runeson et al.; Riley;** see also Michaels & Beek 1995) suggest that some parameters of potential sensory stimulation are partially or totally nonspecific to real-



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ity. With respect to the global array, we disagree. We accept the claim that a parameter may not specify the particular aspects of reality that concern the authors, but we point out that the same parameters may specify something else, that is, some other aspects of reality. If this is the case, then it may be that all parameters of the global array are specific to some aspects of reality. While any given parameter *A* may not be specific to any particular aspect of reality *X,* it may well be specific to some other aspect of reality, *Y* (**Michaels & Oudejans**). This leads us to predict that subjects will perceive *Y.* This could be a problem if the experimenter assesses only the perception of *X;* when *X* is not perceived, the experimenter may (incorrectly) conclude that perception was erroneous and, hence, that *A* did not specify anything. This possibility reinforces our recommendation that experimenters be cautious in evaluating perceptual reports as being "right," or "wrong" (sects. 5.2 and 6.2.6).

## R10. Amodal specification?

**Mace,** together with **Costall et al.** and **Vereijken & Whiting,** describe the history of the term *amodal.* We accept these historical accounts. Our discussion of the hypothesis of amodal specification, however (sect. 3.3.2), is drawn from the contemporary literature, which may diverge from the historical sources.

The assumption that stimulation is redundant across perceptual systems is widespread, extending beyond the concept of amodal specification. For example, redundancy is commonly assumed by students of intersensory interaction (e.g., **Mergner & Becker**), by researchers who study perception and action in simulators and virtual environments (e.g., Kennedy et al. 1990), and in the literature on motion sickness (e.g., Oman 1990). A serious problem with the concept of amodal specification is that redundancy across any two single-energy arrays is rare (contra **Flom & Bahrick; Rosenblum & Gordon,** and **Mergner & Becker;** for an extensive discussion and list of examples, see Stoffregen & Riccio 1991). We noted that the amodal specification view has not addressed the consequences of nonredundant relations among single-energy arrays (sect. 3.3.3). Commentators who support the concept of amodal redundancy (e.g., **Flom & Bahrick; Lewkowicz & Scheier; Rosenblum & Gordon; Vereijken & Whiting**), did not respond to this problem. Focusing exclusively on cases that appear to exhibit amodal redundancy is not likely to lead to a theory of perception that is general.

Our view of amodality resembles James Gibson's view of static perception. "Static" perception is not opposed to "dynamic" perception. It is a specific case (i.e., the limiting case) of perception. Similarly, we believe that redundant relations among single-energy arrays are limiting cases of nonredundant relations among single-energy arrays. They exist, that is, there are a few situations in which the pattern in one single-energy array is isomorphic with the pattern in another single-energy array (e.g., **Flom & Bahrick**).[4] But these redundancies may be irrelevant to perception, if perceivers are directly sensitive to the global array. Amodal redundancy in single-energy arrays corresponds to a pattern in the global array which may be detected. This would differ qualitatively from picking up separate patterns in different single-energy arrays, and then (internally) determining that they were (or were not) redundant.

An analogy can be made to the difference between geometric figures and the lines that they comprise. A triangle, for example, comprises three lines, but a triangle is more than three lines; it is three lines forming a closed figure. In our analogy, each line can represent the stimulation available to an individual perceptual system. If specifications exists only in single-energy arrays, then perception of the triangle, as such, would require the separate perception of each line, followed by some form of internal process that would "recover" the fact of triangularity (that is, permit the perceiver to differentiate "three lines forming a triangle," from "three parallel lines"). Amodal redundancy would occur when the three lines were of equal length (the resulting figure would be an equilateral triangle). By contrast, the pickup of information from the global array would be akin to perception of the triangle as such, that is, perception of a three-sided closed figure. Perception of this kind would not require that triangularity be "built up" through the integration of separately perceived lines. Moreover, equilateral triangles are not "special" in the sense that amodal information is thought to be special. If triangularity is perceived as such, then equilateral triangles need not have any privileged status (as is often attributed to amodal redundancy); they are just another type of triangle. Similarly, if perception is based on the pickup of information in the global array, then patterns that correspond to redundancy at the level of individual perceptual systems would have no special status, and would be neither easier nor harder to detect than any other patterns in the global array.

**Walker-Andrews** understands that the global array differs qualitatively from putative amodal specification. The global array makes it possible, in principle, for perception to be accurate without any comparison of the activity of distinct perceptual systems. As Walker-Andrews notes, perception based on the global array depends upon sensitivity to higher-order patterns, and not upon comparisons between modalities.

## R11. Dimensionality of the global array

**Hughes** and others (e.g., **Burton; Costall et al.; McMichael & Bingham; Peper & Beek; Pittenger**) raise important questions about the dimensionality of the global array. They argue that there are a variety of different global arrays, each having a different number of dimensions, that is, each including a different constellation of types of ambient energy. This argument is based on the facts of sensory loss. **Hughes** argues that blind people, for example, are exposed to a different global array than sighted people, with one global array including optics while the other does not. We disagree. The arguments of **Hughes, Burton, McMichael & Bingham,** and **Peper & Beek** suggest a confusion between the existence of information, on the one hand, and the sampling or pickup of information, on the other. This is clear in Burton's question about how many perceptual systems are necessary to have a global array, and in **McMichael & Bingham**'s suggestion that sensory attenuation or absence can influence the structure of the global array. The global array is not made up of perceptual systems; it is made up of patterns of ambient energy that may be *sampled* by perceptual systems. There is only one global array. It includes relations among all forms of ambient energy.



