10 Object Perception, Object-directed Action, and Physical Knowledge in Infancy

ELIZABETH S. SPELKE, PETER VISHTON, AND CLAES VON HOFSTEN

ABSTRACT Human infants' perceptions and actions on objects are sensitive to physical constraints on object motion. Object perception is guided by constraints that objects move as connected and bounded wholes, on continuous and unobstructed paths, on contact with other objects; object-directed reaching and visual tracking are guided by the constraint that objects move smoothly. Infants' sensitivity to these constraints suggests that humans begin at an early age to develop knowledge of objects and their behavior. The contrasting constraints guiding object perception and object-directed actions suggest that separate systems of knowledge underlie these different achievements.

A central question for psychologists and neuroscientists concerns the nature and organization of human knowledge. This question may be approached through studies of perception (the primary processes by which people gain knowledge of their immediate surroundings) and action (the primary processes by which people put their knowledge to practical use). In this chapter, we explore some insights into knowledge, perception, and action that come from studies of early human development. Developmental studies of object perception and object-directed action provide evidence that knowledge of objects begins to emerge in the first months of life and that this knowledge has a particular content and organization. We hope that the findings of such studies will serve as signposts for neuroscientists, guiding the search for the physical basis of knowledge in the developing human brain.

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Object perception

Object perception is a fascinating achievement, because the boundaries, internal unity, and persisting identities of objects are radically underdetermined by the visual information available in natural scenes. Because objects touch and overlap in complex ways, no simple relationships clearly indicate where one object ends and the next begins (see Marr, 1982). Because the back of every opaque object is hidden and the front surfaces of most objects are partly concealed behind nearer objects, the visual information specifying an object is highly incomplete. Because objects and perceivers are movable, finally, objects frequently enter and leave the field of view. Despite these ambiguities and changes, adults immediately and effortlessly perceive objects as stably bounded, as complete and solid, and as persisting and moving on definite paths when they are hidden. An important task for cognitive scientists and neuroscientists is to explain how these perceptions occur; studies of object perception in infancy provide one approach to this task.

FIGURE-GROUND ORGANIZATION According to the Gestalt psychologists (e.g., Koffka, 1935), the ability to perceive an object as a bounded figure in front of an unbounded background is fundamental to all perception and depends on a tendency to confer the simplest organization on visual scenes. Studies of infants' perception of figure-ground relations provide evidence that this ability exists at an early age. For example, Craton (cited in Arterberry, Craton, and Yonas, 1993) investigated 5-month-old infants' perception of a two-dimensional display of moving dots that is seen by adults as a unitary figure moving in front of a background. After familiarization with the display, infants were presented, in alternation, with a stationary object of the shape of the region adults perceive as the figure and a stationary object with the shape of the region adults perceive as the ground. Looking times to these objects were compared to one another and to the looking times of infants in a no-habituation baseline condition, on the well-documented assumption that infants would look longer at the display they perceived to be more novel (see Bornstein, 1985). If infants perceived the figure-ground relations as adults do, then the infants in the experimental condition were expected to look longer at the test display with the shape of the ground, because only the figure should have been perceived as having a definite shape during the familiarization period. This visual preference was observed, providing evidence that infants perceived the figure-ground relation.

Further experiments have explored the stimulus conditions specifying figure-ground relations to infants. Infants appear to perceive a unitary object in front of a background when the figure and its borders move together either laterally (e.g., Craton and Yonas, 1990) or in depth (e.g., Ball and Tronick, 1971). Certain patterns of nonrigid motion also specify figure-ground relations (Bertenthal, 1993). Finally, infants appear to perceive figure-ground relations in stationary displays in which figure and ground are separated in depth (e.g., Termine et al., 1987). In contrast, infants do not appear to perceive figure-ground relations in stationary, two-dimensional displays in which figure and ground differ only in color and texture (Spelke and Born [1982] in Spelke, 1988) or in which the figure-ground organization is specified by configurational properties such as edge alignment and figural simplicity (Craton and Yonas, 1990). These last findings cast doubt on the thesis that figure-ground organization depends on a tendency to group displays into the simplest, most homogeneous units. The basic process of figure-ground organization appears to depend on an analysis of three-dimensional surface motions and arrangements, in accord with the constraint that moving objects maintain their internal connectedness and their external boundaries.

