CHAPTER 3

Early Cognitive Development: Objects and Space

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Infants and young children face some daunting learning tasks. They must learn to recognize the specific individuals with whom they interact: their friend, their dog, their house, their toy truck (Xu and Carey, in press). They must learn to categorize appropriately the many thousands of kinds of objects that older children and adults pick out at a glance, from cups to telephones to butterflies (S. A. Gelman, this volume). They must become able to keep track of their own position and learn the layout of their surroundings and the locations of objects, so that they can find their way from place to place and locate things that are out of view (see below). They must learn words that refer to surrounding objects, places, and events, while mastering the distinctive ways in which their language allows words to be combined to express thoughts (Bloom, this volume). Perhaps most important, infants and young children must build systems of knowledge that capture the significant regularities in their environment, such as knowledge of the motions of objects, the actions of people and animals, and the structure of social events.

Given these tasks, it is not surprising that infants and young children devote much of their time to exploring and learning about their surroundings. Young infants orient to changes in the environmental layout (Johnson & Gilmore, this volume) and direct their attention to novel objects and events

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(Kellman, this volume, and below). When an event occurs with regularity in a given context—an object appears at a predictable place and time, a mobile turns with every jostling of the crib—infants are apt to learn the regularity, and they may remember it over weeks or months (e.g., Haith, 1993; Perris, Myers, and Clifton, 1990; Rovee-Collier, 1990). Learning about the external environment begins before birth and continues at a rapid pace: For example, newborn infants already have learned to recognize aspects of the sound pattern of their language (Mehler et al., 1988), and they quickly come to recognize aspects of the face of a parent (Bushnell, Sai, & Mullin, 1989).

I. TWO VIEWS OF COGNITIVE DEVELOPMENT

In light of these tasks, it is perhaps natural to view the infant as a general-purpose learning system that discovers and internalizes whatever regularities the perceptible environment presents (see Helmholtz, 1866; McClelland, 1994, for old and new versions of this position). On this view, infants learn with equal ease about any perceptible regularities. With experience, children's knowledge comes to focus on those entities whose perceptible properties and behavior are experienced most frequently and consistently. As their expertise grows, children gradually move beyond the immediately perceptible properties of such entities and discover the deeper properties that adults take to be central in accounting for an entity's behavior: an object's mass, an animal's motivational state, a person's intentions. The domain-specific systems of abstract knowledge that characterize adults' reasoning therefore would emerge late in development, after children had gained extensive knowledge of their perceptible surroundings.

The view of the infant as a general-purpose learner pervades much of the study of cognitive development, but considerable research suggests it is at least partly wrong. Infants appear predisposed to develop systems of knowledge within specific domains including people, inanimate material objects, and places in the layout (Wellman & Gelman, 1992), although the nature of these learning systems and the boundaries between them remain the subject of some debate (Hirshfeld & Gelman, 1994). Early-developing knowledge does not appear to capture the most obvious features of perceptible entities but some of their most deeply reliable, abstract properties (Simons & Keil, 1995). Finally, early-developing knowledge systems may function only in limited contexts, such that distinct systems guide performance in different problem domains (Karmiloff-Smith, 1992).

The domain and task specificity of early knowledge systems may underlie some of the young child's most striking cognitive limitations. Adults can bring distinct systems of knowledge together to tackle new, unanticipated problems: for example, we may use knowledge of number to understand the motions of objects, or knowledge of fluid flow to understand electricity (Carey & Spelke, 1994; Gentner & Stevens, 1983). Unlike adults, infants may not be able to solve new cognitive problems by relating their existing knowledge systems to one another. Contrary to the first view of cognitive development, general-purpose learning abilities may be a late (and partial) achievement, arising only after the child's initial, domain-specific knowledge systems are well established (Carey & Spelke, 1994; Karmiloff-Smith, 1992; Rozin, 1976).

The latter view of cognitive development is suggested by research on infants' developing knowledge of inanimate object motion, human action, number and arithmetic, and the environmental layout. Because knowledge of human action and number are considered elsewhere in this volume (respectively, in the chapters by Miller and Taylor), we focus here on early-developing knowledge of inanimate objects and the spatial layout.

II. DEVELOPING KNOWLEDGE OF OBJECTS

As Kellman's chapter in this volume attests, infants as young as 2 months, and perhaps younger, perceive their surroundings as a stable, three-dimensional layout furnished with objects. Each object in the layout is perceived as a bounded unit, distinct from other objects and surfaces. Infants perceive objects by detecting the patterns of common and relative motion that provide the most reliable information about objects for adults (Kellman, 1993, and this volume). Infants' perception of objects accords with three highly reliable aspects of object motion: (1) objects move *cohesively,* maintaining their internal connectedness and external boundaries (Figure 1A); (2) objects move *continuously,* tracing a connected path over space and time (Figure 1B); (3) objects influence one another's motion only on *contact* (Figure 1C); (see Spelke & Van de Walle, 1993, for discussion). Although object perception is not our current focus, we will return to these general constraints on object motion.

Given that infants perceive objects under certain conditions, we may ask questions about infants' developing knowledge of objects. First, when do infants begin to represent objects that are not currently visible, and how do object representations change over development? Second, when do infants first apprehend the identity of an object that they encounter at different places and times, and how do their representations of object identity change? Third, when do infants first make inferences about the hidden or future motions of objects, and what knowledge guides their inferences at different ages? Answers to these questions may shed light on a central question about early cognitive development: What are the sources of our mature, commonsense knowledge about the physical world and its behavior?

A. Representing Hidden Objects

Infants appear to represent objects that become invisible as early as they can perceive and act systematically on objects that are visible. Object represen-

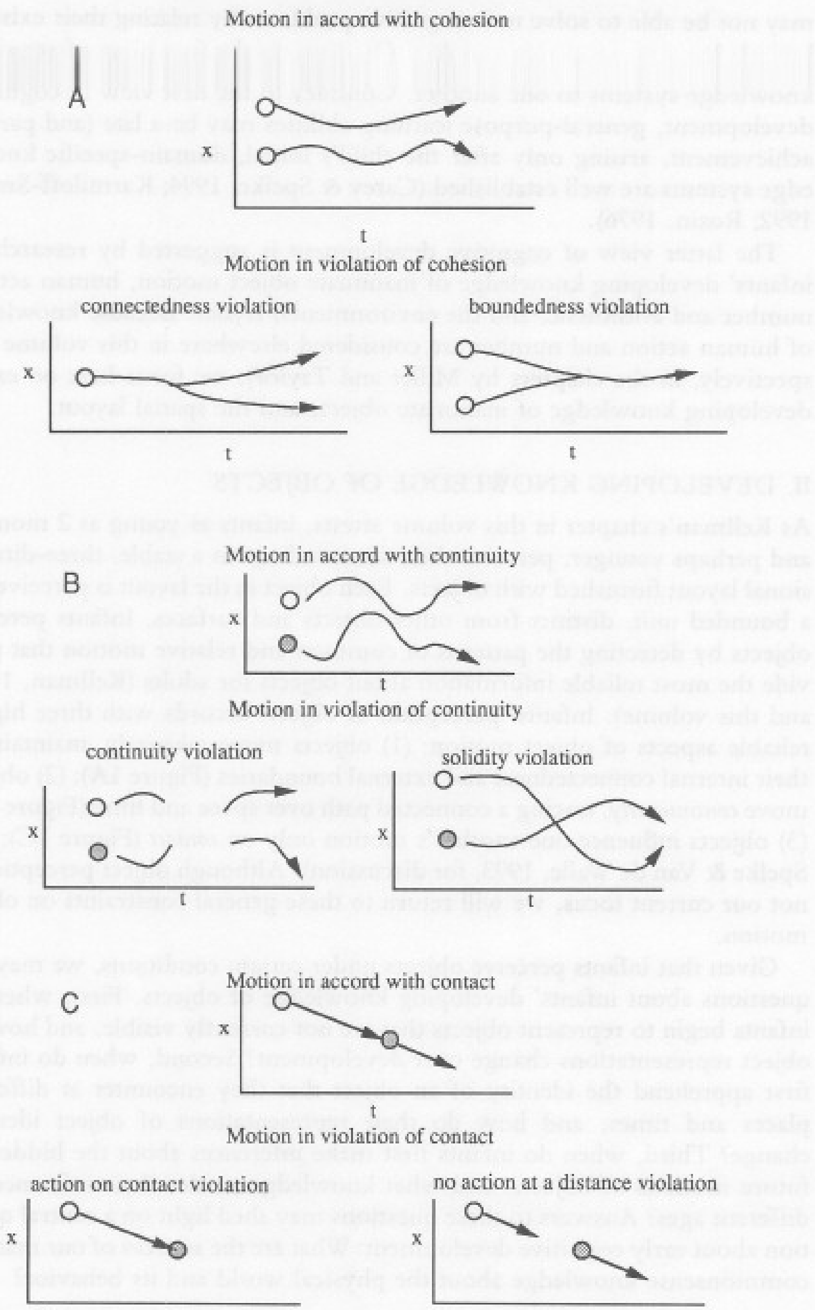

FIGURE 1 Principles guiding infants' perception of objects. (After Spelke and Van de Walle, 1993.)

tations have been revealed by studies of two different kinds of behavior: infants' reaching for objects and their visual attention to events in which objects move from view. We offer one example of each kind of study.

Clifton, Rochat, Litovsky, and Perris (1991) investigated infants' reaching for visible objects and for objects in the dark. Six-month-old infants were presented with objects of two different sizes, a large object similar to a steering wheel and a small object similar to a donut, each with a distinctive sound source at its top (Figure 2). On a series of trials in which the objects were visible, infants had the opportunity to learn the pairing of each object with its sound, and they were allowed to reach for each sounding object. Then the lights were extinguished, the sounds were played, and infants were allowed to reach for the objects in the dark.

Both in the light and in the dark, infants reached differently for the large and small objects: They tended to reach for the donut with one hand directed near the source of the sound, and they tended to reach for the steering wheel with two hands directed to the lateral borders of the object, rather far from the sound source. Infants' reaching in the dark therefore was directed to the now-unseen borders of the object, rather than to the location of the ongoing sound. Infants often reached in the dark by engaging in novel actions, different from those they had performed in the light, that were appropriate to the hidden objects' spatial properties. This experiment and others (Clifton, Rochat, Robin, & Berthier, 1994; Hood & Willats, 1986) provide evidence that infants represent the spatial properties of nonvisible objects, and that such representations inform their reaching.

