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REVIEW

Cognition as coordinated non-cognition

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Abstract We propose that cognition is more than a collection of independent processes operating in a modular cognitive system. Instead, we propose that cognition emerges from dependencies between all of the basic systems in the brain, including goal management, perception, action, memory, reward, affect, and learning. Furthermore, human cognition reflects its social evolution and context, as well as contributions from a developmental process. After presenting these themes, we illustrate their application to the process of anticipation. Specifically, we propose that anticipations occur extensively across domains (i.e., goal management, perception, action, reward, affect, and learning) in coordinated manners. We also propose that anticipation is central to situated action and to social interaction, and that many of its key features reflect the process of development.

Keywords Coordination · Development · Embodiment · Robotics · Situated cognition · Social interaction

> *In short, the practically cognized present is no knife edge, but a saddle-back, with a certain breadth of its own on which we sit perched, and from which we look in two directions in time William James*, 1890, *Chapter* 15.

There can be little doubt that cognition is informed by the past. There can also be little doubt that much of cognition is about the future. What will happen next? Where must I put my hand so that I pick up the cup? If I say what I am thinking, how will my listener respond? Human cognition is magical in its prescience, in its attempts, often successful, to foresee the future. How should we understand this core phenomenon of anticipation (also viewed widely as prediction)? How should we study anticipation so as to understand its underlying processes and principles?

One possibility is to situate anticipation in cognitive computation. This fits the traditional view in which mental life is divided into discrete steps of ‘‘sense-think-act.’’ Cognition, by definition, is about the ‘‘think’’ part, the knowledge and processes that mediate perception and action. From this perspective, knowledge consists of amodal propositions that represent experience, and anticipation is a form of inference that operates on this knowledge to produce further propositions about what is likely to happen next.

This approach has a long and venerable history in cognitive science. It makes considerable sense for many reasons, and has made major contributions to the field. For example, this view has been adopted widely in the study of text comprehension (e.g., Kintsch and van Dijk 1978), problem solving (e.g., Newell and Simon 1972), and reasoning (e.g., Rips 1994). In general, this approach assumes that people have stable models (or schemas) of the logical, causal, and temporal structure of the world, and that a wide

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variety of processes operate on this knowledge. For example, these models support understanding and predicting how rain and sun contribute to plant growth (e.g., Gentner and Stevens 1983), how levers and pulleys work to increase the force on objects (e.g., Chandrasekaren and Josephson 2000; Forbus 1993; Hayes 1985), and how events in a restaurant unfold over time (e.g., Schank and Abelson 1977). In these classic accounts, the knowledge that underlies anticipation is assumed to be fundamentally different in kind, and theoretically separable, from the real time processes of perceiving, acting, and emoting.

In this article, we present an alternative account that is spreading throughout cognitive science and cognitive neuroscience. Although this account takes many forms that are evolving rapidly, four important themes underlie it (among others). These four themes, together, create what we will call the ‘‘magic of human cognition’’ as an emergent consequence. By the ‘‘magic of human cognition’’ we will mean (1) the powerful ability to construct representations and behaviors that support ambitious goal achievement and social coordination, (2) the robustness and adaptability of learning across contextual change, (3) the emergence of intelligence from complex extended interactions between social agents and the environment over a developmental time course. The four themes that we believe create this ‘‘magic’’ are as follows.

First, knowledge has no existence separate from process, but is instead embedded in, distributed across, and thus inseparable from real time processes (e.g., Barsalou 1987, 1989, 1993; McClelland et al., 1986; O’Regan and Noe 2001; Rumelhart et al., 1986; Jones and Smith 1993; Samuelson and Smith 2000; Port and van Gelder 1995; Spivey 2006). From this perspective, there is not a fixed and separate representation of anything.

Second, to understand cognition, it is essential to understand fundamental contributions from what have traditionally been viewed as non-cognitive systems, including goal management, perception, action, reward, affect, social interaction, and development. Rather than cognition being a modular system that operates independently of these other systems, these other systems play central roles in cognition per se, and thus are not really ‘‘non-cognitive.’’

Third, to understand a cognitive process such as anticipation, one must consider the question of how to build it. On way to address this question is to understand how the process develops from birth over time in biological agents. Another approach is to engineer the process in artificial intelligence, for example, in robots.

Fourth, to understand a cognitive process, such as anticipation, it is insufficient to understand the process in isolation. Instead, understanding its coordination with other processes that are typically co-active during real world cognition is also essential. Indeed, understanding how a process coordinates with other processes may be as important, if not more important, than understanding the internal structure of the process itself.

In the next three sections, we develop the second, third, and fourth themes just described in greater detail. Because the first theme—lack of separation between representation and processing—has been addressed widely, we do not address it further. Because the latter three themes have received less attention, we focus on them here. After developing these latter three themes, we sketch an account of anticipation from the perspective of these four principles in the final section.