Perception of Objects in Multiple-Object Arrays
Young infants also perceive the boundaries and the unity of objects in more cluttered visual scenes in which multiple objects touch or overlap. For example, an experiment investigated 3-month-old infants' percep-

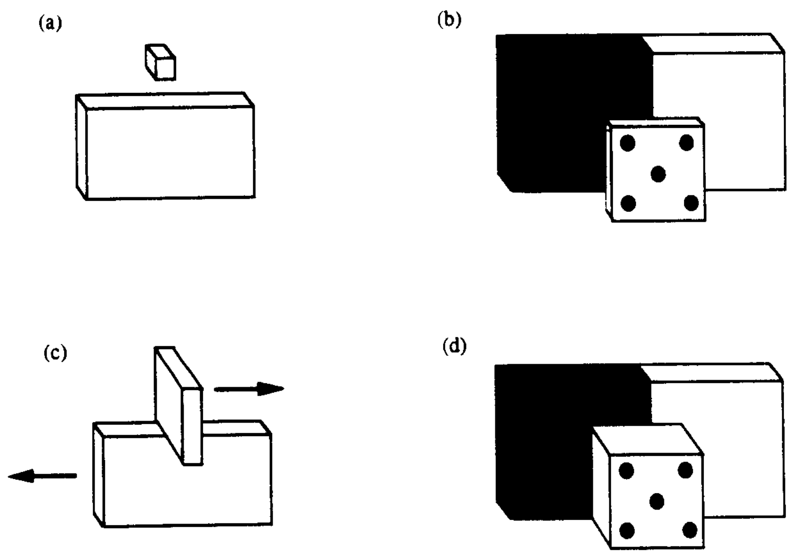

Figure 10.1 Displays for experiments on infants' perception of object boundaries: (a) two stationary, visibly separated objects (after Spelke, Hofsten, and Kestenbaum, 1989); (b) two stationary objects separated in depth; (c) two adjacent objects undergoing relative motion; (d) two stationary objects adjacent in depth (after Spelke, 1990).

tion of the boundaries of two stationary objects that were separated in depth, by familiarizing infants with this display and then presenting test displays in which either one object was displaced relative to the other object or the two objects were displaced together (Kestenbaum, Termine, and Spelke, 1987) (figure 10.1b). If infants perceived a boundary between the two objects, they were expected to look longer at the display in which the two objects moved together. This looking preference was obtained, providing evidence that infants perceived the objects as separate units.

Further research provides evidence that infants also perceive the boundary between two objects that are visibly separated and the boundary between two objects that undergo different rigid motions, but remain adjacent throughout their motion (Spelke, Hofsten, and Kestenbaum, 1989) (figure 10.1a, c). In contrast, young infants evidently do not perceive the boundary between two adjacent objects that are stationary or move together (Kestenbaum et al, 1987; Spelke, Hofsten, and Kestenbaum, 1989) (figure 10.1d). Although young infants perceive object boundaries by analyzing surface arrangements and motions, grouping surfaces into units that are connected and remain connected over motion, they do not appear to perceive object boundaries by analyzing surface colors and textures, dividing the layout into units that are simple and regular.

In visual scenes, objects often are partially occluded by nearer objects, such that different visible surfaces of an object appear in spatially separated regions of the layout (figure 10.2). To investigate whether infants perceive the unity of an object over this pattern of occlusion, Kellman and Spelke (1983) familiarized 4-month-old infants with an object of a simple shape that moved horizontally behind a central occluder (see figure 10.2a). Then the infants were presented with test displays consisting either of the connected, unitary object perceived by adults or of the surfaces that were visible in the original occlusion display, separated by a gap (see figure 10.2d). Infants looked longer at the latter test display, providing evidence that they perceived the center-occluded object as one connected unit. In further studies, infants were found to perceive the unity of this object when its ends underwent common motion in any direction, including motion in depth, but not when its ends were stationary and underwent a common retinal displacement produced by movement of the infant (see Kellman, 1993). These findings suggest that perceived, three-dimensional motion, not retinal displacement, underlies infants' perception of object unity.

