Bridging Ideomotor Theory and Autonomous Development with Perceptuo-Motor Memory*

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***Abstract*— Ideo-motor theory provides a powerful framework for understanding the goal-directed prospective nature of action and the bi-directional interdependence of action and perception in cognitive systems. Autonomous development, driven by intrinsic motivations and value systems, is another a crucial attribute of cognitive systems. In this paper, we argue that joint episodic-procedural memory, realized as a network of perception-action associations, provides a natural bridge between these two areas by providing the requisite common perceptuo-motor representational framework into which a developmental value system founded on network dynamics can be embedded.**

I. INTRODUCTION

Three issues feature strongly in contemporary accounts of cognition: the bi-directional interdependence of perception and action, the goal-directed prospective nature of action, and the importance of autonomous development. Ideo-motor theory, in contrast to sensory-motor theory, provides a powerful framework for understanding the first two of these issues. Ideo-motor theory asserts that perception and action share a common representational framework and that prospection is effected through internal simulation.

On the other hand, cognitive development, whereby the system expands it repertoire of actions and extends the timescale of its capacity for prospection, is driven by motivations and value systems. The challenge is to design systems that combine both ideo-motor based internal simulation and goal-directed action with a capacity for development.

In this short paper, we argue that joint episodic-procedural memory [1], realized as a network of perception-action associations, is a natural bridge between the two, providing the requisite common representational framework and the basis for a developmental value system founded on network dynamics. As a example, we highlight the potential application of a specific information-theoretic network-based metric of ecosystem growth and development as a value system for cognitive development when deployed with joint episodic-procedural memory.

II. IDEO-MOTOR THEORY

Classical sensory-motor action planning treats actions as reactive responses to sensory stimuli and assumes that perception and action use distinct and separate representational frameworks. The sensory-motor view is one directional in that it doesn't allow the results of later processing to influence earlier processing. In particular, it does not focus on allowing the intended actions to impact on the system's sensory perceptions. This is problematic because there is much evidence that perception and action are mutually-dependent and that perception depends on action just as much as action depends on perception, e.g. canonical visuo-motor neurons [2], mirror neurons [3], [4], [5], motor-primed visual attention [6], [7], [8], and many ways in which embodiment influences perception and cognition [9], [10].

On the other hand, ideo-motor theory [11] views action as the result of internally-generated goals. It is the idea of achieving some intended action outcome, rather than some external stimulus, that drives cognitive behaviour. According to this view, actions are initiated by a motivated agent, they are defined by goals, and they are guided by prospection. The ideo-motor principle is that the selection and control of goal-directed movements depend on the anticipation of the sensory consequence of accomplishing the intended action: the agent imagines, e.g. through internal simulation, the desired outcome and selects the appropriate actions in order to achieve it.

According to ideo-motor theory, agents do not pre-select the exact movements required to achieve a desired goal: they select actions based on intended goals and execute them adaptively. Thus, ideo-motor theory captures an anticipatory idea-centred way of selecting actions and as well as a way of mapping intentions and goals to the concrete adaptive control of movements when executing that action [12], [13], [14].

In contrast to sensory-motor models, ideo-motor theory assumes that perception and action share a common representational framework, such as is suggested in the Theory of Event Coding (TEC) [15] and Object Action Complexes (OACs) [16], both of which aim to provide a coupling of the perceptual and motor aspect in a joint perceptuo-motor representation. Because ideo-motor models focus on goals, and because they use a common joint representation that embraces both perception and action, they provide an compelling explanation of why cognitive agents, humans in particular, are so adept at imitation and predisposed to it [17]. (when an agent sees another agent's goal-directed actions and their consequences, the representations that would produce the same consequences are activated in the first agent, provided there is a common perceptuo-motor framework).

Goal-directed action, also known to as the goal trigger hypothesis [15], is a centre-piece of ideo-motor theory. However, to have intentions and goals, an agent must be capable of prospection.