Cognition depends intrinsically on non-cognitive processes

We begin with an analogy (or cautionary tale) that may at first seem far from the issue of anticipation (Smith and Thelen 1993). The lesson of this analogy is that one cannot separate cognition from non-cognitive processes, nor from the coordination of all these processes in real time. The analogy concerns quadrapedal locomotion in cats. Classic theories of motor behavior proposed the construct of a stable central pattern generator (CPG) to explain the patterned regularity of a cat’s alternating limb actions during locomotion. Accumulating findings, however, raised problems for this construct. For example, cats walk with alternating limbs on a treadmill even when their spinal cords are separated surgically from their brains (e.g., Delcomyn 1980). Based on these findings, some researchers made the stretch that the CPG is in the spinal cord. The validity of a CPG has been questioned on many other grounds as well (Thelen and Smith 1994).

Even if a CPG did exist, it alone could not underlie the stability apparent in the alternating limb action of cats walking across real terrains. Cats walk backward, forward, on grass, on hills, on rubble. They side step objects; they walk when one limb is in a cast. Although a stable alternating limb pattern is apparent in all cases, the adaptability and variability of this pattern is remarkable. Moreover, alternating limb movements in these different contexts require fundamentally different patterns of muscle firing to maintain the same global stability of alternation. If a CPG exists, then it must constantly make walking happen in globally similar but appropriately different ways across diverse contexts. Thus, the overall system that produces walking cannot be solely the CPG, but instead could be multiple systems that include a CPG. Another possibility is that there is no CPG and that the global pattern of alternating limbs emerges from a variety of interacting systems.

The importance of ''outside'' systems in walking is analogous with the nature of higher cognition. Theories that separate the ''think'' part from the perceiving, acting, and affective parts fail to recognize the importance of these other systems in cognitive activity (cf. Van Order et al. 2003). Just as there may not be a CPG module that produces walking, there may not be a pure cognitive module that produces cognitive processing. Instead, cognition may emerge from the interaction of many contributing systems, analogous to how cat locomotion emerges from multiple systems. As suggested later, anticipation is also likely to emerge from many systems in this manner. In the following subsections, we outline contributions to cognition from non-cognitive systems, including the systems that implement perception, action, reward, affect, goal management, motivation, and social interaction.

The brain's modality-specific systems. Increasingly, researchers argue that systems in the brain for perception and action are essential parts of the cognitive system (e.g., Barsalou 1999b; Damasio 1989; Glenberg 1997). Rather than the cognitive system being modular, it utilizes mechanisms in modality-specific systems for its fundamental representation and processing activities (both in the brain and in the body). From this perspective, knowledge is represented as simulations in modality-specific systems, not as amodal symbol elsewhere in a self-contained modular system. Understanding perception and action is essential for understanding cognition.

Consider recent findings that support this conclusion. Zwaan et al. (2002) found that when people comprehend a sentence, they construct a visual simulation to represent its meaning. Similarly, Glenberg and Kaschak (2002) found that people construct motor simulations when comprehending sentences (also see Hauk et al. 2004; Zwaan and Taylor 2006). Chao and Martin (2000) found that when people view a static object, they construct a motor simulation to represent how they would act upon it. Simmons et al. (2005) found that when people view a food, they construct taste and reward simulations as they anticipate eating.

Many findings such as these indicate that perception and action play central roles in cognition (for reviews of additional evidence, see Barsalou 2003, in press-b; Barsalou et al. 2003; Martin 2001, 2007). Many behavioral experiments show that modality-specific variables affect high-level cognitive tasks, such as language comprehension. Many experiments in social cognition show that bodily states affect diverse forms of social inference. Many neuroimaging experiments show that the brain's modality-specific systems become active as people perform cognitive tasks. Together, the findings from these diverse areas indicate increasingly that cognition does not operate independently of modality-specific systems for perception and action. Instead, mechanisms in these systems play central roles in cognition per se.

Furthermore, the coordinated relationships between perception, action, and cognition must be identified to characterize cognition adequately. Again, much work shows increasingly that these systems are exquisitely linked. For example, judging the weight of an object lifted by another agent requires simulating the lifting action in one's own motor and somatosensory systems (Bosbach et al. 2005). The visual perception of the lifting event interacts with cognitive simulations of motor and somatosensory activity, such that the cognition in this judgment is distributed throughout many systems, not just a ''modular cognitive system.'' Similarly, the ability of pianists to identify auditory recordings of their own playing depends on their ability to simulate the motor actions that underlie it (Repp and Knoblich 2004). Again, the cognition of these judgments extends into the auditory and motor systems. Furthermore, even the simple execution of motor actions involves complex interactions between systems, as the brain simulates visual and somatosensory models of actions to guide and correct them (e.g., Wolpert et al. 1999; Wolpert et al. 2003). These feedforward models of actions also play extensive roles in anticipating visual perceptions (Wilson and Knoblich 2005).

Findings such as these indicate that perception, action, and cognition interface intricately, something that classic symbolic theories largely ignore. Grounding higher cognition in modality-specific representations provides one solution to this implementing this interface. Because the knowledge representations that underlie higher cognition are grounded in perception and action, they link cognition to the sensory-motor interface.

Perusing the evolution of cognition from the simplest organisms to humans, it is clear that cognition in the simplest organisms began with perception coupled directly to action via hard-wired circuitry. Over the course of evolution, increasingly sophisticated mechanisms evolved to mediate perception and action. Nevertheless, perceiving and acting remained foundational to the system as a whole. A system is not fully intelligent if it cannot perceive the world and effect change in it. As a prerequisite, the detailed structure of perception and action must be linked closely with cognition. Indeed, increasingly powerful perceptual and motor abilities may have prodded the sophistication of cognition forward. Building a cognitive system that fails to integrate these systems is not likely to implement the magic of human cognition.