Further studies of object representations are based on the pervasive finding that infants look longer at novel objects or events (e.g., Bornstein, 1985). In these experiments, infants are presented with a visual display repeatedly until their looking time declines, and then they are presented

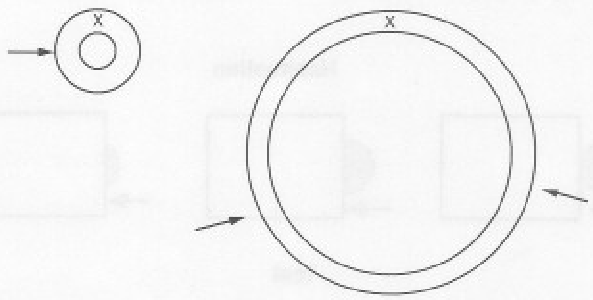

FIGURE 2 Schematic depiction of displays from a study of object-directed reaching in the light and in the dark. Each object was associated with a distinctive sound emanating from the locations marked with Xs. Characteristic points of contact with an object, during reaching with or without vision, are designated by arrows. (After Clifton, Rochat, Litovsky, and Perris, 1991.)

with changes in that display. Typically, infants look longest at the changed display that they perceive as most different from the original display. Although most studies using preferential looking methods have assessed infants' sensitivity to visible events, a number of studies have used preferential looking methods to probe object representations (see Baillargeon, 1993, for review). An experiment by Craton and Yonas (1990) provides an example.

Six-month-old infants repeatedly watched a disc move behind a screen from a visible position to a hidden position (Figure 3). The object was fully visible or fully hidden only briefly and was otherwise partly occluded. What did infants perceive as this object moved from view: a truncated circle that became narrower and narrower until it disappeared, or a complete disk with a stable, circular shape that moved progressively behind the screen? To address this question, the investigators presented infants whose attention to the original occlusion event had declined with complete and truncated disks in alternation. Infants looked longer at the truncated disk, suggesting they had seen (and become bored by) a complete disk during the occlusion event. This experiment and many others (e.g., Baillargeon, 1987; Hespos & Rochat, 1994; Wilcox, Rosser, & Nadel, 1994, 1995; Wynn, 1992; see also below) provide evidence that infants represent hidden objects.

Preferential looking studies reveal interesting limitations on infants' representations of occluded objects. In particular, infants who are presented with a partly occluded object whose parts are revealed in succession appear to perceive the *unity* of the object but not its specific *shape*. Van de Walle and Spelke (in press) presented 5-month-old infants with a square that moved back and forth behind an occluder such that its two sides alternately were visible on the two sides of an occluder while its center remained hidden (Figure 4A). After looking time to this display had declined, the occluder was removed and infants were presented with a complete square and a broken figure in which the previously visible areas of the square were separated by a gap (Figure 4B). Infants looked longer at the broken square,

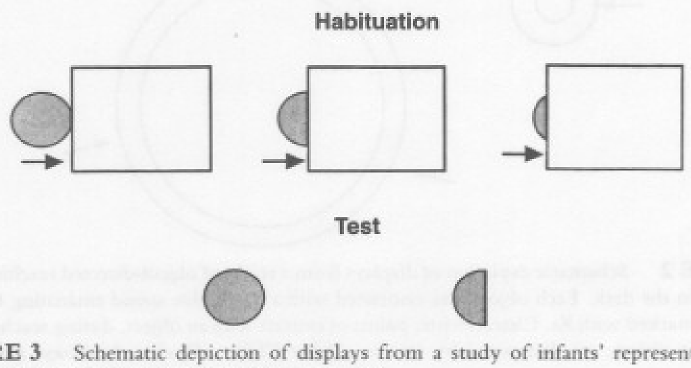

FIGURE 3 Schematic depiction of displays from a study of infants' representations of occluded objects. (After Craton and Yonas, 1990.)

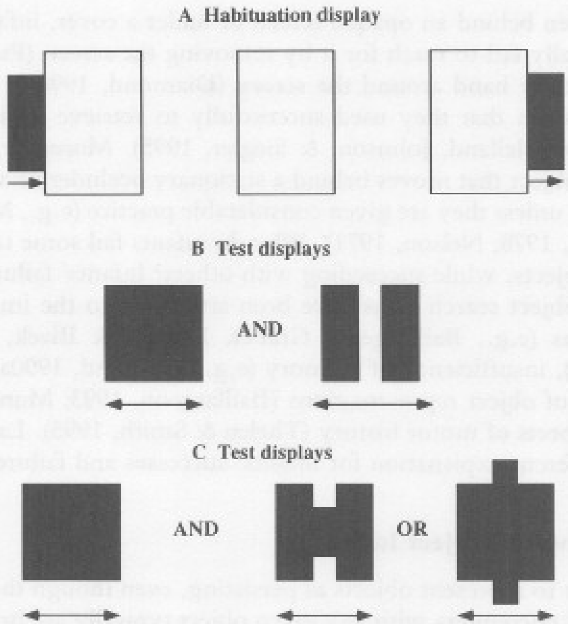

FIGURE 4 Schematic depiction of displays used in studies of infants' perception of the unity and the shape of objects whose parts are revealed over time. (After Van de Walle and Spelke, in press.)

providing evidence that they had perceived the partly occluded square in the occlusion display as one connected object.

In a further experiment, infants were presented repeatedly with the same occlusion display, and then they were shown two fully visible displays with different shapes: a complete square and a more complex form with indentations or protuberances in the previously occluded area (Figure 4C). Adults tested in a separate study reported that the simple square corresponded to the shape of the object in the occlusion event. In contrast, infants looked equally at these two test displays, suggesting that they had failed to perceive the complete shape of the partly occluded square. A number of experiments corroborate the suggestion that young infants fail to perceive the form of an object whose parts are revealed over time (Arterberry, 1993; Kaufmann-Hayoz, Kaufmann, & Walther, 1990; Rose, 1988; Skouteris, McKenzie, & Day, 1992; see Arterberry, Craton, & Yonas, 1993, for discussion). Careful developmental research suggests, moreover, that the ability to perceive the specific shape of such an object develops between 10 and 12 months of age (Arterberry, 1993). We will return to a discussion of this developmental change.

Although the above looking time studies demonstrate that infants represent the unity and stability of occluded objects, young infants have little or no ability to act on objects that are hidden behind visible occluders. If an object is hidden behind an opaque screen or under a cover, infants under 9 months typically fail to reach for it by removing the screen (Piaget, 1954), by directing their hand around the screen (Diamond, 1990b), or even by pressing a button that they used successfully to retrieve a visible object (Munakata, McClelland, Johnson, & Siegler, 1995). Moreover, infants do not track an object that moves behind a stationary occluder or anticipate its re-emergence unless they are given considerable practice (e.g., Moore, Borton, & Darby, 1978; Nelson, 1971). Why do infants fail some tasks involving hidden objects, while succeeding with others? Infants' failures in visual and manual object search tasks have been attributed to the immaturity of action systems (e.g., Baillargeon, Graber, DeVos, & Black, 1990; Diamond, 1990b), insufficiency of memory (e.g., Diamond, 1990a), weakness or instability of object representations (Baillargeon, 1993; Munakata et al., 1995), and aspects of motor history (Thelen & Smith, 1995). Later, we will suggest a different explanation for infants' successes and failures.

B. Apprehending Object Identity

Infants appear to represent objects as persisting, even though their immediate perceptual encounters with any given object typically are brief and sporadic. Do infants also trace the identity of objects that come into view at different places and times, determining whether an object seen at one place and time is the same object that previously appeared at a different place and time? To focus this question, we begin by considering how adults assign identity relations in this situation.

Many philosophers argue that adults' apprehension of object identity relates to our categorization of objects as members of particular kinds (e.g., Geach, 1980; Wiggins, 1980). For example, an object such as a statue can be considered as a statue, a portion of metal, or a symbol of liberty, among many possibilities. Depending on how the object is categorized, the same transformation may lead to different judgments of object persistence and change: melting and remolding, for example, destroys the statue but not the portion of metal. Mature intuitions about object persistence therefore seem to depend on how objects are categorized.

In contrast to these arguments, experiments in visual cognition suggest that perceivers apprehend object identity and object distinctness by virtue of a process that is independent of information for object kind. When visual elements appear at different places and times within a display, relations of identity or distinctness are assigned to the elements in accord with their spatiotemporal properties and irrespective of their categorical identities. A common example occurs when we detect motion at night or in peripheral vision: we often perceive that "a thing" has appeared and moved before we can determine what kind of thing it is (Kahneman & Treisman, 1984). In laboratory studies, adults have been found to represent two distinct alphabetic characters as a single entity when those two characters appear successively within a box that moves continuously across the visual array (Kahneman, Treisman, & Gibbs, 1992). Because this entity is perceived to persist even as it changes both its shape and its category membership (e.g., from an "A" to a "D"), the process that assigns identity relations to the elements evidently does not depend on the process by which the elements are categorized as distinct letters. These disparate studies suggest that adults have multiple processes for tracing persisting objects over time. Studies of infants are beginning to suggest how these processes develop, and how they relate to one another.

A variety of experiments using preferential looking methods provide evidence that infants perceive the identity or distinctness of objects by detecting the spatiotemporal continuity of object motion. In one experiment, for example, infants were familiarized with an object that moved continuously behind two narrow, spatially separated occluders, and then they were presented with fully visible displays containing one versus two objects (Figure 5A). The 4-month-old infants in this experiment looked longer at a fully visible display of two objects, relative to baseline preferences between the displays, suggesting that they perceived a single object in the occlusion event (Spelke, Kestenbaum, Simons, & Wein, 1995). In a further experiment using a similar method, the same finding was obtained at 10 months (Xu & Carey, in press). In a second set of conditions, infants were familiarized with an event involving discontinuous motion: an object moved out of view behind one of the two spatially separated occluders, no motion was

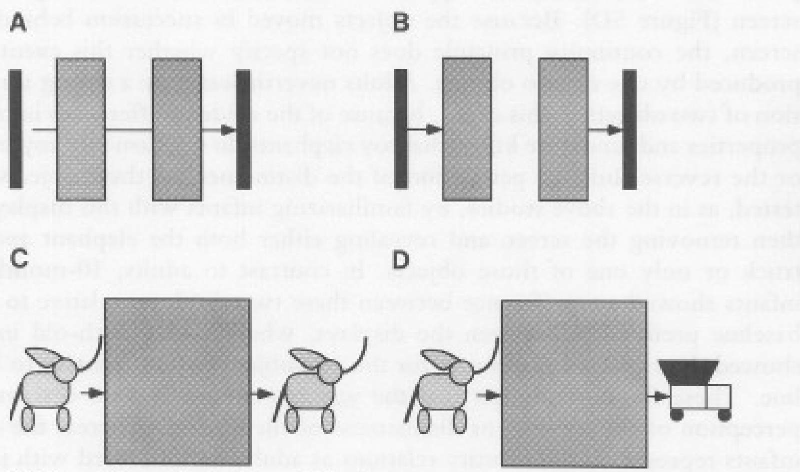

FIGURE 5 Schematic depiction of displays used in studies of infants' apprehension of object identity. (After Spelke, Kestenbaum, Simons, and Wein, 1995; Xu and Carey, in press.)

visible between the occluders, and then an object moved into view from behind the second occluder (Figure 5B). Looking times to the subsequent, fully visible displays provided evidence that both 4- and 10-month-old infants perceived two objects in this occlusion event (Spelke et al., 1995; Xu & Carey, in press). In a third set of conditions, infants were familiarized with an event in which two objects appeared simultaneously on the two sides of a single, wide occluder, and then the objects moved in succession behind the occluder (Figure 5C). Again, 10-month-old infants perceived two distinct objects in this event (Xu & Carey, in press), as did 3- to 5-month-old infants in similar studies (Aguiar & Baillargeon, 1995; Baillargeon & DeVos, 1991; Baillargeon & Graber, 1987).

