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How do animals get about by vision? Visually controlled locomotion and orientation after 50 years

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James Gibson's 1958 paper, "Visually controlled locomotion and visual orientation in animals," was a milestone in his development of a theory of perception that would do justice to ordinary behavior in natural environments. In particular, it provided the first statement of an information-based approach to perception and action, which continues to influence much contemporary work in humans, animals, and robots. In this comment, I discuss the context for Gibson's evolving ideas about perception and offer a brief status report on his theory of visual control.

At mid-career (he was 54 when the article appeared), Gibson's thinking was driven by an enduring puzzle. Since the time of Bishop Berkeley, perceptual theory had been based on a distinction between sensation and perception, one still enshrined in today's textbooks. Sensory processes were direct physiological responses to proximal stimuli, whereas the perception of distal objects demanded further processes of construction, inference, or interpretation. Through his studies of aircraft pilots during the Second World War, Gibson (1947, 1950) came to believe that this account could not explain the success of everyday perception and behavior – in a word, how animals get about by vision.

The elements of Gibson's emerging solution are evident in the 1958 article. First, he replaced elementary stimuli with higher-order patterns and transformations in the stimulation available to a moving eye, which he termed the *optic array*. Just as the retina evolved to register light, so the visual system evolved to register spatio-temporal patterns of light, and subsequent findings in single-cell neurophysiology have indeed borne this out. The crux of Gibson's solution is the claim that these higher-order patterns uniquely specify the environment under ecological conditions, and thus constitute information about it. In particular, he proposed that *invariants* in the flux of stimulation specify constant properties of objects, whereas families of continuous *transformations*, or optic flow patterns, guide behavior. These insights continue to have deep significance for object perception (Koenderink & van Doorn, 1992; Lappin & Craft, 2000; Perotti, Todd, Lappin, & Phillips, 1998) and visual control (Pepping & Grealy, 2007; Warren, 2004).

Second, in the 1958 article Gibson began to reconceptualize the physical environment in behaviorally-relevant terms, that is, in terms of what it *affords* for action. Rather than perceiving space, an animal perceives possibilities for behavior – paths for walking or climbing, barriers, openings, and falling-off places, objects that afford eating, mating, danger, obstacles, or shelter. Given that these environmental entities are constituted by combinations of properties (edges, shape, texture, color, material composition, biological motion) and that such combinations are specified by higher-order optical patterns, Gibson argued that affordances can be perceived (see also Warren & Whang, 1987; Mark, 1987; Adolph, 2005). Matters of meaning and value were thereby smuggled into the domain of perception: animals perceive aspects of the environment that matter for their behavior and survival.

At this stage in his thinking, Gibson was still struggling to salvage an increasingly creaky behaviorism. He sought an “S-R theory of identifying reactions,” in which the stimuli are goal-objects and the responses are acts, and a complementary “S-R theory of control reactions,” in which the stimuli are optic flow patterns and the responses are locomotor behaviors. But Gibson was aware of the limitations of this framework. He couched visual control in terms of the new cybernetics, subsequently realized that one object may have multiple affordances and support many acts (1979), and concluded that the optic array provides not stimuli but information that can be selected for a particular purpose: “Perception is not a response to a stimulus, but an act of information pickup,” (1979, pp. 56–57). This led Gibson (1966) to reconsider the senses as active perceptual systems that seek out and attend to higher-order information. Commentators often associate Gibson with a “bottom-up” as opposed to a “top-down” approach to vision, but as he was fond of saying, this dichotomy is pernicious. Rather than a stimulus-driven hierarchy that assembles elementary features into percepts, perceptual systems are integrated networks with upward and downward pathways that extract higher-order information in a task-dependent manner.

This brings us to the third key contribution of the 1958 paper, the *formulae for a theory of visual control of locomotion*. Gibson’s central hypothesis is that optic flow provides information for both the perception of self-motion (*visual kinaesthesia*) and the control of self-motion, so behavior can be functionally specific to the environmental state of affairs. Visual control is circular, in that self-produced optic flow provides “feedback” that is used for subsequent control. The five formulae he articulates are admittedly rather intuitive, and should be treated as empirical hypotheses. With the advent of computer graphics and virtual reality techniques, they are being submitted to experimental test and revision. Let me attempt a brief status report.

