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Editorial

New trends in Cognitive Science: Integrative approaches to learning and development

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Abstract

A new trend in Cognitive Science is the use of artificial agents and systems to investigate learning and development of complex organisms in natural environments. This work, in contrast with traditional AI work, takes into account principles of neural development, problems of embodiment, and complexities of the environment. Current and future promises and challenges for this approach are defined and outlined.

Keywords: Active vision; Brain development; Cognitive development; Cognitive Science; Embodied cognition; Emergent properties; Ethnography; Interdisciplinary research; Language learning; Learning algorithms; Machine learning; Modeling; Social communication

1. Historical changes in modeling: towards adaptive, interactive intelligence

A widely circulated story about early Cognitive Science efforts has it that Marvin Minsky assigned an undergraduate student "computer vision" as a summer project. The anecdote builds irony with historical hindsight: The optimism of early AI work, like successive theoretical trends in the behavioral and computational sciences, ran into the barrier of Real Complexity: monumentally interactive intricacies of organism–environment dynamics that give rise to human thought and action. Cognitive Scientists have repeatedly discovered that prosaic skills like producing phonemes or tracking objects are quite challenging to capture in models that approach the scale of an real organism. A growing appreciation of behavioral and cognitive details the complexity of anatomical structure and function of real brains and bodies, and the difficulties of describing ecological structures jointly mandate a reconceptualization of models of intelligent behavior. The mandate is to push beyond the symbolic models of human information processing of the 1980s and 1990s, and to meaningfully elaborate on early work on neural networks by incorporating relevant information about neuroscience (e.g., chemistry, physiology, anatomy), concerns about embodiment (e.g., perception–action systems, biomechanics, motor control), and sensitivity to cognitive ecology (e.g., ethnographic data at different levels of detail). Of course, such models must also accurately model high-quality behavioral data from organisms of interest, be they rat or human, infant or adult.

In recent years a community of researchers has made strides in these theoretical and empirical directions. Their work is bringing new questions and problems to the foreground, and demonstrating innovative empirical approaches, as exemplified by contributions to this issue. Although the methods and questions are quite varied, a "family resemblance" of recurring concerns or positions can be discerned (though perhaps not all the contributors would agree with all these formulations):

- Cognition occurs in the context of complex structures, both physical and social, in the environment. In many ways this structure alters, and even sometimes simplifies,

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the computational and behavioral tasks faced by active agents in those environments.
- Problems of embodiment are substantial and important [13]. We cannot fully understand intelligent behavior without understanding how the information-processing system is integrated with, and shaped by, its "platform" for acting and perceiving.
- Cognition is sub-symbolic and distributed. However, it is not all of one simple type (e.g., unsupervised Hebbian learning). In discerning types of learning and cognition, we require contributions from theoretical and experimental neuroscience.
- Nativist accounts that directly ascribe complex cognition to experience-independent products of the genome are not consistent with developmental neuroscience, embryology, or genetics, or with general principles of epigenesis. Such accounts, while sometimes pragmatic in initial models of cognition, are unparsimonious and should be marked as simplified and speculative.

More generally, many proponents of these positions and others have questioned or even rejected the traditional theoretical framework of cognitive psychology and AI. As summarized by Christiansen and Hooker [12], most theories in cognitive science implicitly assume general *centralized control models*. Such models place a disembodied, Cartesian mind at the center of a Ptolemean cognitive universe, wherein the environment (including the body) is separate and subordinate [17,44]. This standard model ignores issues of embodiment and the environment. This is theoretically problematic [12], and contrary to findings from many disciplines. For example, Pentland [43] has shown that a great deal of people's impending behavior can be predicted by where they are and who they are with. Note that not all the social sciences have historically subscribed to this centralized control model: for example, the opposite problem can be seen in pure ethnographic approaches that emphasize relativism, where the environment is given full causal power without considering shared neural and perceptual–motor attributes of individuals within and between cultural groups. The alternative is to reject "either/or" models of both extremes. Instead, we assume that adequate models of cognitive functions require an accurate account of the tendencies and variability of real behavior, a detailed model of the body that provides for and executes the brain's computation, a detailed model of the functions and processes of the neural systems, and detailed models and descriptions of patterns of information on various spatial, temporal, and cultural scales, within the environment. Put otherwise, we assume the major challenge for Cognitive Science is Systems Modeling.

Systems modeling: Testing and falsifying formal theories about specific cognitive functions of organisms with vastly complex nervous system and vastly complex perceptual and motor capacities, interacting in real time and space with highly diverse and changeable environments.

Some proponents go further in breaking from traditional AI, cognitive psychology, linguistics, and anthropology/sociology. Historically, these fields have mostly ignored developmental/epigenetic concerns. Now, however, we know enough about brain development, and about socio-cultural effects on infants'/children's thinking, to infer that a developmental history must be part of any account of mature cognitive functioning. A description of the mature cognitive "profile," while necessary, cannot yield a full explanatory account. A full explanation must include an account of how that profile emerged. A non-developmental view of adult cognition can lead to systematic misconceptions about the adult profile [36,55]. Mature functioning is a product of protracted learning and development in constant interaction with genetically mediated, heterochronous processes of neural change [22,32,46]. Thus, although most papers in this volume do not explicitly consider children of a particular age, or seek to model precise developmental changes, many deal with cognitive processes that are centrally relevant to infants and children, and are controversial: for example, face processing [Bartlett], inductive inference [Nelson and Cottrell], and syntax acquisition [Desai]. Such difficult natural learning problems can be re-cast in developmental terms. This in turn calls for developmental systems modeling.

Developmental systems modeling: We define this kind of modeling as follows: Testing and falsifying formal theories about specific cognitive functions of *developing* organisms with *emerging,* vastly complex nervous system and *emerging* vastly complex afferent and efferent potentials, *through a history of interaction* in real time and space within highly diverse environments that change *on multiple time scales, ranging from moment-by-moment changes to long-term changes over the organism's lifespan*.

Many proponents of modern approaches to developmental systems modeling realize the limits imposed by disciplinary boundaries, and seek inspiration from multiple disciplines. For example, computational models often can be improved by careful attention to what is neurally plausible, to are the precise details of human behavior and cognition. Psychology research benefits from richer grounding in the neural underpinnings of thought and behavior, and from rigorous, well-specified process models of cognition. Cognitive neuroscience benefits from a deeper grasp of how organisms perceive and act in natural environments. All of these disciplines can benefit from greater knowledge of biophysics, embryology, ethnography, genetics, linguistics, physical anthropology, and animal behavior.

What empirical problems are of interest to modern proponents of developmental systems modeling? The wide-ranging list is challenging, controversial, and substantive. It includes such problems as face processing, scene processing, attention, word learning, imitation, shared attention, working memory, navigation, articulation, multimodal perception, fluid motor control, self-awareness, object recognition, and others. The papers in this issue exemplify