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Different perceivers sample different parts of the global array, depending on their needs, interests, and abilities. This is well understood in the context of single-energy arrays. To maintain the context of sensory loss, consider persons who are color blind. They are not sensitive to the full range of frequencies sampled by the normal human eye, yet no one would suggest that color blind people are exposed to an optic array that is any different from the one sampled by the color sighted. There is only one optic array, which is sampled differently by the color blind and the color sighted. Variations in frequency of light are related to the colors of things in the world. Color blind people cannot pick up this particular type of information, and for this reason often do a poor job of controlling their behavior with respect to the color of things. Similarly, there is only one global array. It is sampled differently by people (and species) having different perceptual capabilities. Animals without functioning visual systems (e.g., moles, earthworms, and blind people), will be exposed to the global array, just like other animals. These animals cannot detect or control behavior relative to the illuminated environment, but that does not mean that they are unable to sample the global array. The example of moles and earthworms is important because it illustrates the close functional relation that exists between the capabilities of action and perception systems. As noted in the target article (sect. 6.2.3), the ability of moles and worms to sample the global array is entirely adequate for them to achieve adaptive behavior. That is, these animals can perceive their behavior and control it relative to the same subset of physical referents. In general, each species and each individual can detect certain portions of the global array, which enable it to perceive and control its actions relative to a certain set of physical referents. This explains why blind people walk differently from sighted people: The blind cannot perceive (or control) motion relative to the illuminated environment.

## R12. Research methodology

Our theory will succeed to the extent that it can inspire useful research (as noted by **Pallas;** *cf.* **Leighty et al.; Pittenger; Riley**). In discussing the conduct of research we focus on three issues.

**McMichael & Bingham** assert that analysis of structures in single-energy arrays is a prerequisite for use of the perturbation paradigm in research on perception, but they offer no argument as to why this should be so. As we noted in the target article (sect. 7; cf. Fouque et al. 1999), the perturbation paradigm can be and has been used in research contrasting the pickup of information from single-energy arrays and from the global array. More generally, perturbation of any single-energy array will simultaneously perturb the global array; this cannot be prevented. The theoretical and empirical question is which of these perturbations is detected by perceivers. This has general consequences for research on perception. When an experimenter employs a manipulation of structure in one or more single-energy arrays, that manipulation will also alter (or perturb) the structure of the global array. Thus, effects resulting from such manipulations could be caused by structure in the single-energy array(s), or by structure in the global array. This is why existing research generally cannot be used to evaluate perceptual sensitivity to the global array or, we would argue, to single-energy arrays.

As noted in the target article (sect. 7; cf. sect. R1), new research (and perhaps new research methods) will be required in order to conduct direct tests of the hypothesis that perceivers detect structures in the global array. **Mark**'s suggestion to use techniques for establishing perceptual independence (Ashby & Townsend 1986) is welcome in this context, and should be pursued.

It is also the case that existing methodologies can be adapted to be relevant. Research should begin with an *a priori* derivation of information, either qualitative or, preferably, quantitative, that exists in the global array. For our example we will use the global array parameter identified by Peper et al. (1994), and discussed in section 6.1 of the target article. Equation 1 relates to a situation in which a person must extend the hand laterally (relative to the torso) in order to catch a ball. The relation between optics and haptics expressed in Equation 1 is specific to the affordance for interception (that is, to the hand velocity needed to move the hand to the right place at the right time to make the catch). Neither optics alone nor haptics alone provides the needed specificity.

There is an analogy between the relation of ball movement and hand movement, in this situation, and the relation between distance and velocity in time-to-contact. Time-to-contact is a consequence of the relation between distance and velocity, but it is not necessary to perceive either distance or velocity in order to perceive time-to-contact. It is sufficient to perceive the higher-order relation between the two.[5] McLeod and Ross (1983) and Schiff and Detwiler (1979) tested the hypothesis that knowledge about time-to-contact might be derived from mental calculations based on perceived distance and velocity, as opposed to being based on direct sensitivity to time-to-contact. Subjects viewed films depicting impending collision with the viewer. The films ended before collision, the subjects' task was to indicate when the collision would have occurred. The results in each study were consistent with direct perception of time-to-contact, and inconsistent with calculation of time-to-contact from independent percepts of distance and velocity.[6] If it is possible to perceive time-to-contact without perceiving either distance or velocity, then it may be possible to perceive the required velocity of hand displacement without perceiving, either time-to-contact, or current hand position. That is, in terms of Equation 1, it may be possible to perceive the left-hand side of the equation without having distinct sensitivity to the separate terms of the right-hand side.

