

worth studying. A prerequisite is, however, that we have a good understanding of *what* is being picked up or resonated to – hence Gibson's emphasis on the study of available information for perception.

In rejecting "processing" and other commonly used notions, Gibson seems best to be understood as clearing the field for the introduction of new conceptions of how perception works. To appreciate the viability of the alternative conceptions it is important to realize that a device or mechanism which is sensitive to a higher order property or complex invariant need not be one that does computations over internal representations. As an example, consider measuring the velocity of a vehicle. Following a definition of velocity as displacement per unit time we may take the "rote" computational/representational approach and construct a device which measures distance covered and time elapsed and repeatedly divides one by the other. However, the typical automobile speedometer works in a different way: an electric generator driven by the wheels, providing an output voltage which is a direct analog to the velocity of the car. Nowhere in it is distance or time represented, and nothing like computation is going on.

Generally, as alternatives to computational procedures, one should look for structures whose intrinsic properties and behaviors make them sensitive to that which we want to register. "Smart" mechanisms may thereby be constituted, illustrating the fact that tasks which are complex to describe and understand do not necessarily require complex computational procedures but may be solved by simple special purpose devices (Runeson 1977). "Complexity" is, as it were, in the mind of the beholder, or, more precisely, is a function of the appropriateness of the conceptual structure we are employing. Thus, if perception entails direct mechanisms, it is equally legitimate, and perhaps more intriguing, to find out what principles may enable them to function the way they do. As psychologists we had better not make our participation in the study of perception contingent upon the nature of the sensitivity that constitutes perception. Whatever that nature is, knowledge about it will be psychologically relevant, and psychological methods are indispensable in acquiring such knowledge.

Ullman's addition example is instructively misleading. Because of the assumption that both input and output are in numerical form, a computational solution is dictated. If instead we make the more relevant assumption that the inputs are analog quantities, we can easily imagine noncomputational structures which respond to the sum of the two quantities. And if the input response is logarithmic we obtain the product. . . [See also: Pylyshyn: "Computation and Cognition" *BBS* 3(1) 1980.]

Granted the possibility of direct, smart, perceptual mechanisms, we cannot so far exclude the possibility of computational solutions. The requirement that perceptual mechanisms operate in real time and under severe spatial and power-related constraints may turn out to be an insurmountable barrier for computational models, however (Shaw & McIntyre 1974, pp. 316–19). Generally it seems that the notions of tuning, resonance, and pickup are more specific, and thus scientifically more potent, than the amorphous conceptions of processing and computation. After all, our perceptual systems were designed before the advent of the digital computer, and in our search for useful metaphors we had better not overlook the affordances of "older" fields of technology.

#### Note

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#### Abstract machine theory and direct perception

Ullman, in his attempts to criticize the late James J. Gibson's theory of perception, has erred on two counts. First, he fails to offer anything more than a parody of Gibson's theory by attributing to him a view of "direct" perception and its entailed mechanism which is false and misleading. Perhaps such a straw man provides a more convenient

target for criticism, but it is only a fancy of Ullman's imagination. In addition, or perhaps because of this failure to grasp the issue of directness in perception, Ullman then attempts to criticize the direct approach. But since his blows are aimed at a straw man, they have little relevance to the theory of perception held by Gibson and his followers. Finally, it will be worth noting, with inescapable irony, that the representational/computational account of perception championed by Ullman tends to trivialize the problem of perception by ignoring exactly those issues which Gibson made the central concerns of his ecological approach. Let us now consider the merits of these complaints.

#### Ullman's conception of Gibson's theory is not Gibson's.

There are two Gibsons, the one of over twenty years ago who defined perception as a psychophysical problem of mapping stimuli to percepts (Gibson 1959), and the one of this past decade who defined perception as a function of stimulus information – more precisely, as an experiencing of things in the environment in terms of what actions they afford, rather than a having of experiences or explicit understandings (Gibson 1979). Ullman elects to attack the older characterization of perception and to ignore the more up-to-date one, perhaps because he feels the former fits more nicely than does the latter into the standard cognitive interpretation of abstract machine theory.

Ullman claims that two mappings are involved in direct visual perception: "The first mapping is between various aspects of the environment and some spatio-temporal patterns of the visual array," while "the second mapping is between stimuli and perceptions." Since the first mapping is achieved by physical laws and specifies the domain of inputs to the perceptual system, the crux of the problem of perception must lie in how one interprets the second mapping. But it must be duly noted that this conception of "direct" perception, as the mapping of stimuli into percepts, was such anathema to Gibson that he explicitly denied it. On the contrary, perception, for Gibson, implies a mutuality of animal as both a perceiver of and as an actor in its environment. This view requires a radically different conception of perception from the one proposed by Ullman. It requires a direct (single), bidirectional mapping of environmental information onto behaviors and vice versa – what in mathematics is called a *duality* (Turvey, Shaw & Mace 1978; Turvey & Shaw 1979; Shaw & Turvey, in press; Shaw, Turvey & Mace, in press). By ignoring this reciprocal relation between action and perception, Ullman utterly trivializes the most fundamental problem addressed by Gibson, overlooks the *raison d'être* of the ecological approach, and misses the basic theme of Gibson's last two decades of work. (For example, "How do we see how to do things?" Gibson 1979, p. 1.)