All these studies suggest that infants apprehend object identity in accord with the principle of continuity: a moving object traces just one connected path over space and time (Spelke & Van de Walle, 1993) (Figure 1B). The continuity principle specifies that a single object participated in the event in Figure 5A, because the occluders were not wide enough to hide two objects occupying distinct locations and moving on distinct paths. This principle specifies that two objects participated in the events in Figure 5B and 5C, because no continuous path can connect the appearances of the objects in these events. The same continuity principle may underlie adults' perception of identity relations in rapidly presented visual displays, independently of the specific categories to which the objects belong (Kahneman et al., 1992).

Further studies by Xu and Carey (in press) suggest surprising limits to infants' apprehension of object identity. In these studies, 10-month-old infants were presented with two featurally distinct objects (e.g., a toy elephant and a toy truck) that appeared in succession behind a single wide screen (Figure 5D). Because the objects moved in succession behind one screen, the continuity principle does not specify whether this event was produced by one or two objects. Adults nevertheless have a strong impression of two objects in this event, because of the evident differences in object properties and kinds: we know that toy elephants do not turn into toy trucks or the reverse. Infants' perception of the distinctness of these objects was tested, as in the above studies, by familiarizing infants with this display and then removing the screen and revealing either both the elephant and the truck or only one of those objects. In contrast to adults, 10-month-old infants showed no preference between these two displays, relative to their baseline preferences between the displays, whereas 12-month-old infants showed the expected preference for the one-object display, relative to baseline. These findings suggest that the younger infants had no determinate perception of the identity or distinctness of the objects, whereas the older infants represented the identity relations as adults do, in accord with information about object properties or kinds.

Subsequent studies by Xu and Carey (1994, 1995, in press; Xu, Carey, Raphaelidis, & Ginzbursky, 1995; Xu, Carey, & Welch, 1995) and other investigators (Hall & Leslie, 1995; Simon, Hespos, & Rochat, 1995; Wilcox, 1995) eliminate a spectrum of potential explanations for the younger infants' failure to perceive object identity from information about object properties and object kinds. In particular, this failure cannot be explained by a failure to perceive, attend to, or remember the property/kind differences, by limitations of this preferential looking method, or by idiosyncracies in the tested objects. Infants' failure occurs with real artifacts such as cups and books as well as with toys, and it occurs despite independent evidence that infants are able to recognize the objects as familiar (Xu & Carey, in press) and to perceive toy animals and vehicles as members of different categories (Mandler, 1992; Mandler & McDonough, 1993; Xu & Carey, in press, 1995). Experiments probing infants' representations of identity relations for genuinely animate objects and for people have yet to be completed, and such studies may show that the animate–inanimate distinction already guides perception of identity in younger infants (see R. Gelman, Durgin, & Kaufman, 1995; Premack & Premack, 1995, for arguments to this effect). The above research suggests, nevertheless, that infants as old as 10 months trace the identity of inanimate objects by relying on spatiotemporal information, irrespective of the objects' perceptible properties or category membership. In this respect, 10-month-old infants differ from older infants and adults.

What brings about the transformation between 10 and 12 months and leads older infants to trace object identity in new ways? Although existing research does not answer this question decisively, two lines of study suggest that the development of a propensity to trace the identity of inanimate objects in accord with information about object kind is related in some way to the acquisition and use of names for kinds of objects. The first evidence comes from a finding by Xu and Carey (in press). In one study involving highly familiar objects, looking preferences varied systematically as a function of a parent's report as to the particular words in the child's vocabulary: children who, by parental report, understood two or more of the words naming the object kinds used in the study ("ball," "bottle," "book," and "cup") appeared to represent the distinctness of these objects when they appeared in alternation behind a wide screen; children who did not command this vocabulary showed no such ability. Although Xu and Carey caution that the relation between naming and individuation must be tested further, they suggest that the development of names for categories and the development of abilities to use those categories to trace identity somehow are linked together.

The other source of evidence linking language to perception of object identity comes from recent studies of adults by Simons (in press). Simons presented adult subjects with a computer display containing five distinct natural objects (scanned into the computer from color photographs), each placed randomly in one of nine distinct positions. After viewing this display for 2 s, subjects were presented with a dark screen for 1–7 s followed by a second display. Subjects' task was to say whether the second display was identical to the first. On half the trials, the two displays were identical. On the remaining trials, the two displays differed in some way. Two changes from the first display to the second are most relevant to the present discussion: position changes, in which the second display contained the same five objects, but one object appeared in a previously unoccupied location, and category changes, in which the second display contained objects at the same five positions, but one object was new (e.g., a red baseball cap might be replaced by a yellow hair dryer).

In two experiments with photographs of natural objects, subjects detected position changes with accuracy levels of about 95% and detected category changes with about 75–80% accuracy. Because some subjects reported naming the objects in the displays, naming was discouraged in two further experiments by the use of nonsense shapes instead of objects in familiar categories. Performance remained high on position change trials but declined nearly to chance level on category change trials. In a final experiment, familiar objects again were presented, but naming was eliminated by requiring that subjects speak continuously while performing the task (they repeated a long prose passage presented over a tape recorder). Although this "shadowing" task had no effect on subjects' ability to detect position changes, their ability to detect category changes was sharply reduced. These findings, like those of Kahneman et al. (1992), suggest a basic visual process for tracing object identity that depends on spatiotemporal information (where objects are and how they move) and that is independent of information for object properties and kinds. The findings add to the suggestion from Xu and Carey's experiments that language plays some role in extending abilities to perceive object identity.

The limitations on infants' perception of object identity discovered by Xu and Carey (in press) could be related to the previously described limitations on object representation reported by Van de Walle and Spelke (in press), Arterberry (1993), and other investigators (Kaufmann-Hayoz et al., 1990; Rose, 1988; Skouteris et al., 1992). Infants may fail to perceive the shape of an occluded object whose parts appear in succession because of a general inability to relate information about object properties such as shape to information about object motion and persistence over time. Such a limitation would explain why young infants successfully perceive the connectedness of an occluded and disoccluded object in Van de Walle and Spelke's (in press) experiment: object connectedness is a spatiotemporal property that applies to all objects independent of shape or category membership. This limitation also would explain why the transition from failure to success occurs at the same ages in the experiments of Arterberry (1993) and Xu and

Carey (in press), during the period when most children begin to learn names for objects. This account makes two untested predictions: (1) developmental changes in the form integration tasks of Arterberry and others will relate specifically to the emergence of names for kinds of objects; and (2) adults, like young infants, will fail tests of form integration if they are required to engage in a verbal interference task while viewing a partly occluded object.

C. Infants' Inferences about Object Motion

Adults who view a moving object typically can predict the object's future motion. When we reach for a moving object, for example, we extrapolate its motion and aim toward the position the object will occupy when the reach is complete. When an object moves out of view, moreover, we usually can anticipate how its motion will continue and where it will stop. Both abilities have been studied in young infants, who appear to make successful inferences about the future and the hidden motions of objects under an interesting subset of the conditions that are effective for adults.

An experiment by Hofsten, Vishton, Spelke, Feng, and Rosander (1995) investigated infants' predictive reaching. Six-month-old infants were presented with a small graspable object that moved within reach either on a linear path or on a path with an abrupt turn at the center (Figure 6A). Because linear and nonlinear paths were equally frequent and randomly ordered, the behavior of the ball at the display's center was unpredictable. In order to catch the object, however, infants needed to begin their reach before it reached the center and to aim for a position beyond it.

For each trial, aiming movements were categorized as to whether infants aimed for a position on the side of the display to which the object would move if it continued in linear motion ("linear extrapolation") or on the side of the display on which the object began and would remain if it turned ("nonlinear extrapolation"). As Figure 6B indicates, infants aimed for positions on a line with the object's initial motion, whether or not the object turned at the center. The same patterns of aiming were observed in a second study in which infants received blocked trials with each pattern of motion: even when the nonlinear motion occurred repeatedly, infants aimed their predictive reaches in accord with a linear extrapolation of the object's initial motion, consistently missing the object! In a third study (Vishton, Spelke, & von Hofsten, 1996) linear extrapolations occurred when every path of motion in the study was novel, such that infants had no opportunity to learn about the object's motion paths. These findings provide evidence that infants reach predictively by extrapolating linear object motion.

A recent experiment by Huntley-Fenner, Carey, Klatt, and Bromberg (1995) investigated infants' inferences about hidden object motion using a

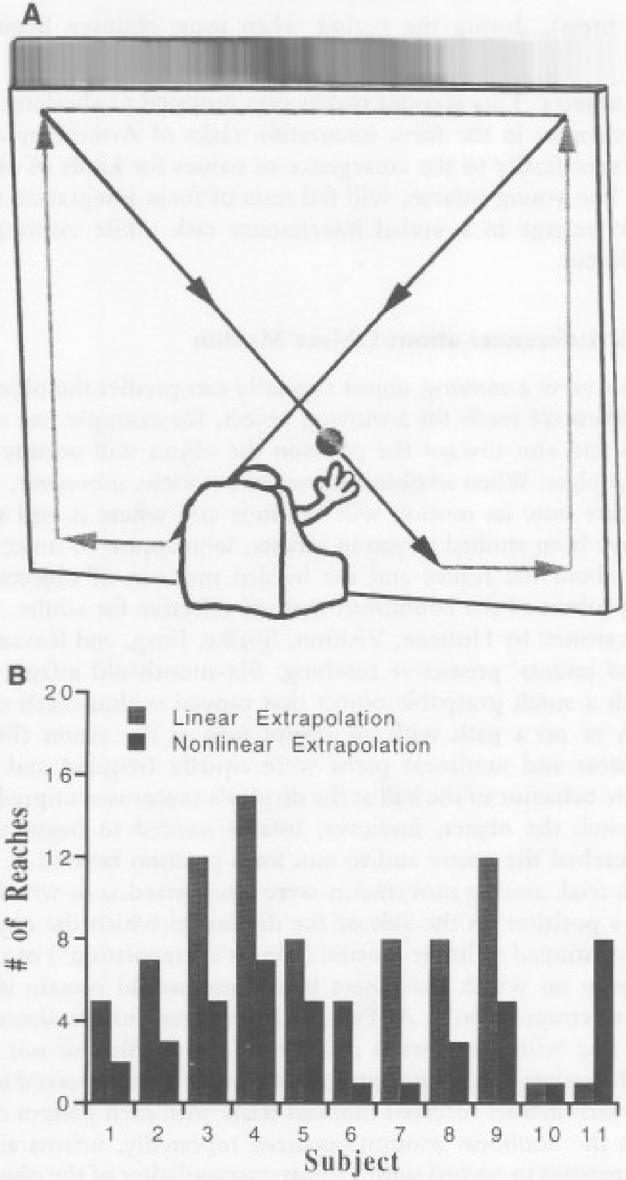

FIGURE 6 (A) Schematic depiction of the four paths of object motion used in the predictive reaching experiments. (B) Numbers of reaches aimed to the linear and nonlinear sides of the display. (After Hofsten, Vishton, Spelke, Feng, and Rosander, 1995; Experiment 1.)

