Infant Cognition

Introductory article

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Cognition comprises the mind's processes for acquiring, interpreting, and storing information, as well as processes for reasoning and thinking abstractly. The period of infancy in humans is generally agreed to be the first two years of life, a time during which children are largely preverbal.

INTRODUCTION

Since ancient times, those interested in the nature of the human mind have turned to infants when asking fundamental questions. What is essential and immutable in the human mind? What is given by the particulars of experience? The motivation for seeking answers to these questions from infants is that they have little in terms of experience and (presumably) all of what is innately given. It was not until the twentieth century that the scientific study of infant cognition began, with most of the foundational research occurring in the final three decades. This research has shown that the traditional nature/nurture dichotomy is misleading. Development is a process of organism–environment interaction from the beginning, even before birth. It is extremely difficult to isolate the individual contributions of nature and nurture because they do not act in isolation. Nevertheless, it is possible to ask which human capacities emerge early and therefore may serve as foundations for subsequent development. Current studies of infant cognition focus on the nature of infants' abilities at particular ages, and the process of development during the first years of life.

PERCEPTION

Perceptual systems are the mind's point of contact with the world. Human sensory organs take in a limited range of information. The problem of perception is to take this limited sensory data and yield the experience of a coherent, multidimensional environment. William James expressed a long and widely held view when he wrote that the infant's world was a 'blooming, buzzing confusion'. Early theorists assumed that infants lacked the abilities necessary to construct a coherent world from sensory data. Current work contradicts this view. Perceptual systems function from before birth, and constraints present at birth provide even newborns with a basis for making sense of sensory data. During the first year, experience and maturation tune and enrich the infant's perceptual capabilities. Vision and audition are the most well-studied types (or modalities) of perception in humans of any age, and they are the focus here. Smell, taste, touch, and proprioception also function from the beginning of life.

Vision

How can we know what infants see? Beginning in the 1950s, researchers began to devise methodological innovations to probe the perceptual processes and experiences of infants. Behavioral measures, such as patterns of visual attention, as well as brain activity are currently used to investigate infant perception. To illustrate, one measure of acuity exploits infants' preference to look at a pattern rather than a blank field. Researchers present infants with two pictures, one a gray field and the other a grating of black and white lines. If infants look longer at the latter, this is taken to indicate that they can perceive the grating pattern. By varying the size of the grating, researchers can test the limits of the infant's acuity. Studies of this sort have revealed that newborns can see, but their acuity seems very limited. Acuity may approach adult levels by 8 months of age.

Beyond the capacity to take in visual information, infants possess systems for interpreting this information – that is, perceiving a three-dimensional world populated by distinct objects. The data available to the eyes are two-dimensional, yet we perceive a three-dimensional world. Adults draw on many cues to depth relations, including the relative motions of objects with respect to one another and the observer's own motion, the different viewpoints provided by the two eyes (stereopsis), the physical activity required to focus on objects, and pictorial cues such as shading, overlap, and perspective. When and how do infants become sensitive to this information as specifying depth?

Early theorists proposed that experience reaching for and manipulating objects at different distances was essential to the ability to interpret visual cues to depth. Modern experimental work has challenged this hypothesis. From birth, well before they are able to reach for objects, infants seem to perceive in three dimensions. A striking demonstration of this is that newborns track an object's size as constant as it moves nearer and farther from them. Because the size of an object's projection on the retina varies as a function of its distance from the observer, perceiving depth is important for tracking size constancy. In one experiment, newborns were familiarized to a cube at various distances. Then they were shown the original cube at a new distance and a similar second cube of a different size. The cubes were positioned so that both projected the same sized image on the retina. Infants stared longer at the novel sized cube, suggesting that they could distinguish between the two sizes and that they recognized the original cube as familiar, despite its new position. Other studies have suggested that infants are sensitive to motion-based depth cues from the first month of life. Infants are not sensitive to pictorial depth cues until late in the first year, suggesting that experience may contribute to their development. Stereopsis is not functional at birth, but matures at between 2 and 4 months of age.

A second challenge in visual perception is to determine which pieces of sensory data comprise a single object. Objects are often partially occluded by others (as when a mother's hand holds a bottle), and boundaries between contiguous objects (books on a shelf, or pencils in a jar) may not be obvious. Adults succeed in perceiving discrete objects by drawing on many cues, including patterns of motion (parts that comprise an object move together), and regularities in the shape and texture of objects. Young infants rely heavily on motion as a cue to object unity. By 2 months of age, infants use common motion as a basis for treating two segments emerging from opposite side of an occluder as part of the same object. The ability to use featural information (shape, color, texture) as a cue to object unity emerges at around 4 months, and may be related to developments in the infant's ability to manually explore objects.