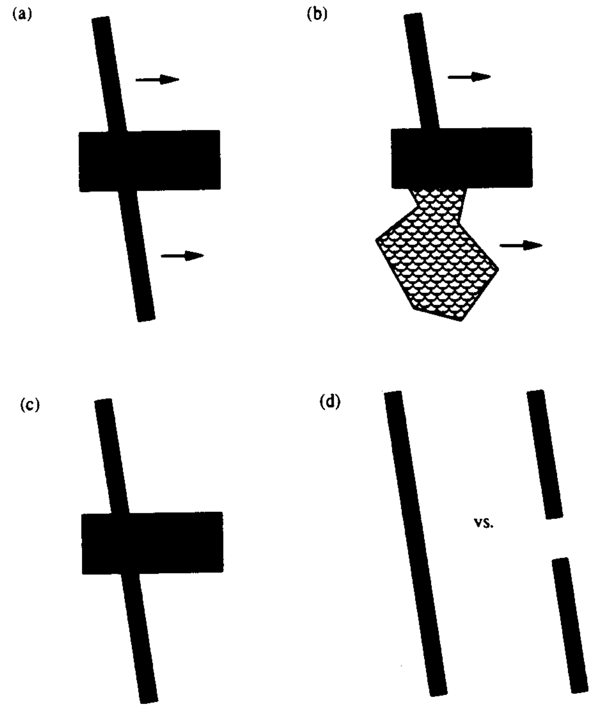

FIGURE 10.2 Displays for experiments on infants' perception of partly occluded objects: (a) Aligned surfaces of the same color, texture, and shape move rigidly behind a central occluder. (b) Misaligned surfaces of different colors, textures, and shapes move rigidly behind a central occluder. (c) Aligned surfaces of the same color, texture, and shape are stationary behind a central occluder. (d) Test displays for an experiment on perception of object unity over occlusion. (After Kellman and Spelke, 1983)

Experiments provide evidence that infants' perception of the unity of a center-occluded object is not affected by the colors, textures, shapes, or alignment relations of the object's visible surfaces. If the ends of a center-occluded object move together, for example, infants' perception of a connected object is equally strong, whether the ends form an object of a homogeneous color and texture and a simple shape (figure 10.2a) or not (figure 10.2b). When a center-occluded object is stationary, moreover, infants' perception of object unity appears to be indeterminate between one connected object and two objects separated by a gap, even when the visible ends of the object share the same color and texture, are aligned, and combine to form an object of a simple shape (see figure 10.2c). Perception of the unity of a partly occluded object therefore appears to depend only on the common motion of the object's visible surfaces. This perception may reflect a sensitivity to a further constraint on object motion: Surfaces normally move together only if they are in contact.

Perception of Objects that Move from View Adults perceive objects to persist when they are fully occluded and to maintain their unity and identity over successive encounters. In experiments using preferential-looking methods similar to those described earlier, infants also have been found to perceive the persistence and the identity of an occluded object under certain conditions. For example, Craton and Yonas (1990) familiarized 4-month-old infants with a disc that moved from a position where it was fully visible to a position where it was fully hidden (figure 10.3a). The object followed an irregular path, such that it was most often seen at a position where it was half in view. Infants subsequently were shown a complete disc and a truncated disc corresponding in shape to the visible surface of the disc when it was half visible. Infants looked longer at the truncated disc, providing evidence that they perceived a persisting object with a constant form over the period of occlusion. In further studies, infants have been found to perceive the persistence of an object during occlusion primarily by analyzing the motion relationships among the object's visible surfaces (Van de Walle and Spelke, 1993) (figure 10.3b). Infants have shown very limited abilities to perceive the form of an object that moves in and out of view by analyzing configural relationships among the object's visible edges (Arterberry, Craton, and Yonas, 1993).

Experiments have investigated infants' perception of object identity over successive encounters by familiarizing infants with events in which objects appear in succession on two sides of a screen (see figure 10.3c–f) and then comparing the looking times of those infants and of infants in a no-familiarization control condition to nonoccluded displays of one versus two objects (Xu and Carey, 1992; Spelke et al., in press, c). These studies provide evidence that both 4- and 10-month-old infants perceive object identity by analyzing the spatiotemporal continuity or discontinuity of object motion: When two object appearances are linked by a connected path of motion (figure 10.3c), infants perceive a single object; when two object appearances are not so linked (figure 10.3d), infants perceive two distinct objects. In contrast, experiments provide no evidence that infants perceive the identity or distinctness of objects by analyzing either changes in objects' speed of motion or changes in objects' colors, textures, and shapes. When objects move into view in alternation on the two sides of a wide screen (figure 10.3e), infants' perception appears to be indeterminate between one and two objects, both when the timing of the appearances specifies uniform, constant speed of motion behind the occluder and when it specifies an abrupt change in the speed of motion. Infants appear to perceive an indeterminate number of objects not only when the objects are visually indistinguishable (figure 10.3e) but also when they differ in color, texture, and shape (figure 10.3f). Perception of object identity evidently accords with the constraint that objects move continuously but not with constraints that objects move smoothly and maintain constant colors, textures, and shapes.