different method. Eight-month-old infants were familiarized with events in which an object was lowered first visibly and then behind a screen to a position on the floor of an open stage (Figure 7). Then a shelf was placed

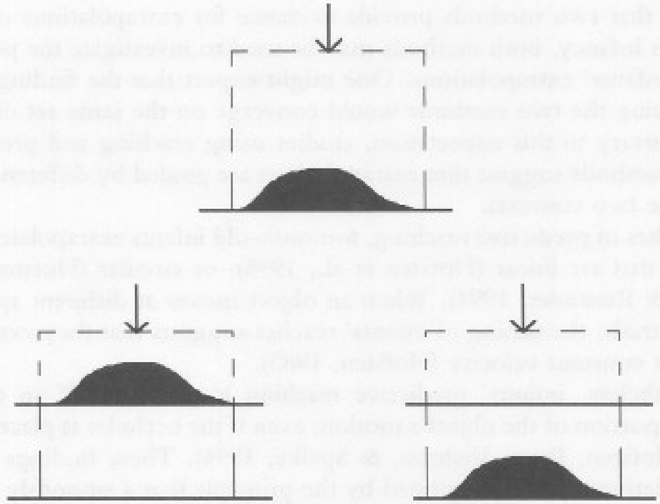

FIGURE 7 Schematic depiction of displays used in a preferential looking study of infants' extrapolation of occluded object motion. (After Huntley-Fenner, Carey, Klatt, and Bromberg, 1995.)

above the stage floor behind the screen, the object again was lowered, and the screen was raised to reveal the object either in a new position on the shelf or in its original position on the floor. When looking times to these outcomes were measured and compared, infants were found to look longer at the outcome in which the object appeared on the floor. This looking preference provides evidence that infants inferred that the hidden object would not pass through the shelf. A considerable number of experiments using preferential looking methods now provide evidence for this inference in infants as young as 3 months (e.g., Baillargeon, 1986, 1987; Baillargeon & DeVos, 1991; Baillargeon et al., 1990; Spelke, Katz, Purcell, Ehrlich, & Breinlinger, 1994; Wilcox et al., 1994, 1995), although some investigators find increases in this ability over the first 8 to 10 months (Lucksinger, Cohen, & Madole, 1992; Sitskoorn & Smitsman, in press) or propose alternative interpretations of some studies (Bogartz, Shinsky, & Speaker, 1995; Cohen, 1995; Thelen & Smith, 1993).[1]

[1] Experiments reported by Spelke, Breinlinger, Macomber, and Jacobson (1992), using a method similar to that of Huntley-Fenner, Carey, Klatt, and Bromberg (1995), provided evidence for extrapolations of occluded object motion at 2½ and 4 months of age. A recent attempt to replicate experiment 1 from that series has failed, however (E. S. Spelke, D. A. King, & Y. Munakata, in preparation). Although the reasons for this failure are not clear, we base no conclusions in this chapter on the findings of Spelke, Breinlinger, Macomber, and Jacobson (1992), pending further study.

Given that two methods provide evidence for extrapolations of object motion in infancy, both methods may be used to investigate the principles guiding infants' extrapolations. One might expect that the findings of the studies using the two methods would converge on the same set of principles. Contrary to this expectation, studies using reaching and preferential looking methods suggest that extrapolations are guided by different principles in the two contexts.

In studies of predictive reaching, 6-month-old infants extrapolate motion on paths that are linear (Hofsten et al., 1995), or circular (Hofsten, 1983; Hofsten & Rosander, 1994). When an object moves at different speeds on different trials, the timing of infants' reaches suggests that they extrapolate motion at constant velocity (Hofsten, 1983).

Nevertheless, infants' predictive reaching is perturbed if an occluder screens a portion of the object's motion, even if the occluder is placed out of reach. (Hofsten, Feng, Vishton, & Spelke, 1994). These findings suggest that predictive reaching is guided by the principle that a smoothly moving object will continue in smooth motion (hereafter, "the principle of inertia") but not by the principle that an occluded object exists and moves continuously (an aspect of the principle of continuity).

In contrast, the preferential looking studies cited above suggest that infants extrapolate object motion in accord with the continuity principle, as do other studies using preferential looking methods (e.g., Aguilar & Baillargeon, 1995; Simon et al., 1995; Wilcox et al., 1994, 1995; Wynn, 1992). Preferential looking studies also provide evidence that infants extrapolate object motion in accord with the principle of cohesion (Figure 1A): If an object moves from view successively at two locations and then is revealed either as a single, cohesive body at one location or as two separate bodies at the two locations, infants look longer at the latter outcome, in accord with the principle that objects maintain their connectedness and boundaries as they move (Huntley-Fenner et al., 1995; see also Spelke, Breinlinger, Jacobson, & Phillips, 1993). Finally, preferential looking studies provide evidence that infants extrapolate object motion in accord with the principle of contact: If two objects move in succession behind a single occluder, with timing that evokes for adults an impression of causality (Michotte, 1963), and then the occluder is removed to reveal that the first object either contacts or stops short of the second, infants look longer at the no-contact test event (Ball, 1973; Kotovsky & Baillargeon, 1994; Van de Walle, Woodward, & Phillips, 1994; see also Leslie, 1988; Oakes & Cohen, in press). This preference provides evidence that infants represented the occluded objects as moving into contact, in accord with the constraint that distinct objects influence one another's motion only if they touch.

Preferential looking experiments suggest, nevertheless, that young infants fail to extrapolate occluded object motion in accord with the inertia principle (Spelke et al., 1994). Infants viewed events in which a ball rolled on a straight line behind an occluder and then was revealed, by the removal of the occluder, at a resting position that was either on or off the original line of motion (Figure 8). Although older infants showed weak preferences for the nonlinear outcome under some conditions, 4- and 6-month-old infants showed no such preferences. These negative findings cannot plausibly be attributed to limitations of the preferential looking method, because the method provided positive evidence for inferences about object motion in accord with the continuity principle (Spelke et al., 1994). In preferential looking contexts, infants appear to infer that a hidden object will move in accord with the principles of continuity, cohesion, and contact but not in accord with the principle of inertia.

In brief, infants make inferences about object motions in at least two contexts: when they reach for a moving object and when they watch an object move behind an occluder. As one might expect, infants' inferences in the two situations accord only with a subset of the constraints on object motion that adults recognize. A comparison of the conditions under which

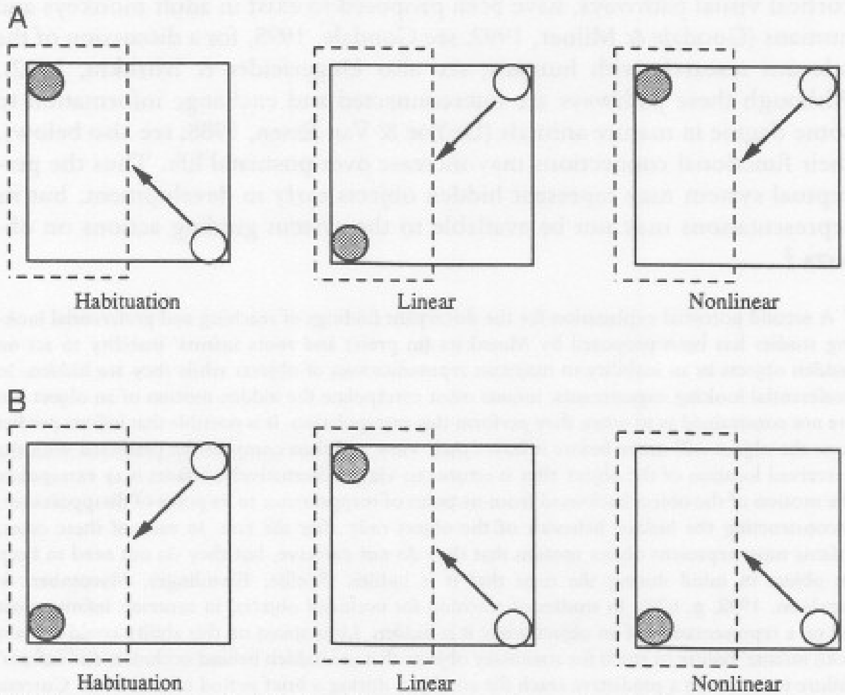

FIGURE 8 Schematic depiction of the displays used in studies of infants' extrapolation of object motion on linear paths. Open and shaded circles indicate the initial and final portions of the object, respectively. (After Spelke, Katz, Purcell, Ehrlich, and Breinlinger, 1994.)

extrapolations occur reveals that the subsets of constraints guiding inferences in the two situations are not the same. In preferential looking experiments, inferences are guided by the principle of continuity but not by the principle of inertia; in predictive reaching experiments, in contrast, inferences are guided by inertia but not by continuity. One interpretation of this "double dissociation" in performance is that infants do not possess a single system of object representation but at least two partly separable systems: a system subserving object-directed reaching (and perhaps other object-directed actions) and a system subserving perception of familiar events and reactions to novelty.

These findings suggest a different interpretation of the discrepant evidence for object representation from the studies reviewed above. Recall that infants steadfastly refuse to retrieve occluded objects until about 9 months (e.g., Piaget, 1954), despite evidence from preferential looking experiments that infants as young as 3 months represent such objects (e.g., Baillargeon & DeVos, 1991). These contrasting findings may stem from differences between infants' two systems for representing objects. Distinct systems subserving object perception and object-directed reaching, residing in distinct cortical visual pathways, have been proposed to exist in adult monkeys and humans (Goodale & Milner, 1992; see Goodale, 1995, for a discussion of the relevant research with humans; see also Ungerleider & Mishkin, 1982). Although these pathways are interconnected and exchange information to some degree in mature animals (DeYoe & Van Essen, 1988; see also below), their functional connections may increase over postnatal life. Thus the perceptual system may represent hidden objects early in development, but its representations may not be available to the system guiding actions on objects.[2]

[2] A second potential explanation for the discrepant findings of reaching and preferential looking studies has been proposed by Munakata (in press) and roots infants' inability to act on hidden objects in an inability to maintain representations of objects while they are hidden. In preferential looking experiments, infants must extrapolate the hidden motion of an object but are not constrained as to when they perform this extrapolation. It is possible that infants predict how the object will move before it leaves their view and then compare the predicted with the perceived location of the object after it returns to view. Alternatively, infants may extrapolate the motion of the object backward from its point of reappearance to its point of disappearance, reconstructing the hidden behavior of the object only after the fact. In each of these cases, infants must represent object motion that they do not perceive, but they do not need to keep an object in mind during the time that it is hidden (Spelke, Breinlinger, Macomber, & Jacobson, 1992, p. 620). In studies of reaching for occluded objects, in contrast, infants must act on a representation of an object while it is hidden. Limitations on this ability could explain both infants' failure to reach for stationary objects that are hidden behind occluders and infants' failure to maintain a predictive reach for an object during a brief period of occlusion. Current experiments are attempting to test this explanation by investigating whether, in preferential looking experiments, infants can actively maintain a representation of a hidden object (Munakata, in press).