Audition

Fetuses respond to sounds prenatally, and remember what they have heard after birth. Prenatal listening may be the source of newborns' preferences for their mothers' voice and for their native language. Speech is central to normal human cognition and development, and therefore much of the research on infant audition has focused on speech sounds. The minimal difference in sound that carries a difference in meaning is called a *phoneme*. For example, in most spoken English *bit* and *pit* differ by a single phoneme. The physical difference between any two phonemes can be described using a continuous metric; for example, it is possible to artificially produce a sound that is halfway between a *bih* and a *dih*. However, people do not perceive speech sounds as varying continuously. Human perception of speech sounds is categorical; that is, physically different sounds that fall within a category are not easily distinguished, sounds that fall in two different categories are readily distinguished, and no 'middle ground' is perceived. Infants seem to perceive speech sounds categorically from birth. Although this might suggest an innate specialization for language, in fact other species, including quail and dogs, also have categorical perception of speech sounds. Language may have evolved to exploit a pre-existing property of the auditory system. Language experience tunes infants' innate categorical perception abilities. Languages differ in the particular sound contrasts they use as phonemic. For example, *r*- and *l*- are different phonemes in English but not in Japanese. Adults find it difficult to perceive non-native phonemic contrasts. Young infants, however, perceive non-native contrasts as well as native ones. By the end of the first year, infants become insensitive to non-native contrasts. Beyond perceiving the elements of language, by 8 months infants are able to learn recurring patterns in language sounds, an ability that probably contributes to their extraction of word units and grammatical patterns.

Speech carries many different kinds of information simultaneously, and infants are sensitive to much of this information. Beyond the level of phonemes, speech has prosodic characteristics including rate, loudness, rhythm, pitch contours, and pauses. The speech that is specifically directed at infants exaggerates these prosodic elements. Infants prefer infant-directed speech and are more sensitive to the exaggerated prosodic cues it provides. By 6 months, infants seem to respond to prosodic features which correlate with clause boundaries. During the second half of the first year, infants seem to become sensitive to the particular prosodic cues to grammatical boundaries in their native language. Prosody also conveys emotion – revealing, for example, whether the speaker is excited or frightened, or wishes to praise or scold. Infants respond to these emotional messages appropriately, even when they are given in an unfamiliar language.

Perceptual integration

Even at the beginning of life, different perceptual modalities speak to one another, yielding the experience of a coherent world in which sights, sounds, and tactile experiences are integrated. Newborn infants turn in the direction of a sound, a response that can provide a basis for connecting sounds with the visual properties of the objects that produce them. Studies have suggested that young infants spontaneously match information across modalities. When infants see two images and hear a soundtrack, they will look at the image that matches the soundtrack. Young infants can match novel images and sounds based on temporal synchrony, as well as matching familiar stimuli based on knowledge about the noises emitted by different kinds of objects (e.g., colliding sponges versus colliding blocks) and correspondences between speech sounds and the facial configurations that accompany them. Infants seem able to match tactile and visual information. For example, in one experiment, 1-month-old infants who were given either a bumpy or a smooth pacifier to suck looked longer at a picture that matched the pacifier in their mouth.

ATTENTION

For adults, perception is an active process. People actively seek out certain kinds of information, directing their attention to do so. From birth, infants strategically deploy attention in ways that are likely to facilitate information extraction and learning. Infants, like many other organisms, habituate to a repeated stimulus, attending less to it over repeated presentations, and dishabituate, or increase their attention, when a novel stimulus is presented. These responses aid the efficient use of attention, by reducing attentional resources for old information, and increasing them for new information. In addition, studies have suggested that infants seek out information-rich stimuli. They scan for edges and contours, prefer moderately complex patterns to less complex ones, and, as just reviewed, seek to integrate information across modalities. These attentional responses provide researchers with tools for probing other cognitive processes in infants.