An Interim Summary: Principles of Object Perception A consideration of infants' successes and failures in the preceding reported experiments supports several suggestions about early developing mechanisms for perceiving objects. First, the conditions under which infants perceive figure-ground relations, object unity and boundaries, and object persistence over a period of occlusion are similar. In all three situations, infants perceive objects by analyzing the arrangements and the motions of surfaces but not the colors, textures, or forms of surfaces. These findings suggest that abilities to perceive figure-ground organization, object unity and boundaries, and object identity are related.

Second, infants' perception of objects depends on analyses of the arrangements and motions of surfaces in the three-dimensional visual layout, not on analyses of the arrangements and motions of elements in any two-dimensional retinal projection of the layout. For example, infants perceive the boundaries of objects that are separated in depth but adjacent in the visual field, and they perceive the unity of a center-occluded object when the ends of the object undergo a three-dimensional but not a retinal displacement. These findings and others (see Spelke, 1990, and Kellman, 1993, for discussion) suggest that the processes underlying object perception occur relatively late in visual analysis.

Third, object perception accords with basic physical constraints on object motion. Three principles, each

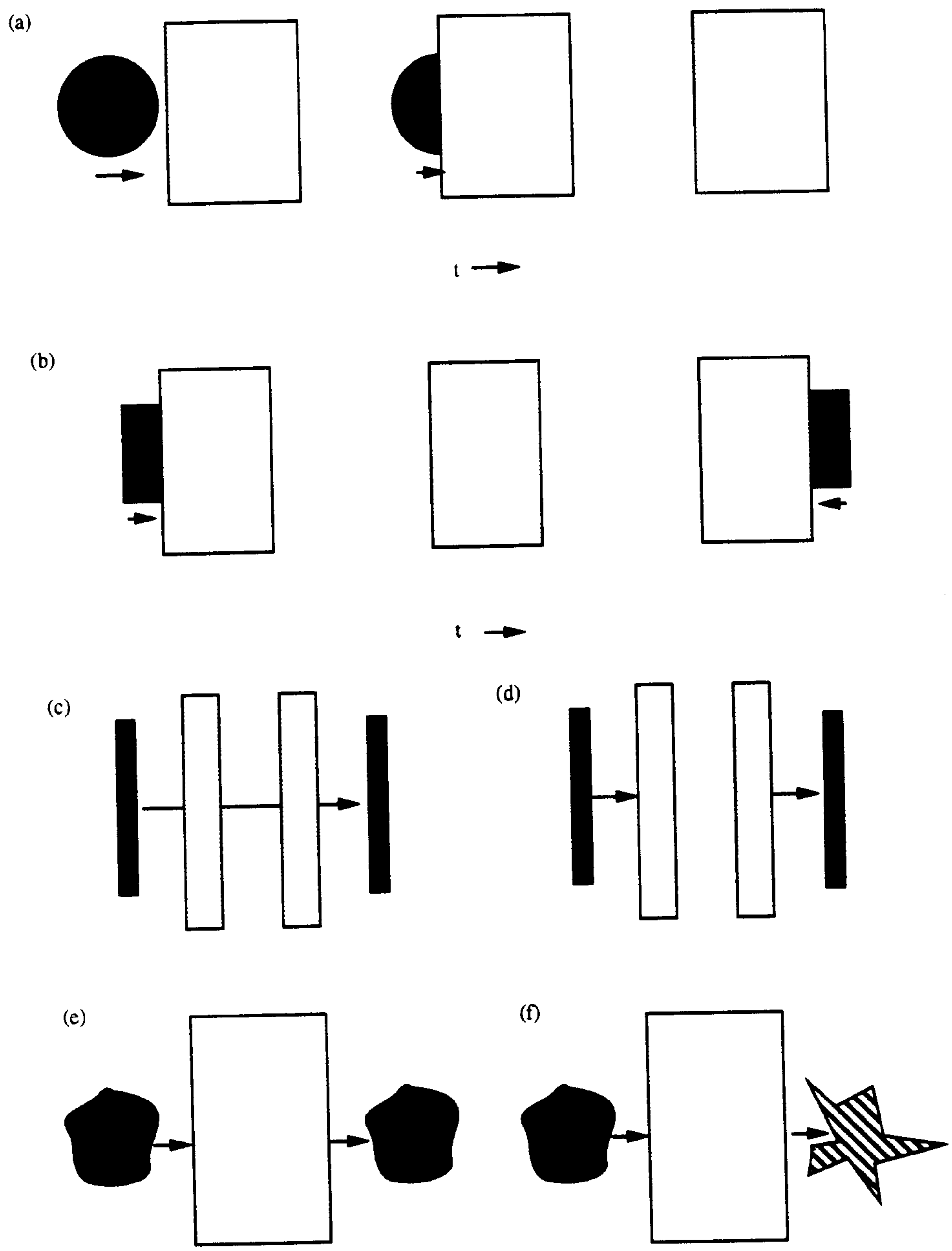

FIGURE 10.3 Displays for experiments on infants' perception of object persistence over occlusion: (a) An object moves from a fully visible to a fully occluded position. (b) An object moves from one partly visible position to a fully hidden position and then to a second partly visible position. (c) An object moves continuously behind two separated occluders. (d) Objects move discontinuously behind two separated occluders. (e) An object moves visibly at a constant speed and is occluded for an appropriate or an inappropriately brief duration. (f) Objects that are different in color, texture, and shape appear in alternation on the two sides of an occluder. (After Craton and Yonas, 1990; Xu and Carey, 1992; Spelke et al., in press, c; Van de Walle and Spelke, 1993) The drawing does not accurately depict the scale or shapes of the objects.

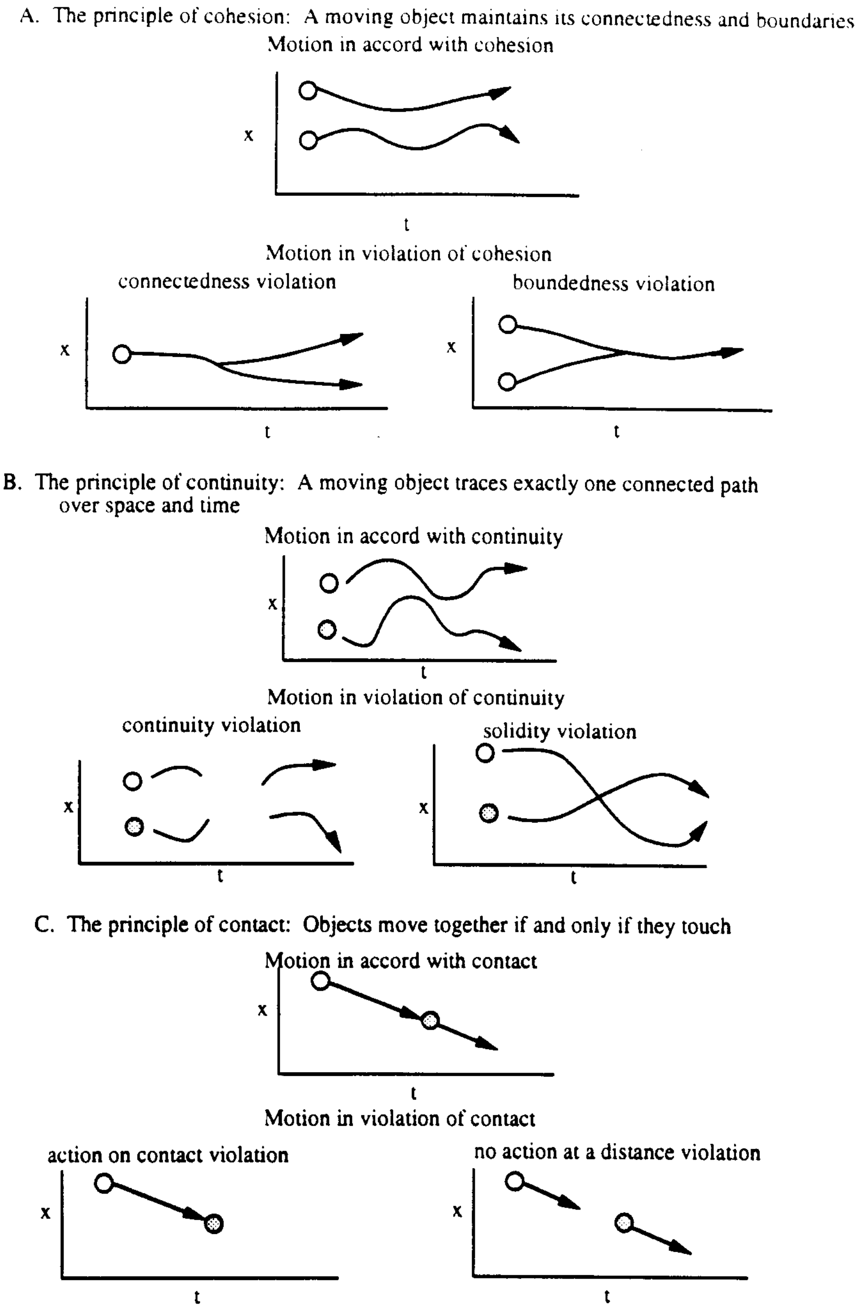

FIGURE 10.4 Principles of object perception and the constraints they encompass.