The brain's affective and motivational systems. Affect regulation and motivation play substantial roles in human activity. Following Damasio (1994), researchers have become increasingly convinced that cognition divorced from affect is not rationale, and that optimal cognitive performance occurs when affective information is included in decision making. Over time, affective information accumulates with events and objects, indicating whether they are generally associated with positive or negative affect. On later encountering these events and objects, average affective information becomes available quickly to support decision making. When this information is lacking, decision making suffers. Thus, affective mechanisms play central roles in cognition, and a full understanding of cognition is impossible without them.

Another example is the central role of the brain's reward systems in learning (e.g., Ashby et al. 2005; Granger 2006). As rewards are experienced for stimuli, cortico-striatal loops integrate this information. Later, when these stimuli are perceived again, associated reward circuits become active and determine actions performed on the stimuli. In this manner, the reward system fundamentally shapes cognitive processing. More generally, motivational processes are central throughout cognition, from initiating basic response systems for hunger, thirst, etc., to controlling the pursuit of complex social and personal goals. Without these systems, theories of cognition are incomplete. Executive systems are also necessary for maintaining goals in working memory, and for deciding when to pursue or drop goals.

Havas et al. (in press) provide still another demonstration of how higher cognition depends on the affective system. While people read texts that contained emotional content, they had their faces configured into bodily states associated with particular emotions. As a result, the time it took them to judge the sensibility of a critical sentence depended on whether the emotion it described was consistent with their current bodily state. The fact that high-level cognitive judgments depended on these bodily states and the affective states that they engendered demonstrates the pervasive dependency of cognition on contributing motor and affective systems (for many related phenomena, see Barsalou et al. 2003). Although emotion, reward, and motivation are typically studied as independent processes, they are tightly integrated with each and with the cognitive system (e.g., Barrett 2006; Barrett et al. 2007).

Systems for social interaction and communication. Researchers who study the evolutionary origins of the human cognition system argue that social pressures shaped human cognition extensively (e.g., Donald 1993; Tomasello et al. 1993). Because increasingly sophisticated social interaction enabled major gains in evolutionary fitness, powerful new mechanisms evolved in the human brain that were absent in earlier species. Included in this list of mechanisms are joint attention, perspective taking, mirroring, imitation, and language. By evolving these mechanisms, humans were able to represent and coordinate complex social activity, which in turn yielded major gains in controlling environmental resources and maximizing reproductive outcomes. From this perspective, failing to include such mechanisms in an intelligent system precludes it from achieving the magic of human cognition.

Contemporary research in social cognition again suggests a rich interdependence among a diverse collection of neural systems. Findings across social psychology, social neuroscience, and electro-physiology show that the visual and motor systems play central roles in social information processing (for reviews, see Blakemore and Decety 2001; Gallese et al. 2004; Iacoboni, in press; Rizzolatti et al. 2002). As the action of an agent is perceived, the motor system simulates the action in the motor system of the perceiver. This simulation produces comprehension of the agent's action and generates visual inferences about what the agent is likely to do next (Wilson and Knoblich 2005). This ''mirror neuron'' circuit epitomizes a mixture of systems from which high-level cognition emerges, in this case, cognition central to social processing.

Mirror systems are also central to learning (e.g., Breazeal et al. 2005). As agents observe the actions of other agents, their mastery of skills is facilitated through the social direction of attention, imitation, and verbal instruction. Humans probably learn important things more often from social interaction than they do from isolated individual interactions with inanimate stimuli. Furthermore, these socially acquired skills are intrinsic to coordinated activity in division-of-labor settings, and also to competitive activity in conflict situations (e.g., Hutchins 1995).

Because human cognition probably evolved to support unusually extensive and sophisticated social interaction, it is likely that mechanisms for processing social information are densely inter-connected with cognitive mechanisms. To understand the human cognitive system, it will therefore be necessary to study cognition in its social contexts, not just when processing non-social information, such as isolated words and sentences.

Putting it together: an example. One scientific approach that makes clear the dependency of cognition on non-cognitive processes is the construction of artificial systems that attempt to exhibit human-like intelligence. Here we present an example of how cognition emerges from multiple domains in an anthropomorphic robot (e.g., Breazeal et al. 2005). Specifically, this example illustrates how a mirror-neuron-like system can develop from multimodal coordination during face-to-face play.

The robot brings the following abilities to the task: (1) the ability to visually track the facial features of a person, (2) the ability to ''motor babble'' by exercising its initial repertoire of facial movements, (3) the ability to sense its own facial configuration, (4) a coarse mapping of ''organ relations'' that roughly relates regions of the robot's own face to regions of the perceived faces of others, and (5) attraction to contingent interactions, where a contingency metric determines whether a visually perceived movement is temporally contingent on the robot's own movement.