If systems for perceiving and for acting on objects initially operate in relative independence, then important changes might occur over cognitive development as these systems become intercoordinated. As adults, we are able to draw on all our powers of reasoning in order to locate a hidden object: we mentally retrace our steps, eliminate physically impossible locations, and deduce the set of places the object might occupy. In principle, any knowledge at our disposal may inform this search, giving us flexibility that infants appear to lack. Nevertheless, even adults' object-directed actions show limitations that are reminiscent of the limitations found in infants. When we attempt to catch a rapidly moving object, we are well advised to keep our eyes on it: sudden, brief occlusion or blackout of an object's trajectory impairs the accuracy of mature reaching (e.g., Whiting & Sharp, 1974). Conversely, adults' perception of object properties such as length is prone to distortions that do not hinder reaching and grasping (Aglioti, DeSouza, & Goodale, 1995; Vishton & Cutting, 1995). These findings suggest that systems for perceiving objects and for acting on objects remain partially distinct for adults, and that mature abilities to coordinate these systems are hard-won achievements that are limited in accuracy, slow in execution, and inconsistent in application.

D. Summary: Object Representations in Infancy

The literature reviewed above supports a number of conclusions. First, capacities to represent and reason about objects emerge at an early age and develop synchronously with capacities to perceive and manipulate objects. Early representations of objects accord with three principles capturing general and highly reliable constraints on how objects behave: continuity, cohesion, and contact (Figure 1). These principles also guide infants' perception of objects, suggesting that a common system of representation underlies object perception and physical reasoning (see Spelke & Van de Walle, 1993, for discussion). Finally, the continuity principle guides infants' apprehension of object identity, before the age at which infants trace the identity of inanimate objects by using knowledge of specific object properties and kinds. Nevertheless, the continuity principle does not appear to guide early-developing actions on objects such as object-directed reaching. Comparisons of the extrapolations of object motion revealed by preferential looking tasks and reaching tasks suggest that infants have at least two systems for representing objects and extrapolating object motions: one system guiding their predictive actions on objects and a second system guiding their interpretations of observed events in which objects move from view.

Studies of adults and older children suggest that the processes by which infants represent objects persist over development. Adults who are prevented from naming objects, or who must respond to visual displays rapidly, appear to trace object identity only in accord with spatiotemporal properties of object motion, whereas adults who reach for rapidly moving objects extrapolate object motion in accord with inertia and are perturbed by periods of occlusion. In addition, adults appear to reason most accurately and consistently about the aspects of object motion that guide infants' reasoning in preferential looking experiments. Whereas adults easily and accurately apply the principles of continuity, cohesion, and contact in reasoning about objects, we often have more difficulty, and make more errors, when we must apply the principle of inertia (McCloskey, 1983, discusses errors in adults' reasoning about inertia). This last phenomenon suggests that the principles guiding early object representations remain central to mature reasoning (Spelke, 1994).

Despite these parallels, adults and older children succeed in representing objects, apprehending object identity, and extrapolating object motion under conditions where infants fail. Studies of children and adults converge to suggest two sources of developmental change. First, children and adults are able to consider an object as a member of a kind, and they can use language to single out and remember kinds of individuals. This change may lead children to become increasingly sensitive to object properties that are informative about object kinds, and to use information about those properties to trace identity. Second, children and adults are able to use knowledge of the behavior of objects to guide actions on objects. In particular, they can use knowledge that objects exist continuously to guide their search for an object that has moved from view. Both changes may depend on emerging abilities to relate distinct representational systems to one another, using representations constructed by one system to guide processes normally subserved by a different system. We return to this change in the next section, because it appears to contribute to the development of spatial representation.

III. DEVELOPING KNOWLEDGE OF SPACE

Like many other species, humans construct representations of the surrounding layout and of the locations of objects. Humans and other animals use spatial representations to keep track of where they are, to navigate from place to place, and to guide their search for objects (see Gallistel, 1990; McNaughton, Knierim, & Wilson, 1995, for reviews). Do these accomplishments depend on a unitary representation of the environment that guides all spatial behavior, or do navigation and object localization depend on a number of distinct representations? If distinct representations underlie performance of different spatial tasks, how do the processes that construct these representations interact, and how do their interactions change with development?

In this section, we consider experiments on infants' and young children's developing knowledge of their own spatial position and of the positions of objects. Because the perceptual systems that give rise to our primary awareness of space are discussed in the chapter by Kellman, we focus on children's abilities to represent the locations of hidden objects over the course of their own movement and to reorient themselves after they have lost track of their own position and heading. Studies of these abilities suggest that mechanisms for representing space emerge early in development and capture the information about spatial position that was most reliable in the environments in which humans and other mammals evolved. These studies further suggest that young children have multiple, task-specific systems for representing space, and that developmental changes in spatial representation depend on the child's growing ability to relate these distinct systems to one another.

A. Aspects of Spatial Knowledge

Investigators from many different theoretical perspectives agree that successful navigation depends on processes for extracting the invariant geometric relations among significant locations in the environment, and that these relations become available to humans and other animals as they move about (e.g., Gallistel, 1990; Gibson, 1979; McNaughton et al., 1995). To navigate successfully in the manner of human adults and other animals, a child must come to draw on a number of processes that inform her about her own movements and about the spatial relations among objects. First, she must be able to perceive and represent the spatial locations of objects relative to herself and from a single perspective (see Huttenlocher, Newcombe, & Sandberg, 1994, discussed below). Information about such "egocentric" locations can be derived from vision, audition, and reaching and is often redundantly specified (for a review see Kellman, 1993). As a child moves, she must be able to perceive that environmental locations remain constant despite their changing egocentric directions (Kellman, 1993), she must perceive the direction and extent of her motion, and she must use information about her own motion and about the unchanging positions of objects to compute changes in her own position (see Bremner, Knowles, & Andreasen, 1994, and below). Information for one's own motion is available in changing optic, acoustic, and kinesthetic arrays (Gibson, 1979) and is used by a wide variety of mobile animals to compute accurate representations of their own changing positions (Gallistel, 1990). Finally, the child must form enduring representations of those spatial relations among objects that are independent of her own position and therefore remain invariant as her position changes. These environment-centered or "allocentric" representations are discussed at length in upcoming sections.

B. Infants' Knowledge of the Spatial Locations of Objects

As adult humans and other mammals explore new environments, they form allocentric representations of significant locations (e.g., Loomis et al., 1993; Montgomery, 1952; Morris, 1981; O'Keefe & Nadel, 1978; Rieser, Guth, & Hill, 1986; Tolman, 1948). When in human life do we become able to form and use such representations? Many of the experiments addressing this question with human infants use variations on a method developed by Montgomery (1952), who studied spatial representation in adult rats, and so we begin by summarizing Montgomery's experiments.

Montgomery's studies are based on a behavioral pattern that rats often exhibit in the laboratory: When food is placed at two locations in a maze, rats tend to collect the food by taking alternating trips to the two locations. Because the rats in early studies always began their trips from a single starting position, their "spontaneous alternation" could reflect either a tendency to alternate two responses (i.e., turning left and turning right) or a tendency to alternate visits to two places (i.e., the food stored in the northern and southern end of the maze). In a series of experiments, Montgomery distinguished these possibilities by allowing rats to search for the food from variable starting positions. Her studies clearly showed that rats alternated their visits to the two places, not their performance of the two responses. This and other experiments (e.g., Tolman, 1948; see Gallistel, 1990, for a review) suggest that the rats formed an allocentric representation of their surroundings, and that this representation guided their locomotion through the maze.

In contrast, Piaget suggested that human infants and young children represent the space around them egocentrically, failing to take account of changes in their own positions when they search for hidden objects (Piaget, 1952, 1954). Piaget's conclusion was based on observations that have been amply confirmed by subsequent studies. In one study similar to that of Montgomery (1952), for example, infants watched as a toy was placed in one of two wells standing side by side on a table, the wells were covered, and infants reached for the toy on several familiarization trials (Bremner & Bryant, 1977) (Figure 9). Infants then were moved to the opposite side of the table and again were allowed to reach for the toy, which was hidden in the same well for half the infants and the opposite well for the others. Regardless of where the toy was hidden, 9-month-old infants tended to reach to the new well, repeating the action that had revealed the toy on the familiarization trial. Acredolo (1978) obtained similar results using a paradigm in which 6-, 11-, and 16-month-old infants learned to anticipate with a head turn the appearance of an experimenter in a window to their right or left. After being moved to the opposite side of the room, nearly all the 6-month-old infants and most of the 11-month-old infants turned toward

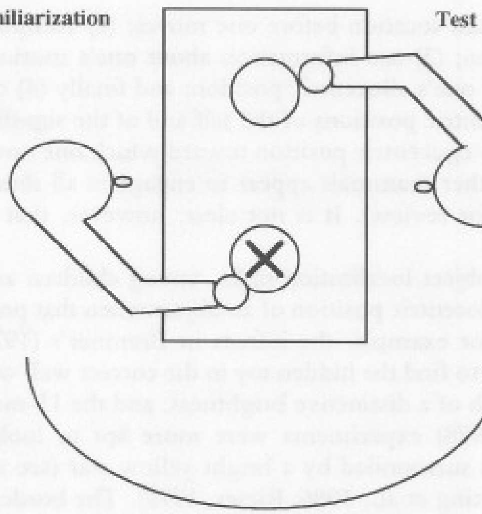

FIGURE 9 Schematic depiction of the setup and findings of a study of infant spatial representation. (After Bremner, 1978.)

the wrong window to look for the experimenter. Only the 16-month-old children searched the allocentrically correct position, as rats would be expected to do.

Although these results suggest that the infants failed to represent the allocentric position of the hidden object, this failure may have occurred in part because the task conditions encouraged young children to learn a particular motor response to bring about a desired result (Bremner, 1978). In further tests using procedures designed to minimize response learning, younger infants were found to form allocentric representations of the locations of events. For example, McKenzie, Day, and Ihsen (1984) trained 6- and 8-month-old infants to anticipate the emergence of a person at one of several locations, over variations in the infant's own heading. On test trials, infants were turned to face in a new direction and were cued that the person was about to appear. Infants tended to look in a novel egocentric direction toward the correct allocentric position. These and other findings (e.g., Bremner, 1978; Keating, McKenzie, & Day, 1986; Landau & Spelke, 1984; Rieser, 1979) suggest that 6- to 9-month-old infants have some ability to represent space in an environment-centered framework. In contrast to adult rats, however, infants are prone to look or reach to egocentric locations when they act repeatedly on an object viewed from a single location and direction (Acredolo, 1990).