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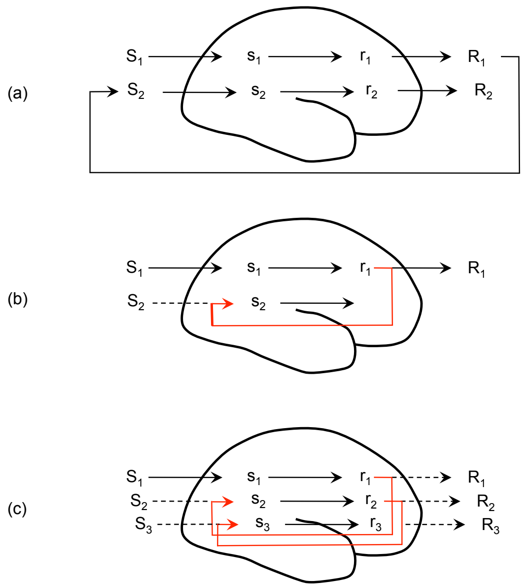

Fig. 1. Internal simulation. (a) stimulus S_1 elicits activity s_1 in the sensory cortex. This leads to the preparation of a motor command r_1 and an overt response R_1. This alters the external situation, leading to S_2, which causes new perceptual activity, and so on. There is no internal simulation. (b) The motor command r_1 causes the internal simulation of an associated perception of, for example, the consequence of executing that motor command. (c) The internally simulated perception elicits the preparation of a new motor command r_2, i.e. a covert action, which in turn elicits the internal simulation of a new perception s_3 and a consequent covert action r_3, and so on (redrawn from [21]).

III. PROSPECTION

Prospection refers to the internal simulation of future possibilities by a cognitive agent and it plays a key role in cognition [18]. Internal simulation is often cast entirely in terms of memory-based self-projection [19], [20], i.e. using recombinations of episodic memory to pre-experience possible futures and project into the experiences of others. However, since action also plays a significant role in our perceptions so too does it play a role in internal simulation [21], [22], [23], [24].

Hesslow's *simulation hypothesis* [21], [23] is perhaps the most influential theory of internal simulation. It builds on three premisses, for which there is an increasing amount of neurophysiological evidence [25]. First, the regions in the brain that are responsible for motor control can be activated *without* causing bodily movement: this allows for simulation of actions (often referred to as covert action or covert behaviour). Second, perceptions can be caused by internal brain activity as well as external stimuli: this allows for simulation of perceptions. Third, the brain has associative mechanisms that allow motor behaviour or perceptual activity to evoke other perceptual activity: this allows simulated actions to evoke perceptions that are like those that would have occurred if the actions had actually been performed. Taken together, the simulation hypothesis suggests that the brain can simulate extended perception-action-perception sequences whereby covert action elicits simulated perceptions, which in turn evoke further covert simulated action, and so on (see Fig. 1).

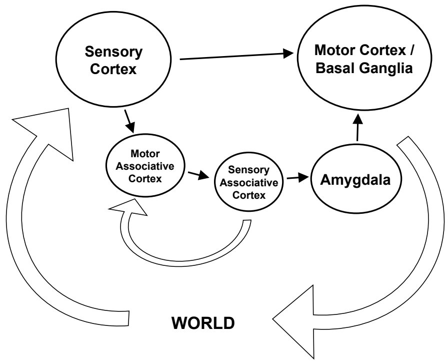

Fig. 2. The Global Workspace Theory cognitive architecture: achieving prospection by sensori-motor simulation (redrawn from [26]) The internal loop comprises two associative cortex elements which carry out off-line simulations of the system's sensory and motor behaviour, respectively. The first associative cortex simulates a motor output while the second simulates the sensory stimulus expected to follow from a given motor output.

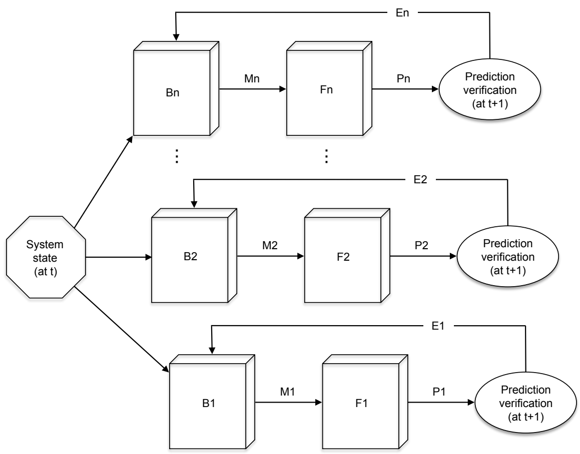

Fig. 3. The HAMMER architecture, showing multiple inverse models (B1 to Bn) taking as input the current system state, which includes a desired goal, suggesting motor commands (M1 to Mn), with which the corresponding forward models (F1 to Fn) form predictions of the system's next state (P1 to Pn). These predictions are verified at the next time state, resulting in a set of error signals (E1 to En). Redrawn from [27]. See also [28] for an alternative rendering of the HAMMER architecture.