The task that couples these systems is an imitation game. As the human developmental literature shows, it is often adults who take the initiative to imitate the facial expressions of infants (e.g., Jones 2006). Hence, as Breazeal et al.'s robot ''motor babbles'' by exercising its repertoire of facial expressions, a human participant imitates the robot. Although the robot cannot see its own face, it can sense its facial configuration via proprioception (i.e., position sensors). As the robot moves its face from expression to expression, it observes visually how the human's face responds. Meltzoff and Moore (1997) posited that the desire to match and to be matched by others is innately rewarding to human infants (also see Meltzoff 1996). This is essential to the robotic simulation, as there is no behavior, no goals, no learning without motivation. In this simulation, a contingency metric allows the robot to determine which regions of its own face the human has chosen to mimic, causing these regions to become salient. Through this process, the robot attentively selects pairings of matched regions between its own face to and those of the human. Via a standard statistical learning algorithm, these pairings teach the system about how perceived visual movements of the human's face map onto the robot's corresponding motor movements.

The inter-modal representations acquired from the coordination of perception and action allow the robot to directly compare its motor movements to observed expressions in the same motor-based coordinate system. Once this representation exists, the robot can mimic facial expressions of the human. The robot can also mimic novel never-produced facial gestures by searching over a weighted blend space of its motor repertoire to find (and generate) an adequate match. Furthermore, this learning increasingly establishes a mirror system that can be used in other tasks (e.g., Rizzolatti et al. 2002). The same representations can be used not only to generate the robot's own actions, but to recognize the same actions in others. Acquiring this ability has profound implications for many other forms of social learning, such as true imitation, social referencing, and other forms observational learning. It develops through the coordination and interaction of diverse component systems.

Cognition emerges from coordinated sets of processes

Divide and conquer is the standard strategy for making progress in empirical research, formal modeling, and AI engineering. Certainly, divide-and-conquer has obvious strengths, including the ability to isolate processes, rule out confounding variables, demonstrate control over phenomena, and establish causal (as opposed to correlational) relationships. In engineering and formal modeling, isolating processes greatly reduces the complexity of systems that must be built and the problems that must be solved. It also makes analytic understanding and formalization easier.

It is far from sufficient, however, to understand cognition well enough so that it can be taken apart. Instead, understanding cognition may require putting it all back together again so that it actually works as a whole. The magic of human cognition may reside not in its specific components but in their coordination. Furthermore, the study of processes in isolation may lead to fundamentally wrong accounts of them, or at least accounts that are different from what they would be in the context of coordinated activity. A stand-alone AI implementation of a process can probably not be plugged effectively into a larger coordinated system without considerable reprogramming, if not complete redesign. Thus, studying and implementing a cognitive process in a complete system that performs many processes together may teach us more about this process than studying and implementing it in isolation.

Just because the cognitive science literature is full of research on isolated cognitive tasks, it does not follow that this approach will eventually produce a complete account of cognition. If we understand how a brain implements many individual processes, it does not follow that we understand how they interact in a coordinated manner. Similarly, just because we can implement many individual processes does not mean that we understand how to implement them together.

A related theme is that agents in the real world do not perform individual tasks in isolation. Instead, they perform sets of coordinated tasks that produce coherent goal-directed behavior. For example, organisms do not perform categorization alone. Instead, they perform categorization together with perception, inference, action, reward, and affect.

Coordination during situated action. Situated action provides one way of exploring coordinated processes (e.g., Barsalou 2003, in press; Brooks 1991; Clark 1997; Glenberg 1997; Robbins and Aydede, in press). In situated action, agents have goals. As they navigate their environment during goal pursuit, they manage goal priorities, based on motivational states and opportunities in the environment. At each moment, they also perceive the environment, categorize entities and events, and draw inferences that go beyond the information given. They also perform many kinds of memory retrieval about possible actions, rewards, affective states, etc. And ultimately, agents act. At each point, they are not only learning about how to perform individual cognitive processes, they are also learning how to coordinate them.

The core set of coordinated cognitive processes associated with situated action includes goal management, perception, categorization, inference, action, reward assessment, and affect (with learning throughout). We suspect that the coordinated processes underlying situated action exist in many species, not just in humans (e.g., Barsalou 2005). It is easy to imagine many other species managing goals, perceiving and categorizing the environment, generating simple inferences about what will happen next, performing actions based on previous rewards, and experiencing affect in response to the outcomes of these actions.

Thus, understanding the coordinated processes that underlie situated action could be informative about intelligence across many species. This particular set of coordinated processes may constitute the core kernel of intelligence that evolved into human intelligence. Because this may be the most basic set of coordinated processes in the human brain, it might make scientific sense to understand it first, both empirically and theoretically. Rather than trying to understand the most advanced human abilities first, such as logic and mathematics, it might be more tractable to understand how these advanced abilities built upon more basic abilities that existed previously, such as the ability to coordinate situated action.

Coordination during social interaction. Another important set of coordinated processes are those that support the unusually sophisticated social abilities of humans. As described earlier, humans are unusual in establishing joint attention and in representing other minds. Humans also have unusually good communication systems that allow them to coordinate shared mental states and complex social activities. Humans are also unusually good at learning from each other via observation, imitation, and verbal instruction. Understanding the coordination of these social processes is probably central to understanding human intelligence.