When children succeed at responding correctly to an object's allocentric position, what processes underlie their achievement? One solution to the above localization tasks is to (1) perceive and represent the allocentric position of a significant location before one moves; (2) compute the extent of one's own motion; (3) use information about one's motion to update the representation of one's allocentric position; and finally (4) combine knowledge of the allocentric positions of the self and of the significant location to compute the new egocentric position toward which one now must move or turn. Rats and other mammals appear to engage in all these processes (see Gallistel, 1990, for review). It is not clear, however, that young children engage in them.

In the above object localization tasks, young children are better able to respond to the allocentric position of an object when that position is perceptually distinct. For example, the infants in Bremner's (1978) experiments were more likely to find the hidden toy in the correct well when the toy was covered by a cloth of a distinctive brightness, and the 11-month-old infants in Acredolo's (1978) experiments were more apt to look at the correct window if it was surrounded by a bright yellow star (see also Acredolo & Evans, 1980; Keating et al., 1986; Rieser, 1979). The borders of the setting in which an object is hidden also appear to mark the object's location for young infants (Keating et al., 1986; Wilcox et al., 1994).

These findings suggest that infants, like other mammals, can use visible landmarks as information for the locations of unseen objects and events. The findings raise further questions, however, about the nature of the representations and processes guiding infants' successful performance in these tasks. For example, do landmarks allow infants to form an allocentric representation of a location, or do they allow the formation of a direct association between themselves and the hidden object, permitting the object to be located by perceptual guidance rather than by spatial knowledge? (See O'Keefe & Nadel, 1978, for extensive discussion of these contrasting strategies for locating objects.) If proximity to a landmark facilitates true spatial knowledge, how much of the environment is incorporated into the infant's spatial representation? Experiments provide evidence that landmarks placed far from a hidden object are less effective as guides to object search (Acredolo & Evans, 1980), suggesting either that the landmark acts as a perceptual beacon or that the infant's spatial representation includes information only in the vicinity of the object. Further experiments could distinguish these possibilities.

As children become adept at independent locomotion in the second year of life, their representations of locations in the environment become more precise, and they become better able to keep track of a hidden object's location in the absence of visible landmarks. For example, Huttenlocher et al. (1994) showed 16- to 24-month-old children a toy being hidden in a long and narrow homogeneous sandbox, smoothed the surface of the sand, called the child's attention away from the display while she remained stationary or turned 180°, and then encouraged her to find the toy. Even the youngest subjects searched for the hidden toy fairly accurately, without any direct landmark indicating its position and independent of the presence of landmarks in the background. By 16 months, children evidently encode and use abstract distance information rather than having to rely on a direct-associative, perceptual guidance strategy. In a further experiment, children were translated to a new position between hiding and search. Even the youngest subjects succeeded in locating the toy, suggesting that they formed allocentric representations of the environment, updated their own position within the environment, and deployed this knowledge to guide their search. Other studies provide converging evidence that 2-year-old children have an allocentric representational capacity (e.g., Acredolo, Adams, & Goodwyn, 1984), although children sometimes have trouble updating their own position (Bremner et al., 1994).

In further studies, young children used allocentric representations to determine the shortest route to a goal. Garino and McKenzie (1988) showed 18- to 24-month-old children an environment containing a chair in which their parent sat behind an L-shaped barrier. After viewing the chair and barrier from overhead or on the ground, the child was placed facing one side of the barrier (such that both the mother and the second side of the barrier were hidden) and was encouraged to move to the mother. Children reliably moved to the mother on the shorter route, avoiding the hidden side of the barrier. The children evidently represented the hidden goal and barrier and used this representation to guide their locomotion.

To locate an object from a novel position in the absence of landmarks, children must represent their own changing position relative to the object. A wide variety of animals accomplish this task through a process of path integration, in which the moving animal updates its position in accord with information about its direction, speed, and acceleration (Mittelstaedt & Mittelstaedt, 1980; Muller & Wehner, 1988; see Gallistel, 1990, for review and discussion). Research with humans provides evidence that path integration is reasonably accurate in adults (e.g., Loomis et al., 1993; Rieser, Guth, & Hill, 1986) and functional in young children (Bremner et al., 1994; Landau, Spelke, & Gleitman, 1984; Lepecq, 1984; Rider & Rieser, 1988) and infants (Lepecq & Lafaite, 1989).

Infants who are tested in the spatial localization tasks described above show higher levels of allocentric localization when they are able to move themselves actively from place to place (Acredolo et al., 1984; see Acredolo, 1990, for discussion) and have prior experience with independent locomotion. Infants who know how to crawl, or who have learned to locomote in a walker, show higher levels of allocentric responding than infants of the same age who have not begun to crawl or use a walker (Bertenthal, Campos, & Barrett, 1984). It is noteworthy that the onset of hands-and-knees crawling correlates with improved allocentric responding when objects in the environment remain in fixed positions but does not correlate with improvement in infants' ability to track changes in the position of a movable object (Bai & Bertenthal, 1992). This dissociation suggests that the increase in allocentric responding by locomoting infants is brought about by the use of path integration or perceptual tracking of fixed environmental positions during self motion, rather than by increased attention to the environment in general.

Studies of young children provide evidence that they update their position without guidance from direct landmarks by means of computations based partly on internal representations of their own movements. For example, Lepecq (1984) familiarized 4- to 6-year-old children with a table in a featureless circular room containing four featurally identical and symmetrically placed buttons, one of which could be pushed to activate a sound (Figure 10). After a child became familiar with the location of the active button, she was blindfolded and walked a variable distance around the table (from ¼ turn to more than one complete revolution). The child's ability to represent the extent of her displacement and to compute her new position was assessed by removing the blindfold, encouraging her to activate the button that produced the sound, and then asking her to return to her initial position. At all ages, children tended to press the correct button and to

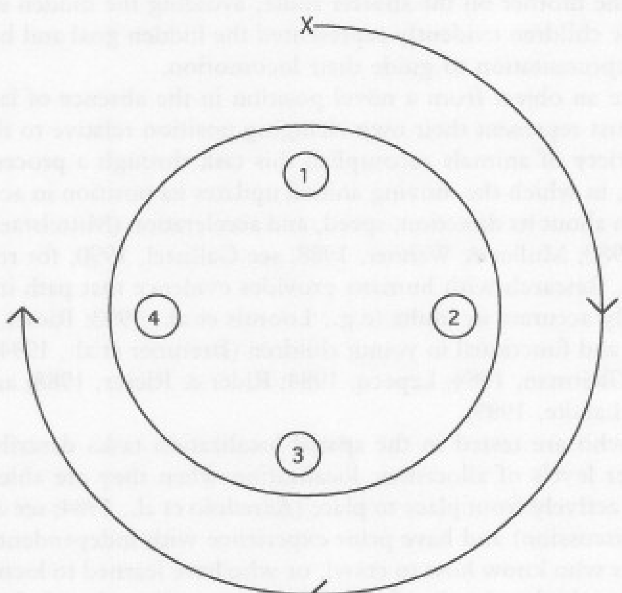

FIGURE 10 Schematic depiction of the display used to test children's path integration abilities. A blindfolded child began at X and walked a variable distance on the path indicated by the arrow. (After Lepecq, 1984.)

return to their starting position with above-chance accuracy, and their two performance measures were highly related. These and other findings (Landau et al., 1984; Lepecq & Lafaite, 1989; Rider & Rieser, 1988) provide evidence that children keep track of the distance and direction in which they move, even in the absence of immediate visual information, and that they use this information to derive the allocentric positions of objects.

C. Spatial Reorientation

We turn now to studies of children's abilities to relocate themselves when they are disoriented. Although animals regularly use path integration and other processes to keep track of their changing positions as they move through the environment, many animals also have systems for re-establishing their position when the path integration system fails and they lose their sense of where they are. To reorient itself in a familiar environment, a disoriented animal must perform some comparison between the environment it now perceives and a representation of the environment it remembers. A variety of studies suggest that this comparison process relies on a representation of the *geometry* of the perceived and remembered environment, a representation of surrounding surfaces, hills, valleys, and enclosures that captures information about the shapes and dispositions of these surfaces (Gallistel, 1990).

The clearest evidence for geometry-based reorientation in animals comes from experiments by Cheng and Gallistel (Cheng, 1986; Margules & Gallistel, 1988; see also Gallistel, 1990). Because their studies are direct precursors to research with young children, we describe one representative experiment in detail (Cheng, 1986) (Figure 11). Cheng and colleagues brought hungry rats into a closed rectangular test chamber, showed them the location of a food supply that was partially buried within the chamber, and then removed the animals, disoriented them, and returned them to the chamber where the food was now fully buried. Based on the studies of rats reviewed above, Cheng assumed that the rats represented the allocentric position of the food during their first encounter with the room (e.g., a rat might

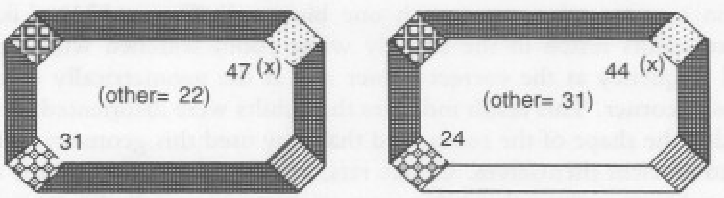

FIGURE 11 Schematic depiction of the testing chambers and the rats' search patterns in an experiment by Cheng (1986).

represent the food as located at the room's northern corner). In order to use this representation to locate the food after disorientation, the rats now needed to re-establish their own sense of orientation (e.g., determining their present heading with respect to north).

Rats were presented with a variety of sources of information that, in principle, could serve to establish their current heading: The corners of the chamber were decorated with distinctive patterns and suffused with distinctive odors, and the brightness of one wall of the chamber contrasted sharply with that of the others. To the investigators' initial surprise, the rats failed to use this information. Instead, rats searched with high and equal frequency at the correct food location and at the geometrically equivalent, opposite location in the room, the two locations that stood in the correct geometric relation to the shape of the test chamber (Figure 11). These findings suggest that the rats reoriented themselves and located the food in accord with the shape of the environment and not in accord with nongeometric properties of the environment.

The failure of rats to reorient by nongeometric information almost certainly did not stem from an inability to detect or attend to that information. Nongeometric properties of an environment such as the brightness of a wall and the quality of an odor are detected by rats in many situations and are used by them in other spatial tasks (see Gallistel, 1990, for a review). Indeed, rats have been shown to learn, over a long series of trials, the locations of stable nongeometric features of the environment (Cheng, 1986; Knierim, Kudrimoti, & McNaughton, in press). These findings suggest that a task-specific system for representing the shape of the environment underlies rats' reorientation in this situation. This system may be used for reorientation in all but the most familiar environments (McNaughton et al., 1995).