- a. *Starting and stopping*: Gibson proposed that to move forward, one should “contract the muscles so as to make the optic array flow outward,” and to stop one should “make the flow cease.” Lee and his colleagues (Lee & Aaronson, 1974; Lee & Lishman, 1975) initially confirmed that human infants and adults indeed stabilize their standing posture by seeking to make the flow cease. A pattern of radial outflow that specifies forward movement induces backward postural sway, whereas radial inflow that specifies backward movement induces forward sway (see also van Asten, Gielen & van der Gon, 1988; Dijkstra, Schöner, Giese & Gielen, 1994; Bardy, Warren & Kay, 1996).

However, subsequent research has demonstrated that things are, naturally, more complicated. In terrestrial animals such as ourselves, postural control is also influenced by somatosensory information from the feet and ankles (Diener, Dichgans, Guschlbauer & Mau, 1984) or even the fingertip (Jeka, Schöner, Dijkstra, Ribeiro & Lackner, 1997), as well as visual information about the distance to surfaces (Paulus, Straube, Krafczyk & Brandt, 1989; Stoffregen, Bardy, Merhi & Oullier, 2004). As Gibson observed in 1958, we live in a sea of information and pick it up in multiple ways.

- b. *Approaching without collision*: Gibson proposed that braking is controlled by “moving so as to cancel the centrifugal flow” at the moment the visual angle of the surface specifies contact. Lee (1976) formally showed that this could be achieved by keeping the rate of change in time-to-contact (τ) near a reference value of -0.5 , and experimental evidence supported the theory (Kim, Turvey & Carello, 1993; Yilmaz & Warren, 1995). Recently, however, Fajen (2005, 2008) has reported data inconsistent with the theory and proposed instead that braking involves keeping the deceleration required to stop within the controllable range, based on the global optic flow rate. Research on this topic thus continues to evolve.

- c. *Steering and obstacle avoidance*: To steer to a goal, Gibson proposed that one move so as to keep the center of outflow within the contour of the target, symmetrically magnifying it; to avoid an obstacle, keep it outside the obstacle's contour, producing skewed magnification. However, there are number of alternative strategies, and the ensuing evidence indicates that humans and animals exploit several of them. First, contrary to Gibson's formula, Rushton, Harris, Lloyd & Wann (1998; Harris & Bonas, 2002) reported that people ignore the optic flow and walk in the egocentric direction of the target. In contrast, Warren, Kay, Zosh, Duchon & Sahuc (2001; Bruggeman & Warren, 2007) found that, in more structured visual environments, reliance on the heading specified by optic flow increasingly dominates, as Gibson suggested. Third, to steer down a corridor, people, like honeybees, equalize the rate of flow on the left and right sides (Duchon & Warren, 2002; Srinivasan, Lehrer, Kirchner & Zhang, 1991). These multiple strategies provide for robust steering control under a variety of environmental conditions. Recently, we have modeled steering and obstacle avoidance as a dynamical system, in which the locomotor path emerges from the agent-environment interaction rather than being explicitly planned (Fajen & Warren, 2003; Warren & Fajen, 2008).
- d. *Pursuit and flight*: Finally, Gibson reasoned that analogous formulae could be used with a moving object, by steering so as to maximize the contour of the prey or to minimize the contour of a predator. But recent research has shown that this is only part of the story. To intercept a moving target, humans, dragonflies, and bats all use a constant bearing strategy: rather than heading directly toward the target, they aim ahead of it by nullifying change in the target's bearing direction in space (Fajen & Warren, 2004, 2007; Ghose, Horiuchi, Krishnaprasad & Moss, 2006; Olberg, Worthington & Venator, 2000; see also Chardenon, Montagne, Buekers & Laurent, 2002; Lenoir, Musch, Thiery & Savelsbergh, 2002). As Gibson proposed, it also appears that the optical expansion or contraction of the target is used to regulate pursuit speed (Warren & Chardenon, 2004). Importantly, the converse strategy is used to avoid a moving obstacle by avoiding a constant bearing direction (Cohen, Bruggeman & Warren, 2008).

The main contribution of Gibson's 1958 paper was to place the problem of visual control on the agenda for psychology and to point out its repercussions for a theory of perception. The fact that animals can successfully get about by vision implies that higher-order information is available to specify the environment and to control action, and that the visual system is designed to exploit it. We are only beginning to understand the implications of these observations for the organization of perception and action.

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