Since we do not doubt that Ullman is a dedicated and competent scientist within his own field, one must be puzzled at his cavalier treatment of Gibson's nearly half a century of work in a related field. Perhaps the fault lies in Ullman's attempt to force Gibson's theory of perception into an unnecessarily narrow conception of machine theory.

**Does perception require "internal" (cognitive) states?** The typical cognitive rendition of perception in machine theory is as follows:  $R(t+1) = F(Q(t), S(t))$ ; where  $R(t+1)$  is the perceptual response (output) which arises at time  $t+1$  as a function  $F$  of some stimulus (input)  $S$  at time  $t$  and some "internal state" of the machine  $Q$  at time  $t$ . Ullman adopts such an interpretation when he argues that a proper understanding of what a person perceives on a given occasion depends not only upon the stimulus input but also upon the current state of affairs of the perceiver – an internal representation. He believes that "internal" states are required to disambiguate those cases in which the same input yields different perceptual effects (as in the case of the Mach illusion example). Ullman's major complaint against what he takes to be Gibson's theory of perception is that it omits the state variable and reduces simply to perception being a function of stimulation, that is,  $R(t+1) = F(S(t))$ .

Two questions might be raised regarding the cognitive interpretation of machine theory: first, is the state-variable  $Q(t)$  a necessary term in all machine descriptions, or might it not be replaced with some other term capable of performing the same *formal* duty? Second, allowing such a state term, or its formal equivalent, need it be given the same *semantic* duty as imputed to it by the cognitive approach, or might it not

be treated as something other than a reified "internal state" which causally mediates perceptual effects? If an affirmative answer can be given to either of the above questions, then Gibson's ecological approach to perception could be accommodated by abstract machine theory, and the cognitive theorists' complaints would be without merit.

Let us assume an animal (machine)  $A$  with some history of interaction with an environment  $E$ , then let  $H(t)$  represent this history of the state of affairs concerning  $A$ 's transactions with  $E$  up to some time  $t$ . This means that  $H(t)$  includes all the effects of  $A$ 's relationship with  $E$ , such as the inputs received, and the outputs afforded. Then, following Minsky (1967), assuming that the (perceptual) state of affairs in which  $A$  participates up to  $t$  constrains its next response  $r_i$  at  $t+1$ , there must be some relation,  $F$ , of the form  $R(t+1) = F(H(t), S(t))$ .

Notice in the above formulation, no state term  $Q(t)$  is needed, in the sense of an "internal" state, which somehow imparts meaning or enriches the input. Rather the term  $H(t)$  refers to the entire history of transactions of the animal with its environment. The reason that this conception of abstract machines is not ordinarily used by computer scientists is that any relation involving an entire history of transaction "would be too hopelessly cumbersome to deal with directly" (Minsky 1967, p. 15). Nevertheless, the most general conception of a machine with a history in no way requires the notion of "internal states,"  $Q(t)$ , but invokes such variables only as a convenience for designing and programming man-made devices, such as computers. For this reason, a computational scheme over  $Q(t)$  (a program) is but a convenient means of providing a device, which has no history in a natural environment, with an artificial "history." The variable  $Q(t)$  has no meaning of its own, except what is derived from the history term  $H(t)$ .

However, even if one adopts this convenience, it is by no means necessary to reify  $Q(t)$  as an "internal state." For, as Minsky (1967) rightly observes, any "internal state" that has no external consequences is irrelevant to the description of a machine's behavior. Since a canonical definition of *machine* need not incorporate such irrelevant states, "it might be better to talk of our classes of histories [internal states] as 'external states'" (Minsky 1967, p. 16).

The fundamental insight suggested by Minsky's observation is that the variables  $Q(t)$  and  $H(t)$  have at least two possible semantic interpretations. Whereas the cognitive interpretation describes them as "internal states," the behavioral interpretation describes them as "external states." This implies that the two views are complementary and, therefore, there must exist commensurate formal characterizations under which the two views possess the same explanatory power. Of course, neither view alone may provide adequate theories of perception. In fact, the ecological approach to perception takes the limitations of both the behavioral and cognitive views as axiomatic, and proceeds upon the assumption that they must be treated jointly and that they entail a mutually defined, integral unit of analysis whose "states" are neither internal nor external. Although it may be useful for methodological reasons to focus temporarily on a single interpretation in isolation, one cannot lose sight of their reciprocal nature without losing something essential.