Internal simulation is an increasingly important element of cognitive architectures, e.g. Shanahan's global workspace theory (GWT) cognitive architecture [29], [30], [26], Demiris's HAMMER architecture [27], [28], and Kawamura's ISAC cognitive architecture [31]. However, these models of internal simulation are very often effected through paired systems that form perception-to-action mappings and action-to-perception mappings (e.g. see Figs. 2 and 3). We will consider the significance of this in Section V.

IV. AUTONOMOUS DEVELOPMENT

Development — the process whereby cognitive capabilities emerge, consolidate, and combine to produce an embodied agent capable of flexible anticipatory interaction — is a key aspect of cognitive systems, in general, and cognitive robots, in particular [32], [33]. Development arises from dynamic interaction with the environment and results in new forms of action and predictive control of these actions: anticipating the outcome of actions as well as anticipating the need for them in the first place.

To act effectively, an agent must be able to infer upcoming events. Here again we see the importance of prospection and, in particular, the establishment of prospective control of these movements in the context of the goals of an action [34], [35]. Development, particularly the prospective aspect, is accelerated by internal simulation, i.e. mentally rehearsing — consciously or subconsciously — the execution of actions and inferring the likely outcome of those actions.

As we have have noted already, a cognitive agent's actions are guided by prospection and directed by goals. They are also triggered by affective motives [36]. However, not only are actions modulated by motivation, but development itself is driven by these same motives. Significantly, these motives are not task-specific; instead they modulate the affective state of the system and, indirectly, the actions in which it enagages [37]. In turn, these motivations reflect an inherited intrinsic value system that constrains behaviour, with actions being selected based on the motivations that manifest the value system [38] (e.g. actions that lead to the greatest decrease in the mean error rate of the system's predictive learning mechanism [37]). From this perspective, the value system "mediates the saliency of environmental stimuli" yielding an intrinsic motivation system that signals the occurrence of important events and triggers the formation of goals which are then acted upon by a behavioural system [39]. However, value systems focus not only on behavioural autonomy but also on constitutive autonomy [40], [41]. That is, they include internal events in the state of the agent, specifically to maximize the potential for development of that system and thereby maintain and enhance the agent's autonomy. This mirrors the concept of a self-aware self-effecting (SASE) agent [42], [43], [44] that incorporates mechanisms for self-modification.

V. JOINT EPISODIC-PROCEDURAL MEMORY

Let us now consider a way to bridge ideo-motor theory and autonomous development. What is needed for development in a cognitive agent that is modelled on ideo-motor theory is a common representational framework for perception and action that can support development through the application of the intrinsic value system, while at the same time facilitating internal simulation and goal-directed action. We suggest that joint episodic-procedural memory [1] may provide this bridge.

The core idea in joint episodic-procedural memory is to unwind the temporal and causal relationships between specific perceptions and actions that are implicit in the mappings of, e.g. GWT and HAMMER, and make them explicit in a weighted network of associations between perceptions and actions, in the manner of TEC and OAC (see Fig. 4). In doing so, it makes the input to the joint perceptuo-motor mapping explicit as perceptual episodic memories and motoric procedural memories. Both the episodic and procedural elements of the joint episodic-procedural memory are drawn from episodic memory and procedural memory which operate associatively in their own right.

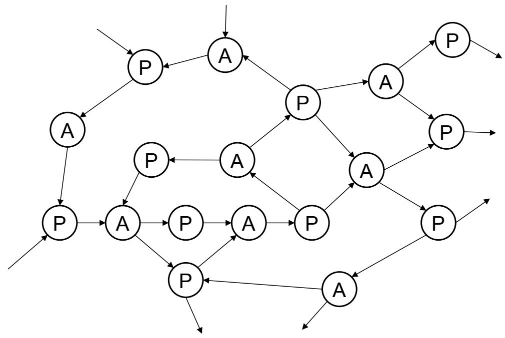

Fig. 4. Joint episodic-procedural memory as an explicit network of associations between perceptions and actions, drawn from episodic and procedural memory, unwinding the temporal and causal relationships between specific perceptions and actions that are implicit in the mappings of other perceptuo-motor representations.