Would humans show the same limitations as rats? To address this question, we adapted Cheng and Gallistel's method for studies of human adults and children (Hermer & Spelke, 1994, in press). In our first study, adult subjects were brought into a rectangular room, watched as an experimenter hid an object in one corner, closed their eyes and inertially rotated themselves until they were disoriented, and finally opened their eyes and searched for the hidden object. Adults were tested in a white, rectangular room with no distinctive nongeometric landmarks to break the room's symmetry, and also in a rectangular room with one blue wall (Figure 12A). Like rats, human adults tested in the entirely white room searched with high and equal frequency at the correct corner and at the geometrically equivalent opposite corner. This result indicates that adults were disoriented, that they encoded the shape of the room, and that they used this geometric information to reorient themselves. Unlike rats, human adults searched the correct corner almost exclusively in the room with one blue wall. Adults evidently were able to conjoin geometric with nongeometric information so as to search in a location "to the *left* of the *blue* wall."

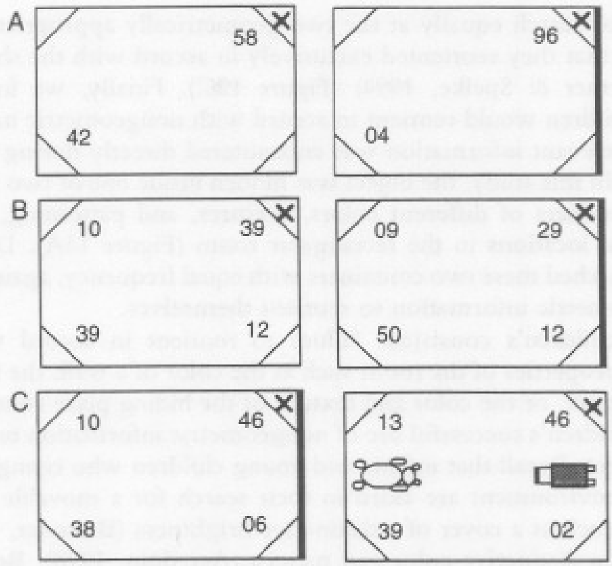

FIGURE 12 Schematic depiction of the rooms and subject search patterns in studies of children's and adults' ability to reorient themselves. (A) The percentage of search in each corner by adults in the all-white room (left) and the room with one blue wall (right). (B) The percentage of search by children 18–24 months in the same two rooms. (C) The percentage of search by children the same age in the room with one blue wall (left) and the room with toy truck and toy bear landmarks (right). (After Hermer and Spelke, 1994.)

We next tested children 18–24 months of age in these two conditions, using a similar procedure. In the all-white room, young children searched equally often at the correct corner and the geometrically equivalent opposite corner (Figure 12B). This search pattern indicated that they, too, were disoriented and that they reoriented in accord with a representation of the shape of their surroundings, like adults and rats. In the room with one blue wall, to our surprise, children continued to search equally at the two correctly shaped corners, irrespective of the location of the blue wall. Children's performance therefore resembled that of rats and contrasted with that of adults.

Further experiments explored a variety of possible reasons for children's failure to reorient in accord with the room's nongeometric properties. For example, we investigated whether children would reorient more effectively if the symmetry of the room were broken by more salient nongeometric information, by testing children in a room containing two distinctive toys of similar global dimensions but different colors, textures, and identities, each placed between two corners flanking a short wall (Figure 12C). We also investigated whether children would reorient by using nongeometric landmarks if they were given several minutes to play with each landmark before the study. These manipulations had no effect on performance: children continued to search equally at the two geometrically appropriate corners, suggesting that they reoriented exclusively in accord with the shape of the room (Hermer & Spelke, 1994) (Figure 12C). Finally, we investigated whether children would reorient in accord with nongeometric information when the relevant information was encountered directly during search for the object. In this study, the object was hidden inside one of two identically shaped containers of different colors, textures, and patterning, placed in symmetrical locations in the rectangular room (Figure 13A). Disoriented children searched these two containers with equal frequency, again failing to use nongeometric information to reorient themselves.

Young children's consistent failure to reorient in accord with nongeometric properties of the room such as the color of a wall, the identity of a nearby object, or the color and texture of the hiding place contrasts with oriented children's successful use of nongeometric information to relocate a hidden object. Recall that infants and young children who change position within an environment are aided in their search for a movable object by landmarks such as a cover of a distinctive brightness (Bremner, 1978) or a window of a distinctive color and pattern (Acredolo, 1978). Because this contrast suggests that reorientation and object search depend on task-specific systems for representing the environment, our next experiments tested that suggestion more directly.

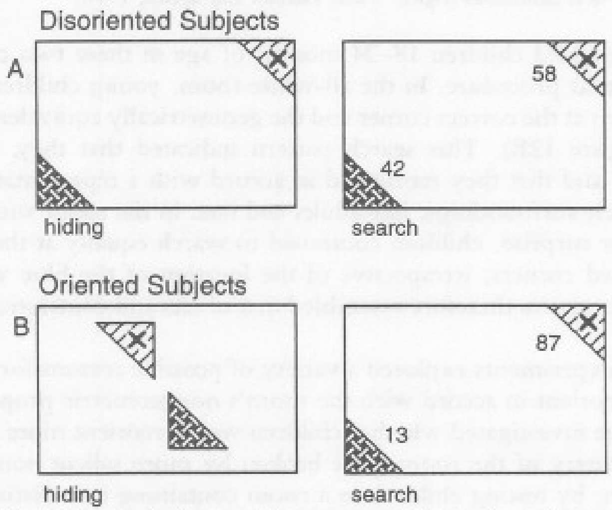

FIGURE 13 Schematic depiction of the rooms and children's search patterns in a study contrasting children's ability to reorient themselves and to locate a moving object. (A) The percentage of search in each container by children who were disoriented. (B) The percentage of search by oriented children who located an object in a movable container. (After Hermer and Spelke, in press.)

In one set of studies, children searched for a toy hidden in one of two distinctive containers in opposite corners of the all-white, rectangular room (Hermer & Spelke, in press) (Figure 13). Children in one condition were given the standard reorientation task: After an object was hidden in one corner, children closed their eyes, were turned until they were disoriented, opened their eyes, and searched for the object. In a second condition, the two containers stood in the center of the room while the object was hidden, children closed their eyes but remained at rest while the containers were placed in the same corners as in the first condition, and then children opened their eyes and searched for the object.

The children in these two conditions faced exactly the same environment at the time of object search, but their tasks were different. Because those in the first condition had lost track of their own position, they needed to reorient themselves in order to find the object. In contrast, children in the second condition were oriented but had lost track of the position of the object, because the object and its container were moved while their eyes were closed. Children's search patterns differed markedly in the two conditions: Whereas disoriented children searched the two containers equally, oriented children preferentially searched the container with the appropriate nongeometric properties (see Figure 13). This finding suggested that distinct representations underlie reorientation and search for movable objects.

A final, double dissociation experiment provided strong support for this suggestion. In this experiment, we again compared object search by children who were disoriented and children who were not. All subjects searched for an object in a distinctively colored and patterned container, after first watching as the object was hidden in one of two containers flanking a short wall of the rectangular room (Figure 14). Then the subjects closed their eyes (and, in one condition, were disoriented) while the two containers were moved quietly across the room to the opposite short wall (Figure 14). This transformation broke the original associations between the geometric and nongeometric properties of the object's hiding location: For example, if the object originally was hidden in a pink container on the left side of a short wall, the pink container now appeared on the right side of a short wall.

Although both disoriented and oriented children viewed exactly the same environment throughout this experiment, the thesis of task-specific systems for reorienting and for locating movable objects predicts that their search performance would differ on the first search trial (before all the children discovered that the toy had moved with one of the containers). Because disoriented children found themselves in a room that was geometrically equivalent to the room in which the toy was hidden, they should not notice that the containers had moved and should confine their search to the corner with appropriate geometry. In contrast, oriented children should infer at

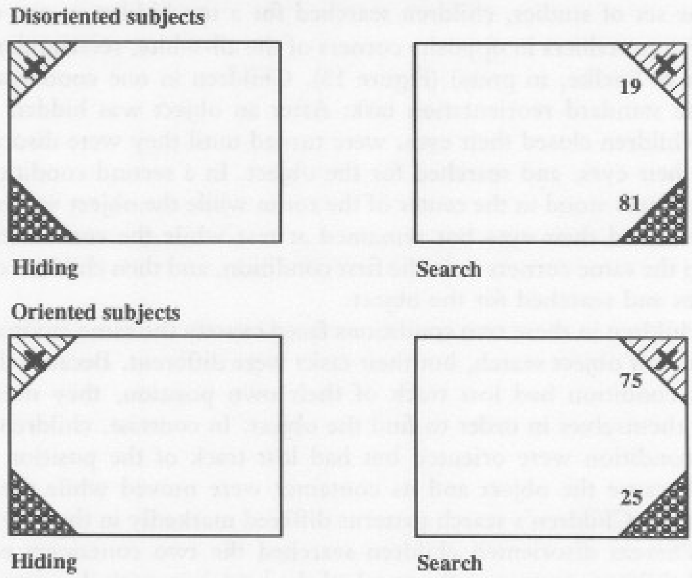

FIGURE 14 Schematic depiction of the room and children's search patterns on their first trial in a study contrasting children's ability to reorient themselves and children's ability to locate a movable object. (After Hermer and Spelke, 1995.)

once that the containers have moved (because, e.g., the two containers previously located to a child's left now appeared to her right). Like the children in the previous experiment, therefore, they should search for the toy in the container with the correct nongeometric properties. As Figure 14 indicates, these predictions were supported: Disoriented subjects searched the geometrically appropriate container, whereas oriented subjects searched the nongeometrically appropriate container.

This last experiment provides evidence that reorientation depends on spatial representations that are task-specific: When children are unsure of their position, they rely on a representation of the shape of the environment to reorient themselves; when they are trying to locate a movable object, they rely on the properties of the container holding it. A similar dissociation has been found in adult rats (Biegler & Morris, 1993). Moreover, these representations are informationally encapsulated: they operate only on a subset of the information that the child has perceived and currently holds in mind. When children closed their eyes before the first search trial, they had no way of knowing whether they would be called on to reorient themselves or to find a displaced object. The subsequent search performance of oriented children therefore provides evidence that all the children encoded the non-geometric properties of the box in which the toy was hidden at the start of the trial. Nevertheless, the disoriented children searched for the object by geometry alone: They appeared unable to conjoin geometric and nongeometric information about the object's location so as to infer that the object had moved. Task-specificity and informational encapsulation are hallmarks of modular cognitive systems (Fodor, 1983). The present findings therefore are consistent with the thesis that reorientation depends on a "geometric module" (Cheng, 1986).

Children and rats may appear unintelligent when they reorient themselves in accord with the shape of the environment. Geometry-based reorientation is not likely to be an adaptive strategy in today's carpentered, symmetrical settings, where distinctive colors and patterns (for humans) and distinctive odors (for rats) might signal orientation more effectively than the shape of the layout. Over the course of mammalian evolution, however, the shape of an animal's surroundings may have been the most reliable kind of information specifying environmental locations and directions. Despite changes in foliage, snowfalls, fires, and other events that occur during an animal's lifetime, the macroscopic shape of the environment, its hills, cliffs, and ravines, would have persisted. Studies of reorientation suggest that young children reorient in accord with the most reliable information available in the environments in which mammals evolved.