In addition, many of the basic processes that support situated action probably contribute to social coordination as well. It is also probably important to study social processes together with those for situated action, given that much social behavior revolves around goal-pursuit in the environment (e.g., Barsalou 1999a; Barsalou et al. 2003; Smith and Semin 2004).

Coupled bodies and minds: an example. We illustrate the coordination of social cognition with perception and action in a robot that represents other minds. The key ingredients are correlations that emerge from coupled agents who have similar bodies and similar cognitive systems, and who are interacting in a shared situational context. This recipe produces abilities associated with the magic of human cognition, such as ‘‘mind reading’’ inferences about the internal states of others.

An agent engaged in a task with another agent who has a similar body and a similar cognitive system can detect the following correlations:

- correlations between the appearance of the self and the appearance of others (e.g., hands to hands, feet to feet),
- correlations between the behavior of the self and the behavior of others (looking to an object),
- correlations between one’s bodily behaviors and one’s internal states (e.g., looking left and remembering what was on the left; maintaining the memory of a goal and looking in the direction of the goal),
- correlations between the external states of another and one’s own internal states (seeing where someone looks, looking there oneself, and thinking about that location).

Numerous experiments in humans document these correlations. One large area of research shows that bodily states and affect are tightly coupled (e.g., Strack et al. 1988; for reviews, see Barsalou et al. 2003; Niedenthal et al. 2005). When a person adopts a bodily state associated with an affect (e.g., a posture or facial expression), the affect is elicited (e.g., slumping produces negative affect). These body-affect correlations, in turn, support empathy through mirroring (e.g., Blakemore and Decety 2001; Gallese et al. 2004; Iacoboni, in press; Rizzolatti et al. 2002). If a person’s face mirrors the facial expression of another agent, the previously established correlation between the somatosensory experience and the associated affect produce the affect. As a result, the perceiver adopts the same affective state as the agent. Other time-locked multi-modal cues further facilitate learning this mapping, such as the affective speech that accompanies facial expressions between caregivers and infants (e.g., Fernald 1989).

Through such couplings and coordinations, an artificial device, such as a robot, can develop ‘‘human-like intuitions’’ about the internal states of others (e.g., Breazeal and Aryananda 2002; Gray et al. 2005). Consider a robot developed by Breazeal (2003) that learns to perform affective appraisal (e.g., Plutchik 1991; Izard 1977). During face-to-face interactions with a human, heterogeneous processes in the robot become tightly coupled over time. When the robot imitates the human’s facial expressions, body-affect pathways in the robot evoke the corresponding affective state. Affective information in the human’s speech signal reinforces this response. All of these multi-modal states are time-locked because of the similarity in bodies and body-affect mappings. As a result of these correlations, the robot learns to associate its internal affective states with the facial expressions of humans.

Significantly, this ‘‘existence proof’’ from robotics illustrates how similar correlations in humans between perceptual, motor, and affective states could produce the ability to ‘‘mind read.’’ From the acquired coordination of multiple systems emerges one of the most important facets of human intelligence.

The incremental process of development

Developmental researchers have argued for decades that studying adult cognition in isolation will never be successful (e.g., Bjorklund and Pelligrini 2000). To the contrary, understanding the mature adult system requires understanding the history of biological growth, social interaction, and cognitive processing that produced it. Smith and Gasser (2005) proposed that the developmental process in humans is successful because the developmental environment contains several important characteristics. First, partially redundant sources of sensory-motor information in the learning environment allow babies to educate themselves, without teachers, simply by interacting with the world. Second, an incremental learning process over the course of development creates capabilities—such as understanding the cause and effect relations among actions and rattles—that could not exist genetically at birth. Third, rich statistical structure in the physical world is central to this incremental learning process. Not only does this structure scaffold development of the adult cognitive system, it remains a continual source of constraint and support during adult learning and behavior. Fourth, extended exploration is essential for the development of a mature cognitive system, where exploration discovers structure in the physical world, and also produces important cognitive skills, ranging from simple motor behaviors to creativity. Fifth, the development of a mature cognitive system depends on extended experience with other agents who constitute rich sources of instruction at many levels, including knowledge, skills, and meta-cognition. Sixth, the development of a mature cognitive system depends on extended experience with other agents operating together in a shared environment. As agents share information symbolically and non-verbally, important knowledge, skills, and meta-cognition develop.

From this perspective, the system-level properties that are the signature of human cognition only emerge from an extended history of coordinating cognitive and non-cognitive processes in situated action and social interaction. Anticipation is one such system-level property likely to develop from a long history of coordinated development. Although the development of individual processes is certainly important, the development of their coordination is no less important. Furthermore, the development of coordination may affect the internal structure of individual processes. If so, then fully understanding an individual process cannot be achieved by studying it in isolation, or even in coordination during adulthood. Instead, understanding the developmental history that coordinated the process with other related processes during its development is essential.

Also essential is an understanding of the training regimens that structure the development of coordination. Critically, these regimens typically include structure in the physical world and interactions with social agents. Relatively simple raining regimens may often arise implicitly to produce simple coordination initially, followed by more explicit and complex regimens that produce increasingly sophisticated coordination. Interestingly, there may be no other way to establish the kind of flexible, programmable coordination seen in humans. Although genetically based coordination may be sufficient in simpler species, multiple, overlapping, training regimens may be the only way to achieve human levels of coordination. Indeed, the magic of human cognition may reflect the results of training regimens to a considerable extent.

