Letters

Building a better baby: embodied models of infant cognition

In a recent review, Denis Mareschal advocates the use of computational models as a tool for studying the development of object knowledge in young infants[1]. The review highlights a wide array of models that investigate how infants are able to construct and maintain representations of objects after losing perceptual contact with them. By systematically evaluating the strengths and weaknesses of these models, Mareschal not only provides an invaluable resource to developmental researchers, but also helps to illustrate the emerging dialogue between developmental theory, behavioral research and computational modeling.

As a challenge to model-builders, Mareschal concludes by acknowledging the gap between existing models and the full range of behavioral phenomena revealed by object-knowledge studies. A recent modeling perspective that might narrow this gap is the 'agent-based' approach[2]. Agent-based models represent a broader perspective than that described by Mareschal, extending beyond a simulation of the organism's internal cognitive architecture to include the organism's body and the physical world that it inhabits. This approach is part of an emerging trend in cognitive science toward investigating embodied knowledge, which is constrained not only by the structure of the environment, but also by the physical and psychological structures of the agent[3–5].

There are two key features of the agent-based approach that make it particularly relevant to the developmental issues raised by Mareschal. First, agent-based model-builders often question the necessity of invoking representational strategies for explaining prospective behavior[6–8]. As a concrete example, consider the problem of tracking a moving object that passes behind a screen. By the age of three months, infants are able to anticipate the reappearance of an occluded object[9]. According to one view, anticipatory tracking is accomplished by using a representation of the occluded object's position and trajectory to compute its reappearance. Recent modeling work using an agent-based perspective, however, suggests that infants need not rely on a representational strategy to track occluded objects[2,10]. For example, Schlesinger and Barto simulate an agent-based model of visual tracking that illustrates how sensorimotor or body-based strategies lead to future-oriented behaviors through interaction with the physical environment[10]. The tracking model is represented by a simple eye that learns by reinforcement, not only to track a moving target, but also to anticipate the target's point of reappearance when it passes behind a screen. Perhaps more interestingly, when a partially visible obstacle is placed behind the screen, in the target's path, the model no longer anticipates the target's reappearance. Like human infants, the model seems to 'know' when the moving target will or will not reappear.

A second key feature of agent-based models is that they possess a body. It should be kept in mind that embodied models need not simulate entire bodies in realistic detail. For example, the 'body' of the Schlesinger and Barto model is an oculomotor system comprising a simple retina with muscles that shift the fixation point[10]. This contrasts with the 'dis-embodied' or physically buffered models described by Mareschal, whose outputs are internalized processing results, such as category assignments, implicit decisions, or precursors to motor signals that are not carried out. The critical feature of agent-based models is that they make contact with the physical world (i.e. through sensors and motor effectors). Finally, keep in mind that the implementation details (e.g. whether the body is represented by a robot or a computer simulation) ultimately depend on the specific research goals of the individual model-builder.

Why should having a body be important? One answer is that it gives us the means to simulate many of the behaviors generated by infants in both experimental and natural settings. For instance, imagine infants participating in a looking-time experiment, who move their head and eyes, shifting their attention from one part of the visual display to another. In addition, note that habituation is defined and measured *behaviorally*, by a decrease in the frequency or duration of fixations toward a visual display. Insofar as many of the concepts that developmental psychologists investigate in young infants are studied with behavioral methodologies, we are compelled to increase the behavioral realism of the models that we use to simulate those same behaviors[11]. I believe that by incorporating more of the infant's body into the computational-modeling design process, we can begin to bridge the gap that Mareschal describes between our models and the wide variety of behaviors that infants produce.

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