Many questions remain concerning the nature of the spatial representations guiding young children's reorientation: For example, are young children's geometric representations egocentric or allocentric? Do these representations include the whole environment or only local views of it, and do they capture movable or only fixed features of the environment? Studies investigating some of these questions are in progress. We close, however, by raising three interrelated questions about the development of spatial reorientation. First, when do children begin to use geometric and nongeometric information more flexibly in reorientation tasks? Second, does the geometric system found in children and rats persist over this developmental change, or is it reorganized as older children begin to orient more flexibly? Finally, what underlies adults' more flexible performance?

In order to approach these questions, we began to investigate developmental changes in spatial representations by repeating the reorientation studies with 3- and 6-year-old children. In the rectangular room with one blue wall, disoriented children searched for an object that was hidden either directly behind the blue fabric or in a corner next to the blue wall. When the object was hidden behind the blue wall, children of both ages succeeded on nearly all trials (Figure 15). When the object was hidden in a corner, children aged 6–6½ years succeeded almost as well as adults, but younger children searched equally at the two geometrically appropriate corners (Hermer, 1994). These findings suggest that the ability to use nongeometric information does not emerge in an all-or-none fashion: children come to use the blue wall to locate an object behind it well before they can use the blue wall to locate an object to its left.

The ages at which children succeeded at each of the above search tasks

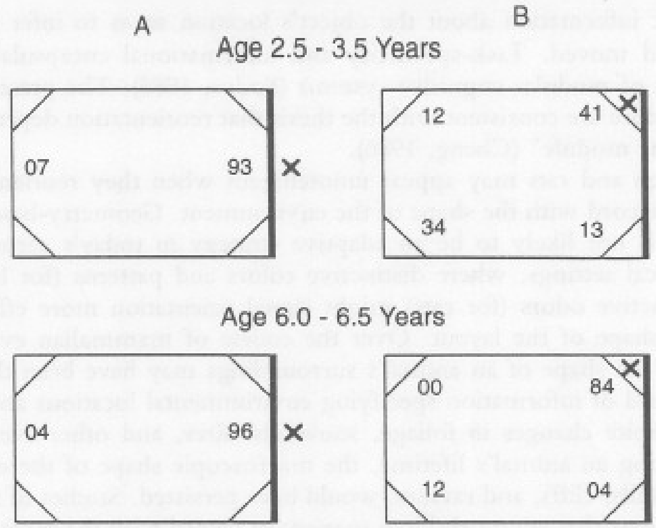

FIGURE 15 Schematic depiction of the rooms and children's search patterns at direct and indirect reorientation tasks.

roughly matched the ages at which a separate group of children, whose conversations were recorded in the CHILDES language database (MacWhinney, 1991), began producing phrases that would have uniquely specified object location and orientation. At about 2½–3 years, those children began to produce phrases like "behind the X"; at about 6 years, the children started to produce phrases involving "left" and "right" (Hermer, unpublished data, 1994). Although many factors could explain these roughly converging developments, they raise the possibility that cognitive changes related to the development of spatial language lead to increased flexibility in reorientation tasks.

Further research with adults provides tentative support for this suggestion. We have investigated how adults reorient themselves in a room with distinctive geometric and nongeometric properties while they perform other, concurrent tasks. The same type of verbal shadowing task that disrupted adults' ability to encode object properties in Simons's (in press) experiments, reviewed earlier, was found to disrupt adults' ability to use nongeometric information in the reorientation task. In contrast, shadowing had little or no effect on adults' ability to reorient in accord with the shape of the room (Hermer, Spelke, & Nadel, 1995). These findings suggest that the geometric reorientation process found in rats and children is preserved in adults and is impervious to interference from concurrent language production, whereas the ability to use nongeometric information is vulnerable to such interference.

Finally, the suggestion that language underlies the representation of conjunctions of geometric and nongeometric information is supported by studies comparing memory for such conjunctions by speakers of different languages (Levinson, in press). In a significant minority of the world's languages, spatial relationships between objects are not described egocentrically (e.g., "The cow is *to the left* of the horse") but geocentrically (e.g., "The cow is *to the north* of the horse"). Recent experiments with speakers of such languages, and speakers of left/right languages such as English, have probed how the speakers remember and reproduce spatial relations among objects. Subjects are asked to remember two objects in a given spatial relationship while facing in one direction (e.g., a cow to the left/north of a tree) and then are rotated 180° and asked with neutral language to reproduce the relationship. Speakers of egocentric language tend strongly to reproduce the egocentric relationship between the objects, reversing compass point relations. In contrast, speakers of geocentric languages tend to reproduce the geocentric relationship, reversing left/right relations.

Spatial language thus appears to influence the representation of conjunctions of geometric and nongeometric information. Language may provide an especially useful medium for representing conjunctions of spatial and nonspatial properties of the layout. Whereas systems for representing the environmental layout may be confined to capturing geometric information, and systems for representing movable objects may be confined to capturing local properties of objects or surfaces, language can bring these sources of information together, specifying that an object or surface with one set of properties stands in a particular geometric relationship to another object or surface. As children acquire spatial language, they may come to use their language system to encode information more flexibly in spatial tasks.

D. Summary: Spatial Representations in Infants and Young Children

During the second half of the first year, infants become able to represent spatial locations in an environment-centered framework. Although the capacities of young infants to form allocentric spatial representations are limited, they appear to correspond to the allocentric representations formed by human adults and other mammalian species, as these have been assessed by behavioral studies. Infants also are able to maintain a sense of orientation both by using direct perceptual guides when these are available and by using internally generated information about their own changing position. Finally, young children are able to reorient themselves using a representation of the shape of the environment, as do other mammals. In contrast to older children and adults, however, young children do not reorient in accord with nongeometric information that they perceive, remember, and use in other tasks. In this respect, young children resemble adult rats and differ from older humans.

As in the case of object representation, development appears to bring increases in abilities to represent and use spatial information. In reorientation tasks, increases in the flexibility of children's performance roughly coincides with advances in children's use of spatial language. This finding is reminiscent of Xu and Carey's (in press) studies of developmental changes in object perception, and it suggests a linkage of some kind between the development of language and the development of flexible cognitive performance. In addition, adults' more flexible reorientation processes appear to be vulnerable to interference from simultaneous language tasks, although adults' geometric process for reorientation evidently is not. This finding is reminiscent of Simons's (in press) findings in the domain of object representation. It suggests that the geometric process used by young children is preserved in adults, and that this process operates in relative independence from the processes allowing use of nongeometric information. Finally, adults' abilities to conjoin geometric and nongeometric information appear to vary across people whose languages capture different aspects of these relations. All these findings suggest that children's core processes for representing the environment and using spatial representations to guide behavior are supplemented by later-developing, more flexible processes that are connected in some way to language.

IV. THEMES AND PROSPECTS

Although this chapter has focused on a variety of cognitive abilities with different developmental courses and different internal constraints, common themes emerge from our review. First, core representational capacities appear to develop early in life, allowing infants and young children to gain knowledge of objects and places that are not accessible to immediate perception. Second, early-developing representations appear to be attuned to the information that provides the most reliable and effective guide for action and learning. Third, several distinct, task-specific systems appear to underlie children's earliest representational abilities: The object representations that guide infants' apprehension of object identity, for example, appear to be distinct from those that guide object-directed actions such as reaching, and the spatial representations by which young children relocate hidden, movable objects appear to be distinct from those by which they reorient themselves. Infants' cognitive performance may be limited by the task specificity of their representational systems, leading to errors and inconsistencies that are puzzling to adult observers.

Early-developing systems for representing space and objects appear to persist over the course of later development, but children's cognitive performance becomes increasingly flexible as they grow. It is possible that language and associated memory systems contribute to the growth of flexibility by providing a domain-general medium in which the representations constructed by task-specific systems can be conjoined. Whether or not language plays this role, it now seems clear that cognitive advances occur as children link separate knowledge systems together in novel ways (Carey & Spelke, 1994; Karmiloff-Smith, 1992).

Studies of early cognitive development suggest a number of fruitful directions for further inquiry. First, understanding of human cognition may advance considerably from research in comparative cognition, exploring parallels between early-developing cognitive abilities in children and in other animals. Many of the cognitive problems confronting young children are faced by other animals. Studies of the processes by which animals of various species solve these problems may shed light on the processes by which infants and children solve them, while highlighting those aspects of human problem solving that are unique to us (see Gallistel & Gelman, 1992; Thelen, Bradshaw, & Ward, 1981, for additional examples of this approach).

Understanding of human cognition also may advance through studies exploring parallels between early-developing representations and the representations used by adults in tasks that require rapid decisions and discourage use of language. Where such experiments suggest common processes in the adult and child, investigators may exploit the distinct advantages of the two populations to shed further light on the nature of those processes. In particular, studies of adults allow probes into the nature and limits of representations across a broad range of tasks, whereas studies of infants and young children allow focused investigation of the principles and processes by which representations are constructed by individuals who lack an extensive base of knowledge, and whose knowledge systems interact less extensively than those of adults.

Third, future experiments may fruitfully probe the relation between verbal and nonverbal representations, the changes in cognitive performance that occur as children acquire language, and the cognitive differences that arise between speakers of different languages. Language may function as a common, domain- and task-general medium of representation in which children can conjoin the information that their multiple cognitive systems provide. The processes by which separate representations become conjoined, in language and perhaps in other symbolic systems, provide fertile terrain for research.

Finally, we expect fruitful interactions between investigations of the nature and development of cognitive abilities in the young child and investigations of the nature and development of representational systems in the human brain. The principal themes of this chapter—that cognitive systems begin to function early in development, that distinct systems represent different aspects of objects and environments for different purposes, and that the linkages among these systems increase with development—are supported not only by behavioral studies of infants and children but by anatomical and physiological studies of the brains of humans and other mammals. It is now widely believed that the primate cerebral cortex forms at least two partly distinct systems of object representation (e.g. Goodale, 1995) and multiple systems for representing space (e.g. McNaughton et al., 1995). Functional imaging studies suggest that distinct representations are activated in distinct task contexts, even in the presence of the same stimulating events (e.g., Petersen & Fiez, 1993). Behavioral and neural experiments therefore converge to suggest that human cognition is the product of multiple systems of representation, and that human flexibility results in part from the orchestration of these systems.

The study of the neural basis of early cognitive functioning is itself a nascent field (see Diamond, 1990a; Johnson & Gilmore, this volume; Neville, 1995, for promising beginnings). We have not emphasized specific parallels between brain development and cognitive function in this chapter, because so little is known about the early development of the neural structures underlying humans' representations of objects and the spatial layout. With continued study of early cognitive development, human and animal cognition, and brain function, the outlines of these linkages should emerge, bringing new insights into brain and cognitive development.

Acknowledgments

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