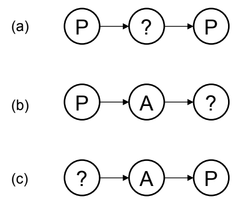

Fig. 5. The network model of joint episodic-procedural memory facilitates prospection in three senses: (a) prospection by predicting the outcome of an action carried out in given perceptual circumstances, (b) prospection by predicting the action required to achieve a goal in given perceptual circumstances, and (c) abductive inference of the perceptual states that explains an outcome of a given action.

This framework allows one to expose the mapping dynamics explicitly and development can then be facilitated by adjusting and adapting the network structure — its topology, strength of association, and mutual activation — as a function of an intrinsic value system [39].

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VI. A Value System for Autonomous Growth and Development

So how might joint episodic-procedural memory faciliatate development? They key is to identify a value system that can leverage the network structure and dynamics. One possible way to do this is to adapt the information-theoretic model of growth and development in ecosystems first proposed by Ulanowicz [45]. Ulanowicz advocates the use of a macroscopic and phenomenological[1] description of growth and development in ecological and other far-from-equilibrium system, modelling organization in systems using network flows between the components. The approach targets the essential role played by cybernetic coupling manifested as positive feedback cycles in dissipative systems to effect autonomous behaviour, in general, and homeostasis, in particular. However, rather than focus on the dynamics of individual components, it models the network organization at a macroscopic level using the average mutual information as a function of measurable network flows. This function includes an explicit term reflecting the size (and growth) of the network. Ulanowicz uses the term "ascendancy" to refer to this amalgamation of size and organization. Ascendancy can be interpreted as an index of the potential for emergence in a system. The ascendancy function can be cast in a form that separates the terms due to flows from outside the network, flows due to internal exchanges (including those produced by positive feedback cycles), export flows, and network dissipation. The flows due to internal exchanges — the internal network ascendancy — captures the autonomous element of the system, again expressed in terms of measurable network flows.

Significantly, Ulanowicz posits a principle of optimal ascendancy: "An autonomous system behaves over an adequate interval of time to optimize the internal network ascendancy subject to thermodynamic, hierarchical, and environmental constraints". The process of growth and development in an autonomous system (and, by default, the maintenance of autonomy itself) is thus cast as a variational principle, the internal ascendancy being the objective function which is optimized. Note that optimize does not necessarily mean maximize. While increased ascendancy reflects greater development and greater order in the network, this must be balanced against a need to retain some disorder, or entropy, to provide the flexibility and redundacy necessary to adapt to unexpected events.[2]

With its focus on network dynamics, the variational statement of optimal ascendancy provides a plausible intrinsic value system for use with joint episodic-procedural memory. In particular, we suggest that development and ideomotor theory can be bridged by adjusting the connectivity, association strength, and mutual activation in joint episodic-procedural memory to achieve optimal ascendancy during internal simulation. This form of autonomous development echoes that envisaged in the inception of simulation hypothesis according to which dreams in young children play a role in the formation and refinement of internal simulation and improved cognitive ability [46].

[1]Phenomenology in this context is different from, but compatible with, its more normal Husserlian meaning.

[2]Ulanowicz notes that the ecologist H. T. Odum once remarked that "any entity using minimum entropy as an adaptive strategy has a death wish!" [45], p. 133. This need for balance is what "subject to thermodynamic, hierarchical, and environmental constraints" refers to in the principle of optimal ascendancy.

VII. Conclusions

We have presented the case for joint episodic-procedural memory as a bridge between ideo-motor theory as a framework for goal-directed internal simulation for prospective action planning, on the one hand, and cognitive development, on the other. The key idea is that it affords the opportunity to leverage models of growth and development that target network dynamics by unwrapping the causal dependencies implicit in alternative forward and inverse models into an explicit perception-action network and applying intrinsic developmental value system to the network. We noted one potential approach, optimal ascendancy, based on an information-theoretic model of ecosystem growth and development. It remains to show that a network with optimal ascendancy does in fact exhibit improved cognitive behaviour, e.g. though improved prospective capacity or the ability to recruit novel actions in unforeseen circumstances, either through intrinsic measures of increased autonomy [47], [48] or through empirical investigations of cognitive behaviour.

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