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The nature of cognitive development

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Theories of cognitive development have led to enduring and fierce arguments that have been long on rhetoric but short on evidence. Constructivist theory has roots in Piagetian notions of cognitive development as proceeding from self-directed action during infancy. Nativist theories subsequently became popular by producing claims of cognitive precocity, but left open many central questions concerning mechanisms of development. Now, a new view of constructivism is experiencing a renaissance, having achieved greater psychophysical, computational and neural plausibility.

Debates concerning developmental origins of human concepts are enduring and relentless, rooted in the ancient and more recent philosophizing of such eminent thinkers as Plato, Aristotle, Descartes and Hume. Inaccessibility to any empirical contributions to the argument hampered emergence of a viable theory of concept acquisition until the last century, when Jean Piaget devised techniques to elicit behaviors in infants that were suggestive of a developing system of knowledge, centering on the great themes discussed originally by Kant: object, space, time and causality [1]. The essence of Piaget's theory is 'constructivism': the building of concepts from simpler perceptual and cognitive precursors. Consider, for example, development of the 'object concept' – the notion that objects maintain their existence and properties, such as location or trajectory of motion, in the absence of direct perceptual input. On Piaget's theory, newborn infants have no object concept; they have to learn, with the aid of a set of basic reflexes (see Box 1). This constructivist view of development was challenged by the nativist view, according to which object concepts arise earlier than co-ordinated manual behavior, so they must be innate (Box 1).

Constructivism strikes back

A recent article describing an information-processing approach to cognitive development in infancy holds promise for the goal of accounting for infant acquistion new knowledge. Cohen and colleagues [2] propose a set of principles that make explicit the progression towards new knowledge in a bottom-up fashion. The Cohen *et al.* account is diametrically opposed to the competent-infant view held by nativism: instead of a group of high-level cognitive capacities that remains constant across development (such as deductive reasoning and object representation), Cohen *et al.* posit a set of general-purpose sensory, perceptual, and lower-level cognitive processes that are operational at birth and serve to guide knowledge acquisition across domains. These include sensory processing of auditory and visual input, short-term memory, allocation of attention, and primitive categorization. Principal developmental changes concern *expansion* of these rudimentary skills, the 'content' of information, and what constitutes a 'unit' of information.

Central to the theory is the idea that units of information are elaborated and enhanced with improvements in information-processing skills. Initially, the system has access only to information that is relatively simple, but with time, infants integrate the lower-level units of information into more complex, higher-level units, these higher-level units serve as the components for even more complex units, and so forth. There is a bias to attend to the most complex units that the system can handle. If it fails to process the highest units (owing, say, to immature attentional capacity or increased cognitive load), then lower units are utilized. This hierarchical approach to cognitive development is repeated across domains, underlying skill acquisition and proficiency over a range of tasks, throughout our lives in fact. Concepts are thus formed incrementally and progressively, in a manner broadly consistent with Piagetian theory but not tied to a single, determinate developmental mechanism, such as self-directed manual activity. Information-processing theory provides an excellent account of the development of object perception in early infancy, which proceeds in part-to-whole fashion: infants respond initially only to the components of occluded-object displays (i.e. those surfaces that are directly visible), failing to take account of those object constituents that are hidden from view.

Cohen and colleagues' extensive and elegant work on development of understanding of physical causality (see [3] for a review) provides another cardinal example of these principles. Leslie and Keeble [4] had proposed a

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Box 1. Theories of cognitive development: historical background

In Piaget's constructivist theory, the neonate enters the world outside the womb with only a minimal set of reflexes and a motivation to learn. Their experience of the visual world consists of a sensory 'tableaux', a series of fleeting images that change with every object movement and every shifting gaze. Object knowledge begins in earnest with the advent of manual coordination, at around 4–6 months. At first the infant repeats and rehearses well-known behaviors, but soon progresses to exploration of novelty. When she discovers hiding and uncovering (a universal favorite among children), she begins to establish spatial relations among objects, including the self as one object among many. The infant thus achieves 'objectification', the distinction between objects and events, and discovers the permanence and stability of objects that come in and out of view. More cognitive developments stem from further experience, but the important point is that the infant's own behaviors are a vital contribution to knowledge construction.

A nativist assault

The constructivist view of development was challenged by a then-radical set of claims made by Bower [10]. Using measures that were conducive to the limited behavioral repertoire of young infants (such as operant conditioning of pacifier-sucking), Bower produced a series of reports purporting to document highly precocious cognitive accomplishments in young infants, such as detection of apparent violations of object permanence by 2-month-olds [11]. Some of these findings proved difficult to replicate [12], but nevertheless, this work spawned a generation of researchers dedicated to the idea of the 'competent infant'.

If infants provide evidence of object knowledge prior to facile manual behaviors, so goes the argument, then whatever developmental mechanisms that lead the infant to this point must operate outside self-directed action – contrary to Piaget's claims. Taking this possibility further, object concepts might arise independently of *all* experience, and are, in this sense, innate [13]. An additional, implicit assumption that underlies much of this recent work is that of continuity across development in other fundamental cognitive mechanisms, such as reasoning, event prediction, decision-making, hypothesis testing and deduction [14].

The competent-infant view has a kind of parsimony, in that developmental continuity avoids the supposed philosophical pitfall posed by the necessity to account for novel forms of knowledge in inductive learners, sometimes known as Fodor's paradox [15]. But there is a problem, both for the view and for the paradox: development *happens*. Thus, a serious challenge for these views comes from evidence that newborns do not perceive occlusion [16], and without veridical perception of occlusion, a functional object concept is obviated. In other words, evidence from infants between birth and 4 months suggests that there really is a fundamental developmental change occurring, in just the way Piaget envisioned: initial responses only to what is directly visible, progressing to perceptual 'filling-in' of partly and fully hidden objects.