What kind of architecture? If these ideas are anywhere near correct, a key problem becomes the nature of the architecture that underlies the development of coordination. One way to approach this issue is to ask how one might build an artificial agent whose system-level properties emerge from a developmental history. Hybrid approaches offer one potential solution. Specifically, researchers could build upon the (considerable) success of the classic sense-think-act approach and implement hybrid systems that attempt to exhibit coordination between traditional cognitive and non-cognitive processes. Specifically, researchers could start with a mature theory of symbolic cognition and attempt to coordinate modules that implement goal management, perception, action, affect, reward, social interaction, and development. Building a hybrid system may be feasible, at least to some extent. Success would be of considerable theoretical interest and significance because it would suggest that the modular approach is feasible. Furthermore, success might suggest that the cognitive system per se includes something similar to the relatively modular cognitive system in classic symbolic theories. At a minimum, success would indicate that these theories capture important functionality in the brain.

An alternative strategy, and one that we believe cognitive science should consider, is to develop new architectures motivated explicitly by the attempt to integrate diverse domains of natural intelligence, including goal management, perception, action, cognition, reward, affect, social interaction, and development. From studying these domains together and assessing what it would take to build computational systems that integrate them, alternative architectures may emerge that are much more powerful than previous ones.

The development of coordination: an example. A recent attempt to engineer social referencing in a robot illustrates how a sophisticated ability can emerge developmentally from the coordination of multiple systems. Social referencing is the ability to use the emotional reaction of another agent to help form one's own affective appraisal of a novel situation, which can then be used to guide subsequent behavior (e.g., Feinman 1982). In human infants, social referencing arises under conditions of uncertainty and ambiguity, when one's own intrinsic appraisal processes are not adequate (e.g., Campos and Stenberg 1981). Social referencing is an important form of emotional communication and is a developmental milestone for human infants in their ability to learn about the environment through social interaction. It is also a behavior built from many component processes, including emotional empathy (bootstrapped from early facial imitation as discussed above), joint attention, and the ability to form affective memories (associating positive or negative valence to stimulus representations in memory).

Thomaz et al. (2005) observed the development of social referencing in a robot and reached the following conclusions about the developmental process. The robot's social referencing ability emerged in real-time from the dynamic coordination of multiple systems during interactions with a human agent. When the robot encountered a novel object, the object appraisal mechanism tagged the object as novel, which biased the affective system to evoke a mild state of anxiety. In turn, the robot's face expressed a heightened state of arousal as it looked upon the novel object. The robot also looked to the human's face to soothe itself, reflecting a previously established correlation. The human then reacted in a naturally instructive way, noticing the robot's anxious reaction to the unknown object, and showing the object to be safe. For example, the human often picked up the object and shared her positive reaction to it with the robot.

Consider further aspects of how this social referencing process develops. As the human gazes toward the novel object and reacts to it affectively, the robot's attentional focus is drawn to the object as well. By computing relative looking-time towards various objects in the environment, the robot establishes the novel object as the referential focus. As the robot's attentional focus shifts to the human (while maintaining the novel object as the referential focus), the robot extracts affective information from the human's face and voice, using the empathic mechanism described earlier. The resulting change in the robot's internal affective state triggers an encoding process that establishes a memory of the object, tagged with the robot's affective state. Thus, the novel object is appraised with socially communicated affective information and committed to long-term memory.

Over time, the robot becomes increasingly sophisticated in its ability to perform social referencing. Although this ability is not present initially, it emerges from the soft assembly of existing processes following interactions with adult agents. If this is how social referencing develops, then viewing it as a pre-existing modularized process is misguided. Instead, this fundamental cognitive ability results from extended practice at coordinating simpler processes.

The ''developmental'' achievements of this robot should be interesting to human developmentalists for several reasons. First, these achievements provide a measure of how well we currently understand development. To the extent that we understand the core developmental principles that produce human intelligence, we should be able to apply these principles when engineering artificial intelligence. Second, robots serve as physical platforms on which we can model complex coordinated processes across domains (e.g., empathy, social referencing). Robotic platforms allow researchers to present real time tasks in physical and social environments to embodied cognitive systems that are softly assembling processes repeatedly across development.

Anticipation as coordinated non-cognition

In this final section, we apply our themes to the cognitive process of anticipation. We first describe important situations in which anticipation plays central roles. We then describe how anticipation relies critically on non-cognitive processes. Finally, we describe how viewing anticipation as coordinated processes differs from thinking about it as a single process.

Choosing situations. We believe that optimal rates of progress in understanding cognition depend on the judicious choice of situations for scientific study. As suggested earlier, we believe that situated action is one particularly important case. Because situated action occurs ubiquitously across species and is central for survival, it seems central to understand. To the extent that many cognitive processes evolved to support situated action, studying and understanding this situation should be essential to understanding these processes. For these reasons, we begin with situated action. Because social interaction also appears highly central in human intelligence, we consider social situations as well.