These issues lie at the very heart, not only of Gibson's theory of direct perception, but also of abstract machine theory. Ironically, cognitive science might come to a better understanding of Gibson through a careful reexamination of its own conceptual foundations.

**Perception as a function of ecological "machines."** From the above argument, it should be clear that what cognitive theorists take to be a necessary presupposition of perceptual theory, namely, the existence of so-called "internal states",  $Q(t)$ , is nothing more than a convenient fiction of contemporary computer science methodology, which allows the programmer, in lieu of evolution and learning opportunities, to provide machines which have no natural histories,  $H(t)$ , with artificial ones. Hence the apparent "indirectness" of perception is but an arbitrary feature, bestowed upon machine models by the semantics of the cognitive approach, which readily disappears under more naturalistic (evolutionary, developmental, and learning) interpretations of machine theory. Still it is, of course, quite fair if, for the sake of the convenience, "cognitive" or other theorists should choose to construct algorithmic models of perceptual phenomena; such programs may provide a useful summary of the complex histories of

animal-environment transactions by which the perceptual systems under study might have become attuned. On the other hand, such theorists should be admonished to be circumspect and not take the "internal state" description fostered by this methodological tool as being a blueprint of the ghostly states of mind – a veritable *deus ex machina*.

If such cognitive (indirect) models of perception are neither formally nor theoretically necessary, then how should one conceptualize perceptual systems in terms of machine theory so as to capture their essential nature, namely, their ability to become attuned in design and function through evolution, development, and experience? Indeed, it is incumbent upon the ecological theorist to provide, so far as is possible, machine theoretic models which are at least as formally precise as those provided by cognitive theorists such as Ullman (1979b). Clearly, ecological theorists have no quarrel with abstract machine theory per se, if it is properly construed so as not to obscure or trivialize the fundamental problems of perceptual theory – for example, how perceptual systems become attuned by their histories.

In closing, to avoid ending on a negative note, let us take a tentative first step toward an abstract machine formulation of Gibson's theory of perception, one that captures the difference between the indirect (cognitive) approach and the direct (ecological) approach. Notice that in the traditional abstract machine conception as given by  $R(t+1) = F(H(t), S(t))$ , there is no necessary reciprocal relation between inputs  $S_i$  and outputs  $R_i$  to express the mutuality of constraint postulated by the ecological approach to exist between perception and action. To wit: the things that an animal perceives constrains what it does, and what an animal does constrains what it perceives. For example, seeing the portal through which I wish to pass guides my locomotion toward it and through it, while every step I take in this regard refashions the optical flow of perceptual information for distance, direction, and rate (Lee 1974). In short, perceptual information has determinate consequences for action, and action promotes informational changes of significant consequence to perception. Hence action enters as a variable into perception no less than perception enters as a variable into action. All of this suggests, moreover, that there is an intrinsic mutual compatibility between an animal and its environment, which is, after all, the fundamental premise of Gibson's theory. As a rough first pass, this mutuality of constraint between the animal, as actor and perceiver, and environment, as acted upon and perceived, minimally requires the following machine theory formulation (cf. Patten 1979):  $R(t \pm 1) = F(H(t), S(t))$  as before and additionally,  $S(t+1) = F(H(t), R(t))$ .

In accordance with the earlier discussion, there is no necessary sense in which any of the above variables should be taken as being "states" in an animal. Rather, the animal as actor/perceiver is more aptly thought of as being functionally defined over the constraints specified by these dual equations. Furthermore, since the environmental terms  $R(t+1)$  and  $S(t+1)$  (the action consequences of perceptual histories and the perceptual consequences of action histories, respectively) directly specify each other, then no "between" variables are causally or epistemically required to mediate this mutual relation. It is for this reason that both action and perception may be said to be *direct* (Shaw & Bransford 1977b). Indeed, animal and environment as physicalistically understood are both functionally defined, in a distributive fashion, over these equations. No animal construed as a psychological entity exists in the nether world *between* the equations; hence there are no formal hooks upon which to hang the ghostly garb of "internal states."

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### What kind of indirect process is visual perception?

**Introduction: historical note.** It is hard to disagree with the main points of Ullman's paper. Even Kant (1781) pointed out, in opposition to empiricist philosophers, that perception requires a "manifold" of sensory data to be *segmented* (to separate objects), *grouped* (to link parts of the same object), *classified* in accordance with flexible schemata (for example, dogs, trees, and polygons come in many