The work on development of object perception, therefore, forces the developmental cognitive scientist to explain the emergence of new knowledge. Notably, accounts of object-concept development have emerged that do not rely on inductive learning (the focus of Fodor's paradox), or on coordinated manual activity (the focus of Piaget's theory), such as maturation of visual mechanisms responsible for filling in spatial and temporal gaps in the optic array [9,17].

cognitive 'module' that responds more strongly to *causal* events, in which moving objects meet criteria for launching than to events with similar constituents, but missing a crucial spatial or temporal component. ('Launching' refers to an event where an object enters the scene, striking a second object, which immediately begins to move in the same direction as the first.) These experiments were based exclusively on observations of 6- to 6.5-month-olds. By testing infants outside this limited age range, Cohen and colleagues were able to establish a developmental trajectory from processing of lower-level perceptual features to a robust and flexible comprehension of causality. Younger infants (4-month-olds) ignore causality per se, and respond most strongly to the amount of continuous motion in a display. Slightly older infants (5.5-month-olds) show a trend towards processing of spatial and temporal components of causal events, and 6.25-month-olds appear to categorize events as either truly causal or non-causal. But 6.5-month-olds fail to recognize causality when complex objects are used in these events. Ten-month-olds can handle the extra processing load presented by object complexity, and perceive causality in realistic object events. However, older infants too fall back to processing lower-level features when events are made even more complicated by changing objects across trials.

Arguments from plausibility

Kellman has challenged developmental theories to meet criteria of psychophysical, computational and neurophysiological plausibility [5]. The research on development of object perception and causality described previously is making significant progress towards these objectives. As to the first, these experiments are firmly anchored in adult work, studies that examine perceptual completion [6], and causal perception [7]. With regard to the second, several computational models of object concept development have emerged recently (reviewed in [8]), and in this recent paper, Cohen *et al.* have presented a model of development of causality perception that maps well onto behavioral evidence from infants.

The third challenge, that of neurophysiological plausibility, is perhaps the most daunting, given how little is known about the precise neural substrates of many cognitive functions, and how these structures develop in humans. Yet even here, the information-processing approach is beginning to forge crucial links with appropriate literatures. For example, it might be that perceptual completion is accomplished with relatively low-level visual mechanisms in areas V1 and V2 (for spatial filling-in) and inferotemporal cortex (for coding persistence of objects briefly out of view), and the evidence from infants suggests that maturation of these systems relies on input during a sensitive period [9]. The Cohen *et al.* causality model, likewise, is rooted in plausible principles of neural development, such as Hebbian learning.

A theoretical renaissance

The work on development of object perception and causal perception shares a common theme: programmatic explorations of age differences and display attributes that determine veridical (and non-veridical) responses to stimulus events in infancy, relative to reports from adults. These investigations shed light on the fundamental nature of cognitive development: its origins in relatively simple processes, its characteristic hierarchical structure, and a host of plausible mechanisms of change. The constructivist approach, then, offers hope that answers to these central questions of cognitive science are tractable, and provides a way forward for those who seek developmental theories that are both explicit and explanatory.

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Out-of-body experiences: from Penfield to present

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Can the brain, when stimulated, yield entirely novel experiences? Blanke *et al.* (2002) describe a patient who reported spontaneous out-of-body experiences during electrical stimulation of her angular gyrus. These findings, although apparently extraordinary, agree with much earlier reports from a patient tested by Wilder Penfield. Such studies can provide clues about the nature of conscious experience.

Blanke *et al.* recently described a preoperative epilepsy patient who reported spontaneous out-of-body experiences during electrical stimulation of her right angular gyrus [1]. This study is both interesting and important because it addresses the problem of whether brain activity induced by local stimulation can elicit familiar experiences only, novel combinations of familiar experiences, or experiences that are entirely novel.

The 43-year-old woman in the study suffered complex partial seizures and had temporarily implanted subdural electrodes to identify the epileptic focus. Stimulation at two specific electrode sites over the angular gyrus at the parietal-temporal junction elicited novel vestibular illusions of falling or floating (Fig. 1a). Initial stimulation led to sensations of 'falling from a height' or 'sinking into the bed'. Higher amplitude stimulation led to the report of an apparent out-of-body experience. She reported that 'I see myself lying in bed, from above, but I only see my legs and lower trunk'. In actuality, the patient was lying in bed with her upper body supported at a 45-degree incline. It is worth noting that despite the patient's shift in perceived vantage point, her description of the items in view remained veridical – that is, she did not report seeing her entire body and face from above. Subsequent stimulation led to vestibular illusions of lightness and floating above the bed close to the ceiling. Moreover, when the patient was instructed to watch her legs, stimulation of the same site led to the patient to report that her legs had become shorter or that they appeared to be moving towards her face. Similar effects occurred when she attended to her arms.

The findings suggest that distortion of vestibular and somatosensory processing in the angular gyrus can lead to out-of-body experiences. However, given the extraordinary nature of these reported experiences and possible variability in cortical organization among epileptic patients, one might wonder how to consider such a single, albeit remarkable, clinical report.

Pioneering investigations of electrical brain stimulation

Wilder Penfield, a pioneer at investigating the effects of electrical stimulation in conscious humans under local

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