As described earlier, situated action includes the following processes: goal management, perception, categorization, inference, action, reward, affect, and learning. During situated action, an agent is typically moving around with a goal in mind, perceiving the environment, and categorizing what is present. Once categorizations are made about perceived objects and events, the categories accessed generate likely inferences about events, actions, rewards, and affects that could follow. The agent then selects an action and performs it. Events in the world follow that produce rewards, which in turn produce affect and learning. Over time, this approximate cycle iterates constantly, taking many variations that depend on current conditions and the agent's expertise (including developmental level).

In social situations, other agents are also present. They, too, are typically pursuing goals that may be competitive or cooperative. They, too, are having cognitive and affective states. They may further model behaviors that serve as instruction, and may offer instruction explicitly, either verbally or by doing.

Situated anticipation. Where does anticipation arise in these situations? Everywhere, in intricately coordinated manners. Once a goal is selected, plans and possible courses that plans could take are anticipated. Relevant stimuli in the environment are anticipated as well. When entities and events in the environment are perceived and then categorized, category knowledge generates anticipations in the form of categorical inferences, including potential actions that could help achieve the current goal. As these actions are entertained, their consequences are anticipated, including reward and affect. As feedback is encountered, it specifies whether anticipations were correct or incorrect, producing extensive learning at multiple levels. We assume that neural simulations underlie all these anticipations in the relevant modality-specific systems (Barsalou, in press).

The coordination among all these anticipations is extensive. An active goal must coordinate with perception to identify goal-relevant information in the environment. The goal must also coordinate with working memory to maintain goal-relevant information, such as relevant stimuli in the environment to find. Once a relevant entity is identified, extensive coordination between memory, perception, and action must occur to interact effectively with it. As the consequences of actions become available, coordination between anticipated rewards and affects must occur to evaluate what has happened so far, and what to do next, if anything. Further coordination must occur with goal management, starting the cycle all over.

Many additional anticipations arise in social situations, falling under classic topics in social psychology, such as person perception and causal attribution. On perceiving an agent act, for example, a social perceiver anticipates further actions that are likely to follow. Perceiving an embodied state, such as a facial expression or posture, similarly produces anticipations about subsequent actions. Inferring the mental states of agents also leads to extensive anticipations about what the agents will do next. Situations, too, play central roles in producing anticipations, given that particular behaviors occur in particular situations. In general, tremendous amounts of anticipation occur during social interaction. Again, we assume that neural simulations in the relevant modality-specific systems underlie these anticipations (Barsalou, in press; Decety and Grèzes 2006).

Anticipation is central to instructional interactions and to collaborative work. In instructional settings, the teacher generally anticipates what should happen next in the domain of study much better than can the student. The teacher's job is often to teach students sequences of operations that achieve goals, including mental operations and assessments, not just physical actions. As students become increasingly competent, they become increasingly adept at anticipating what to do next and what should happen as a result, no longer requiring the teacher's assistance. In collaborative work, each co-worker must anticipate what other co-workers will do, and how the collaborative process will evolve. Extensive coordination between agents in all these settings is essential for success.

Studying situated anticipation empirically. How should a rigorous experimental psychologist approach the study of situated anticipation? Obviously, the situations just described are so complex that controlling and analyzing them with classic methods is not feasible. Nevertheless, we believe that these situations should play a central role in motivating experimental research.

Typically, experimental paradigms are chosen with little, if any, interest in their ecological relevance. Instead, the primary reasons for selecting a paradigm are ease of implementation in the laboratory, potential for rigorous control, and tractability in mathematical modeling. For example, research on anticipation in cognitive psychology has been dominated by research on lexical and semantic priming from words. Clearly, much elegant work has resulted from this approach. We believe, however, that this work likely to have little impact until it demonstrates its applicability to real world problems. What potential implications does our understanding of semantic priming have for situated action and social coordination? Because these situations are usually not considered when choosing research paradigms, these paradigms have little potential for informing our understanding of them.

Attempting to rigorously understand situated action and social interaction have tremendous potential to drive experimental research forward. Consider how framing experimental work in this manner could generate novel and potentially valuable research paradigms. Specifically, consider situated action. Researchers could take each specific form of anticipation in situated action described earlier and develop a paradigm for understanding it. Although these researchers would be isolating mechanisms, they would be isolating mechanisms that belong to a larger coordinated system that we know is central to human (and non-human) activity. As researchers increasingly understand specific forms of anticipation in situated action, they could begin to study the coordination of different forms. Although this would increase the complexity of experimental paradigms, studying small subsets of a coordinated system in a controlled manner is feasible.

By framing experimental investigations in this manner, entire systems of coordinated processes from multiple domains can be investigated that ultimately yield the magic of cognition. Anticipation would be studied in goal management, perception, action, reward, and affect. Not only would we understand individual anticipation processes, we would understand a set of individual processes that operate together in an ecologically important situation.