For adults, it is important not only to allocate attention effectively to the current environment, but also to anticipate future events and direct attention accordingly. Some researchers have found that, as young as 3 months, infants direct their attention in anticipation of an event. For example, an infant might see pictures appear in alternation on the right and left side of a screen. After exposure to this pattern, infants look to where the next picture will appear before it actually appears. Infants show anticipatory looking for more complicated patterns as well, with performance on these improving during the first year.

The ability to coordinate one's own attention with the attention of a social partner (joint attention) is a critical contributor to cognitive development. Infants depend on social partners not only for survival, but also for instruction in key domains including language and culture. Systematic attention to social partners starts early. Newborns prefer pictures of faces to other patterns, and research suggests they form preferences for familiar voices and faces. Young infants attend preferentially to eyes over other facial features, respond to shifts in gaze direction, and direct their own attention in accord with another at person's gaze. Gaze-following becomes more robust at between 6 and 18 months of age. By 12–18 months, infants use an adult's gaze direction to interpret the reference of the adult's utterances and emotional expressions.

MEMORY

Development depends on the ability to retain information in memory. Many of the findings discussed so far imply memorial abilities in infants. For example, in order for infants to respond differently to familiar and novel stimuli they must have formed memories of the familiar stimulus. Moreover, since infants seem to prefer sounds heard prenatally, memory may begin before birth. Infant memory has been assessed by many other procedures including retention of conditioned responses, search for hidden objects after delays, response to novel and familiar items after delays, and deferred imitation. Infants remember for long periods as well as short ones. Infants in the first few months of life can retain memories for days or even weeks, and studies with older infants indicate retention of new information for many months.

A central debate concerns the nature of infant memories. Do they include declarative representations, or are they limited to procedural representations? The latter claim concerning infants derives, in part, from Piaget's theory that infant intelligence is limited to sensory-motor abilities (that is, organized ways of acting), and does not include abstract, conceptual representations (but see the section on conceptual structure, below). Much of the evidence for memory in young infants seems to be procedural in nature. For example, 3-month-old infants can learn to kick their feet in order to activate a mobile, and retain this response in memory for long periods. While this act of learning clearly involves procedural memory, it is not clear whether infants also form a more explicit memory of the task. The clearest evidence for declarative memory would be verbal report, which is not available from infants. Researchers have used deferred imitation as a measure of declarative memory in infants. Infants are shown a novel toy, on which an experimenter models a novel action. Infants are not allowed to touch the object until they return to the laboratory after a delay. At that point, if they are able to reproduce the modeled actions, this indicates that they could be recalling the prior event, and representing information that is not strictly procedural. Infants as young as 6 months succeed at producing deferred imitations when the task is not very demanding.

CONCEPTUAL STRUCTURE

In the minds of adults, knowledge is organized around a set of basic concepts, which comprise the building blocks of everyday reasoning. We form mental models of objects in the world, their physical properties, and their causal interactions. We distinguish between inanimate objects and intentional agents. We extract and manipulate information about number. Underlying these systems of knowledge is a general ability to form conceptual categories. How is infants' knowledge organized? Does it reflect the basic concepts that organize adult knowledge? Working in the early part of the twentieth century, Jean Piaget was among the first scientists to frame and address these questions, which continue to focus much of the current research on infant cognition.

Recent experiments have yielded evidence for structured knowledge much earlier in infancy than Piaget's observations indicated. There is currently debate concerning the implications of these findings for the nature of the infant mind. Some theorists have taken these findings as evidence for innate concepts or processing modules dedicated to particular core notions in human cognition. An alternative proposal is that innate constraints on information acquisition enable rapid learning in key domains. Others have argued that specific innate concepts are both neurologically implausible and unnecessary to account for infants' abilities. In considering these alternatives, it is relevant to keep in mind that recent experiments also indicate that infants' knowledge representations differ in significant ways from those of adults. Adult concepts are multifaceted because they are embedded in webs of knowledge, or *folk theories*. Infants' knowledge representations may contain parts of or precursors to mature knowledge. The challenge is to specify the nature of these partial representations.

Object permanence

A basis for much of cognition is the ability to form mental models of objects which can be held in mind and used when the object is no longer available to the senses. Mental models are most useful if they represent the physical properties of objects, such as their solidity, location in space, and continuous existence over time, as well as their particular features. Piaget argued that the ability to form such mental models (which he termed *object permanence*) was not achieved until the end of infancy, at around 18 months, based on his robust observations that young infants fail to search for an object that has been hidden from view and that difficulties on search tasks persist well into the second year of life.

