

symbolic capacity are grounded “in the structures and processes that underlie robotic capacity.” (See also Clark, 1987, for relevant commentary.)

This is surely entirely consistent with Ballard et al.’s contention (sect. 5, para. 1) that “deictic computation provides a mechanism for representing the essential features that link external sensory data with internal cognitive programs and motor actions.” It is interesting, given his status as a pioneer symbolist, to note that Newell 1990, pp. 159–60) writes: “one thing wrong with most theorizing about cognition is that it does not pay much attention to perception on the one side or motor behavior on the other. It separates these two systems out.” Newell accepts that the loss from so doing is “serious – it assures that theories will never cover the complete arc from stimulus to response,” but presents it as a regrettable necessity because “the sorts of considerations that go into perception and motor action seem too disparate to integrate.” Ballard et al. do the field a service by indicating how this integration might occur. To the extent that separating perception and cognition is unhelpful, “confusing” the two (the long-standing charge against me) seems an entirely reasonable thing to do.

From double-step and colliding saccades to pointing in abstract space: Toward a basis for analogical transfer

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Abstract: Deictic pointers allow the nervous system to exploit information in a frame that is centered on the object of interest. This processing may take place in visual or haptic space, but the information processing advantages of deictic pointing can also be applied in abstract spaces, providing the basis for analogical transfer. Simulation and behavioral results illustrating this progression from embodiment to abstraction are discussed.

Ballard et al. argue for use of deictic primitives, or pointers to objects in the world, as a means by which the nervous system exploits external structure, extracting data with respect to current points of interest, rather than constructing representations in arbitrary frames. Simulation and experimental work from our laboratory support this position at the embodiment and higher levels, and also suggest how deictic pointers to objects in abstract spaces might provide the basis for analogical reasoning.

Ballard et al. present the oculomotor saccade as a classic example of a deictic pointing mechanism. That the nervous system can prepare more than one saccade during a single reaction time likely reflects the dense temporal organization of visual events in the real world, and highlights the importance of accurate responses to these events. In this “double-step” saccade problem the retinal information that defines the site of the second target with respect to the current eye position or deictic pointer is “invalidated” by the first saccade. The retinal error is effectively an offset defining the movement required to attain a visual target, but the offset is only valid with respect to the pointer, that is the eye position, from which it was specified. Thus, the targeting saccade must start from that position, or the pointer must be updated to account for the intervening change in eye position. Results in “colliding saccade” studies from the Schlag laboratory (Schlag & Schlag-Rey 1990) indicate that this kind of pointer manipulation takes place at a relatively low level, likely in the brainstem. We have recently demonstrated by simulation how such a relatively low level system that compensates for neural transmission delays provides the neural basis for performing double-step saccades, and also explains the colliding saccade phenomena (Dominey et al. 1997a), illustrating an embodiment level computation that

assures reliable interaction between the oculomotor sensor-effector system and the environment.

Although pointer updating that compensates for single eye movements may take place at a relatively low level, we (Dominey et al. 1995a) propose that more complex sequential behavior requires deictic binding manipulation at the level of interaction between cortex and basal ganglia, in agreement with the pointer manipulation scheme suggested by Ballard et al. In this model, a recurrent network corresponding to the primate prefrontal cortex encodes sequential state, and these states are bound to behavioral responses via learning-related plasticity in corticostriatal synapses. The recurrent state system thus maintains an ordered set of pointers whose referents are specified via learning in the corticostriatal synapses.

We studied sequence learning tasks in which a series of spatial targets are sequentially presented and must then be sequentially selected, by choice from among all the targets, in the correct order. We can simulate the task in two conditions: one in which the saccade choice to the current sequence element is made from the location of the previous element (deictic condition), and another in which saccades are made from an arbitrary central fixation (arbitrary condition). Simulation results demonstrate that the deictic condition is more effective in terms of number of trials to learn the task. Why? Consider the sequence ABCBDC in which each letter corresponds to a target in space. In the arbitrary condition, this sequence is ambiguous in the sense that not all elements have unique successors, for example B is followed by C and by D. Hence, the sequence cannot be learned as a set of associations, but requires more elaborate context encoding. In the deictic condition, the required context is explicitly provided by visual input. The sequence is executed as transitions or saccades between elements AB BC CB BD DC, and the ambiguity is removed as all of these transitions are unique. Problem complexity is reduced by use of deictic versus global reference, as the necessary context defining the previous sequence element is provided directly by visual input, rather than from memory.

This system is robust in simulating human and nonhuman primate behavior and neurophysiology results (Dominey 1997; Dominey & Boussaoud 1997; Dominey et al. 1995a), but it fails in analogical transfer in sequence learning, in which deictic pointers must refer to objects in an abstract space. If we define the surface structure of a sequence as the serial order of its elements and the abstract structure in terms of relations between repeating elements, then the sequences ABCBAC and DEFEDF have identical abstract structure (123213) and different surface structures, and are thus isomorphic. Humans learn such abstract structure and transfer this knowledge to new, isomorphic sequences (Dominey et al. 1995b; 1997b) displaying a simple form of analogical transfer. The model learns surface structure, but fails to learn abstract structure. We modified the model to represent sequences in terms of abstract rather than surface structure. Using the same cortico-striatal pointer manipulation mechanism with abstract rather than surface structure pointer referents, the modified model now displays human-like performance in learning abstract structure (Dominey et al. 1995b), and thus can provide the basis for analogical transfer.

A central process in analogical reasoning is the identification of structural isomorphisms between source and target objects or problems (Thagard et al. 1990). This requires the identification of structural relations (abstract structure) in the deictic frame of the source object that can then be mapped into the deictic frame of the target problem. Our simulation results indicate that the manipulation of deictic pointers in sensory (e.g., visual or haptic) domains extends naturally into abstract spaces where the referent objects correspond to abstract rather than surface structures, thus providing the basis for analogical transfer.

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