Along with classic experimental work, qualitative and descriptive methods would be valuable as well. Before beginning analytic laboratory work, it is essential to describe the component processes of the target situation, and to document the underlying patterns of coordination. Rather than relying on arm chair assessments of what a target situation contains, rigorous assessments of its content should be made, using standard observational and correlational techniques. Such studies could be viewed as analogous to the extensive documentation of phenotypes that preceded more analytic laboratory work in genetics. Before identifying genetic mechanisms, it was necessary first to identify the hereditary distributions of phenotypic patterns to be explained. We believe that a similar state of affairs exists in cognitive science. We first need to identify the components of important situations, such as those for situated action and social interaction, along with their statistical patterns of distribution. Once we have this descriptive information, laboratory paradigms can then be used to isolate important processes, identify their properties, and establish their coordination with other processes.

Implementing situated anticipation. How should situated anticipation be implemented in AI systems? What is the best way to implement all the forms of anticipation that occur across domains during situated action and social interaction, and to create effective coordination between them? An obvious answer is robotics, more specifically, robotics in social environments under developmental training regimens.

Building an autonomous agent that captures the magic of human cognition requires the inclusion of all relevant domains, including goal management, perception, action, categorization, inference, affect, learning, and communication. Furthermore, these autonomous agents need to operate effectively in situated action and social interaction. Given the central role of developmental accumulation, judicious choice of training regimens within these situations is central as well.

Getting all the processes from these domains to work increasingly together across a developmental trajectory requires solving the coordination problem. Solving the coordination problem may also help specify the individual processes correctly in the first place. Clearly, there may be times when implementing a process in a circumscribed toy domain has its benefits. Ultimately, however, the process must work effectively together with other processes across domains in a complete autonomous agent. For these reasons, we believe that the gold standard for implementing anticipation should be implementing it in robots who experience developmental trajectories in social domains.

Anticipation, goals, and higher-level coordination: examples. Piaget's (1952) book, *The Origins of Intelligence*, presents an insightful case of how anticipation emerges in infants. Piaget placed, for the very first time, a rattle in his 4-month-old infant's hand. As the infant moved the rattle, it came into sight and made noise. The sight and sound aroused and agitated the infant, inducing further bodily motions and causing the rattle to move even more rapidly in and out of sight, and to make even more noise.

Infants at this age have very little organized control over their hands and eyes. They cannot yet reach for a rattle. If given one, they do not necessarily shake it. If the infant accidentally moves the rattle, however, visual, auditory, and somatosensory consequences result, capturing the infant's attention. As these unintentional events repeat, the infant increasingly gains intentional control over shaking the rattle. Piaget allowed the infant to play with rattle repeatedly for several days and observed the emergence of anticipatory action. At the mere sight of the rattle, the infant would begin to move its hands in the coordinated pattern acquired from past experience. The unplanned and untaught relations between actions and outcomes constituted a self-organizing system that led to anticipatory representations of cause and effect. Piaget referred to such patterns as *secondary circular reactions*, namely, perception-action loops that arise from an embodied multimodal system behaving in the physical world.

Piaget believed that these emergent perception-action loops are foundational for development because they create opportunities for learning. In the rattle example, the repeated activity teaches the infant how to control its body, what actions bring held objects into view, and how sights, sounds and actions correspond to one another. Importantly, this learning happens without an initial goal. Instead, the goal—the intention to shake the rattle—emerges from simply placing an embodied organism who has sensory-motor systems, a motivational system, and a memory in a particular physical environment.

A more recent example of how a new goal emerges through anticipation during perception-action cycles is the experimental procedure known as ‘‘infant conjugate reinforcement’’ (Rovee-Collier and Hayne 1987). Infants (as young as 3 months) are placed on their backs, with their ankles attached by a ribbon to a mobile suspended overhead. The mobile, which produces interesting sights and sounds, provides the infant with many time-locked correlations. Significantly, infants themselves discover these relations through their own movement patterns. The faster and harder infants kick, the more vigorously the mobile jiggles and sways. Further kicking results as the perception-action cycle repeats itself. Infants become so highly engaged that they smile, laugh, and become angry when the contingency is removed.

The goals and perception-action cycles that emerge from rattle and mobile shaking illustrate how complex forms of anticipation emerge from placing an embodied agent in a physical situation that complements its intelligent capacities. As the agent learns to anticipate all the relevant streams of information, they become exquisitely coordinated with one another, and intelligence emerges. We suspect that much of human cognition—and especially its magic—emerges in this manner.

Conclusion

We realize that we have made ambitious requests. We have requested that researchers integrate non-cognitive domains with cognition. We have requested that researchers study the coordination of processes, not just individual processes in isolation. We have requested that researchers study the developmental time course of coordinated processes in situated action and social interaction.

These requests arise from our increasing belief that cognition is more than a collection of independent processes. Instead, we believe that cognition, and especially the magic of human cognition, emerges from deep dependencies between all the basic systems in the brain, including goal management, perception, action, memory, reward, affect, and learning. We also believe that human cognition greatly reflects its social evolution and context, as well as major contributions from a developmental process. Because we believe that human cognition reflects all these dependencies, we believe that it is necessary to change how we study it.

The process of anticipation is a paradigm case for our themes. Anticipations occur across all domains in a highly coordinated manner. Anticipations are central to situated action and to social interaction, and they grow in sophistication as the result of a developmental trajectory. We believe that our understanding of anticipation will proceed most rapidly if examined from this perspective. We also believe that the results of such study will move cognitive science and cognitive neuroscience forward significantly.

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