However, search tasks impose demands that may mask infants' representational abilities. In particular, they require means–end abilities, which have been linked to prefrontal cortex, an area of the brain that undergoes critical development toward the end of the first year. More sensitive experimental techniques have revealed that young infants form mental representations of objects and their positions in space. To illustrate, in one experiment, 3-month-old infants were shown a screen rotating through 180 degrees until their attention to it had declined (that is, until they had habituated to it). Then a block was placed on the far side of the screen and infants saw one of two events. In one, the screen moved 120 degrees and then stopped. This was a novel stopping position for the screen, but one that was physically possible given the presence of the now hidden block. In the other, the screen continued to move through 180 degrees. Because this rotation was familiar from the habituation event, if infants did not remember the object hidden behind the screen, it should have been uninteresting to them. However, if infants represented the hidden block, this event should have been surprising because the screen seemed to move through the space occupied by the block. Infants looked longer on the apparently impossible trials than on the possible trials, suggesting that they represented the existence of the block behind the screen. Further evidence for infants' representational abilities comes from studies of reaching: infants reach for an object in the dark, so long as they have been shown the object before the lights go out. Moreover in these studies, infants reach differently depending on the size of the object, indicating that they hold in mind the object's size as well as its continued existence and location.

Physics

During the first few months of life infants are sensitive to two principles that are deeply intuitive to adults – the principles of solidity (an object cannot pass through the space occupied by another object), and continuity (objects exist continuously in time and space). In the experiment described above, for example, infants not only tracked the block's continuous existence behind the screen, but also responded as if both the block and screen were solid. The principle of continuity also provides information about the number of individual objects present in a scene. By 4 months of age, infants seem to be sensitive to this aspect of continuity. In addition, young infants seem to be sensitive to the causal properties of events. When one object moves toward another, contacts it, and then the contacted object immediately moves off, adults perceive the first object as causing the second to move. Infants differentiate between these apparently causal events and similar events that do not appear causal to adults because of a gap between the objects or a delay before the second object is 'launched'.

Infants' representations of physical reality differ significantly from those of adults. Infants seem to be less sensitive to the constraints imposed on object motion by gravity and inertia than they are to the constraints imposed by solidity and continuity. Across a range of physical phenomena, infants seem to begin with an initial all-or-none representation, only later changing their perception to reflect the relative properties of objects. Although young infants use spatiotemporal information to determine the number of individual objects that are present in a scene, they are less able than older infants to use featural information to do this.

Infants also differ strikingly from older children and adults in that their ability to express their physical knowledge is extremely limited. Visual habituation procedures reveal abilities in very young infants, but other procedures reveal apparent deficits in physical reasoning in much older children. This discontinuity has led to a number of hypotheses concerning the nature of infant cognition and its development. It has been suggested that infants' mental representations are inaccessible to general reasoning systems or action systems because they are encapsulated in particular processing modules, are implicit, or are weak. Current work is directed at elucidating and distinguishing between these alternatives.

Intentionality

The abilities to distinguish between inanimate objects and intentional agents, and to interpret the actions of the latter, are critical to human functioning. Adult folk psychology explains human action in terms of the actor's underlying psychological states. Recent experiments have explored the infant precursors to this system of knowledge.

Infants possess several propensities that may facilitate learning about human action. Newborns attend selectively to faces and voices, and are highly responsive to the contingent response patterns that are typical of social partners. They also spontaneously imitate some of the behaviors they observe, including facial gestures and arm movements. By 6 months, infants respond to shifts in other people's gaze direction by directing their own attention in the same direction. This sets the stage for later developments in joint attention.

Beyond these sensitivities, do infants analyze actions in terms of desires, perceptions, and intentions? A number of studies indicate that 18-month-olds interpret the behavior of other people in terms of their intentions and attentional states. To illustrate, on observing a person attempt and fail to complete a novel action, 18-month-olds infer the person's goals and reproduce the intended action. Recent findings suggest that 6- to 9-month-olds understand certain actions as being goal-directed. It has been hypothesized that imitation provides a basis for infants' interpreting other's actions in terms of underlying psychological states by allowing infants to connect their own internal experiences and actions with the actions of other people. This possibility is consistent with recent findings indicating common neural substrates for the perception and production of actions.

Number

Adults extract and mentally manipulate information about number. Observing flowers in a vase, we can represent the fact that there are precisely six flowers. Moreover, we can predict the resulting number of flowers for transformations such as removing two flowers or adding four.