Experiments can address this question empirically. Here, we propose one such experiment. As in the experiments of Peper et al. (1994), subjects would be instructed to catch balls that approach at an angle to the line of sight (i.e., so that the arm must be extended laterally, relative to the torso, in order for catching to occur). Catching would require the subject to adapt $V_h$, the lateral velocity of the hand, to the ratio between the instantaneous sideward ball-hand distance and $\tau$, the optical parameter related to time-to-contact.

The essential manipulation would be to vary the values of the optical and haptic parameters in Equation 1, but to do so simultaneously in such a way that the required velocity of the hand would not change. The $\tau$ parameter could be manipulated using the deflating ball paradigm (e.g., Savelsbergh et al. 1991), and $X_h$ could be manipulated by changing the perceived direction or location of the arm through the manipulation of eigenvectors of its inertia tensors (e.g.,



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Garrett et al. 1998; Pagano & Turvey 1995; Riley & Turvey, in press; Turvey 1996). The crucial manipulation would be to combine a later (perceived) arrival of the ball (by deflating the ball during its approach) with a closer (perceived) location of the hand. These manipulations could be combined so that they co-varied, that is, so that the value of Equation 1 remained constant across the variation in its constituent parameters. When this was the case, we would predict that catching (and, by implication, hand velocity) would be accurate (that is, that subjects would respond on the basis of the constant value of the global array parameter), despite the fact that $\tau$ would not be specific to time-to-contact and $X_h$ would not be specific to hand position. That is, the manipulation would produce an overestimation of the place of contact if subjects relied on the haptic information only, and an overestimation of time-to-contact if they relied on optical information only. Specific predictions (both quantitative and qualitative) could be made in situations like this to validate the use of global array in ball catching, and, more generally, in the perceptual guidance of action.

## R13. Concluding remarks

Is the animal-environment interaction specified in patterns of ambient energy? As emphasized by many of the commentators, the answer to this question is central to any theory of perception and action. We have argued that specification does not exist, and cannot exist, in patterns that are confined to any single form of ambient energy. This is due to the facts of motion in a relativistic universe. As reinforced in our response, behavior is controlled relative to many physical referents that are independent of one another, so that motion relative to one referent may be independent of motion relative to another. Crucially, motion relative to any given referent often does not create or alter structure in all forms of ambient energy. This means that, as a matter of physics, it is not possible for the structure of pattern in any given form of energy to be uniquely related to an animal's motion relative to the physical environment. If scientists assume that each form of ambient energy constitutes a qualitatively distinct "input" to perceptual systems, then the absence of specification in single-energy arrays would preclude any theory of direct perception, and would require that theories of perception include some mental mechanism that could "recover" information about reality from impoverished or nonspecific stimulation.

We have presented a very different view of the stimulation available to perceptual systems. We have pointed out that forms of ambient energy, while they differ qualitatively, do not exist independently. Just as there is structure *within* any given form of energy, there also is structure *across* or between forms of ambient energy. We have argued that these multi-energy patterns, which make up what we call the *global array,* are uniquely structured by the animal-environment interaction. If this is true then specification exists, and it is possible, in principle, for perception to exist, to be direct, and to be used (through exploration, differentiation, and learning) in the guidance of adaptive action.

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NOTES

**1. Pailhous et al.** believe that our position is that pickup of information from the global array is "localized in associative areas." This is not our position.

**2.** The same problem applies to **Wade,** who discounts examples that we drew from vehicular travel as being "artificial." Humans (together with their domesticated animals) have routinely traveled using vehicles, such as ships, for thousands of years. To refer to vehicular travel as artificial begs the definition of the term. Note that we do not claim that everything is natural; rather, we stress that the distinction between natural and unnatural or artificial is meaningful only if it can be defined.

**3.** This suggests that **Runeson et al.** may endorse the concept of partial or occasional specificity (sect. R2).

**4.** Amodal redundancy may be less common than is supposed by supporters of the amodality view. Consider speech, which is often thought to give rise to redundant patterns in optics and acoustics (e.g., **Rosenblum & Gordon; Walker-Andrews**). The acoustic waveform that reaches the ears is structured by the activity of several anatomical structures, including the lips, tongue, jaw, and larynx. The tongue is often not visible, or only partially visible, and the larynx is never seen. This means that the visible part of speech (e.g., movements of the lips and jaw) corresponds to only a portion of the acoustic waveform. In other works, the acoustic and optical patterns are not identical; they are not amodally redundant.

**5.** For similar reasons, the hypothesis raised by **Brenner & Smeets** that detecting information in the global array should take more time than in single-energy arrays may not be correct. It may well be the case that the detection of higher-order relations (within- or between-energy arrays) take less time than the detection and combination of their constituent parts.

**6.** Estimates of collision time were strongly correlated with collision time as depicted in the films, but tended toward underestimation of collision time. This might suggest that perception of time-to-contact was inaccurate and, therefore, not based on the (nominally accurate) information available in the stimulus films. An alternative interpretation of the underestimates is that they are artifactual results of the use of a paradigm in which subjects made judgments, rather than using perception to control action. This is supported by the extraordinarily precise levels of timing that are regularly observed in research on the control of interceptive action (e.g., Bardy & Laurent 1998; Bootsma & van Wieringer 1990).

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