Habituation experiments have revealed infant abilities that may be related to mature number knowledge. First, young infants are sensitive to features associated with exact small (1–3) numbers. Infants habituated to one number of items (e.g. three dots) dishabituate to a new number (e.g. two dots), but not to a novel display with the same number of items. This sensitivity extends to sounds and events as well as visual stimuli. In addition, when 5-month-old infants observe objects added to or subtracted from a hidden display, they look longer when an incorrect number of items is revealed than when a correct number is revealed. Moreover, recent studies suggest that infants form approximate representations for large numbers that allow them to distinguish between sets with large proportionate differences (8 versus 16), but not small proportionate differences (8 versus 12).

Whether these findings reflect sensitivity to number *per se* has been debated. Number is often correlated with other perceptual dimensions, including density and overall amount, and studies with infants do not always successfully control for these features. Moreover, some of the findings concerning small sets could be accounted for by infants' establishing representations of each individual object involved, rather than extracting the number of items in the set.

Categorization

Adults group together perceptually distinct individuals as being the same kind of thing. The resulting conceptual categories provide a means for efficient information storage and retrieval as well as a basis for inferring the properties of new exemplars.

From early in life, infants seem to be sensitive to category structure. Older infants spontaneously sort objects into categories. Young infants manifest a sensitivity to category structure in their patterns of attention. For example, in one experiment, having been shown a series of pictures of cats, 3-month-old infants generalized habituation to new cats and dishabituated to dogs. In addition, like adults, infants seem to structure their categories around the prototype, or most central member, of the category. Having been familiarized to members of a category, infants respond to the category's prototype as if it is highly familiar, even if they have not seen that item before.

Infants categorize artificial stimuli (e.g. dot patterns) as well as real ones (e.g. photographs of animals), and they attend not only to individual features but also to correlations between features in doing so. During the first year of life, infants can group items into relatively broad categories, such as *vehicle* or *animal*, as well as more narrow, basic level categories, such as *dog* or *car*. Different kinds of experiments tap different levels of category sensitivity in infants. In visual attention tasks, infants are sensitive to basic level categories, but on tasks that involve manual manipulation infants sometimes perform better with broad categories than with basic level categories. Infants, like adults, categorize more efficiently when given the opportunity to compare members of a category to one another or to members of a contrasting category.

Adult category knowledge includes not only the perceptual attributes shared by members of a category but also the underlying, often unobservable properties that unite a class. We understand that dogs not only tend to look, smell, and sound alike, but also that they share deeper, important properties including species-typical behaviors and internal structure. A question of long-standing debate is whether infants' categories are exclusively based on perceptual features or instead include more abstract knowledge. Investigating this question has proven difficult, because deep properties are strongly correlated with perceptual attributes, and therefore infants' propensity to group items may not provide unambiguous evidence concerning their knowledge about deep properties *per se*. Nevertheless, as young as 7 months, infants group together items from broad categories which differ from one another on many perceptual dimensions (e.g. a dog, a bird, and a rabbit), and they distinguish between members of different categories which are similar on several dimensions (e.g. a bird and an airplane), suggesting that they base category judgments on more than raw perceptual similarity. Older infants actively seek commonalities beyond the level of surface similarity. By the end of the first year, infants apparently infer that members of a kind share properties that are not immediately observable. By 13 months, infants may begin to understand the link between conceptual categories and language: hearing diverse members of a kind given the same name leads infants to seek out commonalities between them. Finally, by 18 months, infants selectively learn feature correlations that are meaningful (e.g. having wheels and rolling versus having wheels and squeaking), suggesting that they seek the underlying causal explanations for these correlations.

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Inference using Formal Logics

Intermediate article

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CONTENTS

Formal logics are used fundamentally in mathematics, natural language syntax and semantics, computer programming languages, and artificial intelligence.

INTRODUCTION

Logic is fundamental to a variety of disciplines. Logic provides insight into the nature of mathematics and human mathematical reasoning. Logic provides insight into the syntax and semantics of human language. Logic is an important tool in the design and implementation of computer programming languages. Logic also holds the promise of playing an important role in the development of artificial intelligence (AI). We will briefly consider each of these motivations in more detail.

Metamathematics

The idea that human thought is governed by linguistic rules started with the development of syllogisms by Aristotle. A syllogism is a pattern of inference. For example, if all men are mortal, and