encompassing two constraints on object motion, suffice to account for the findings of all the studies cited thus far (figure 10.4). According to the *cohesion principle*, objects maintain their connectedness and their boundaries as they move. Objects therefore are distinct from the background, and two objects are distinct from one another, if they are separated in space or undergo separate motions. According to the *contact principle*, distinct objects move together if and only if they touch. The two commonly moving ends of a partly occluded object therefore are perceived to be in contact behind the occluder, whether they appear simultaneously (as in figure 10.2a) or successively (as in figure 10.3b). According to the *continuity principle*, an object traces exactly one connected path over space and time: The path of one object contains no gaps, and the paths of two objects do not intersect. An object therefore is seen as persisting when it moves from view, and two object appearances that are linked by a continuous path of motion are seen as appearances of a single object.

The cited experiments suggest limits to young infants' abilities to perceive objects. In particular, infants do not appear to perceive objects by grouping together surfaces with a common color, texture, or shape, by grouping surfaces into units with a simple form, or by grouping together surfaces that move smoothly. Infants fail to perceive objects in accord with the latter properties, even though infants within the same age range have been shown to be sensitive to surface color, surface texture, configural object properties such as symmetry and alignment, and kinematic relationships such as smoothness of motion (see Spelke, 1990). Gestalt configurational properties are detectable by infants, but they do not appear to provide the basis for infants' perception of objects. These findings cast doubt on the thesis that object perception results from a general tendency to confer the most regular organization on perceptual experience.

Observing Object Motions We turn now to studies investigating in a different way infants' sensitivity to constraints on object motion, by comparing infants' looking times to fully visible events in which an object moves either naturally or unnaturally. This research is based on the assumption that infants will look longer at an unnatural object motion if they are sensitive to the constraints that it violates (see Baillargeon, 1993). A variety of experiments provide evidence that infants infer that objects will move in accord with some, but not all, of the constraints to which adults are sensitive. Specifically, infants appear to be sensitive to the constraints on objects that are captured by the principles of cohesion, continuity, and contact.

For example, experiments by Spelke and colleagues (in press, a) investigated 3-month-old infants' reactions to events in which an object either moved as a whole (consistent) or spontaneously broke apart (inconsistent with the cohesion principle). Infants first were familiarized with a stationary object, and then they were tested with two events in which a hand grasped the top of the object and lifted it into the air (figure 10.5). In one event, the object moved as a whole and came to rest in midair. In the other event, the top half of the object rose into the air while the bottom half of the object remained on the surface. Looking times to the outcomes of these events were recorded, beginning when all or part of the object came to rest in midair, and these looking times were compared to the looking times obtained in a baseline condition, in which the same outcome displays appeared with no preceding events. The infants in the main experiment looked longer at the event outcome in which the object broke in two, providing evidence that infants inferred that the object would move in accord with the cohesion principle.

Further experiments using similar methods provide evidence that 6-month-old infants infer that one visible object will not pass through a second object, in accord

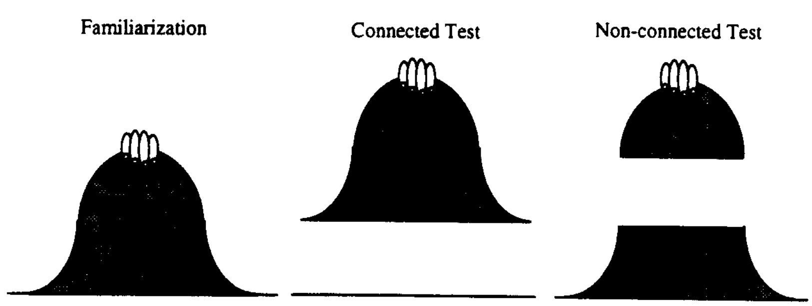

Figure 10.5 Displays for a study of infants' extrapolations of visible object motion in accord with the cohesion principle. (After Spelke et al., in press, a)

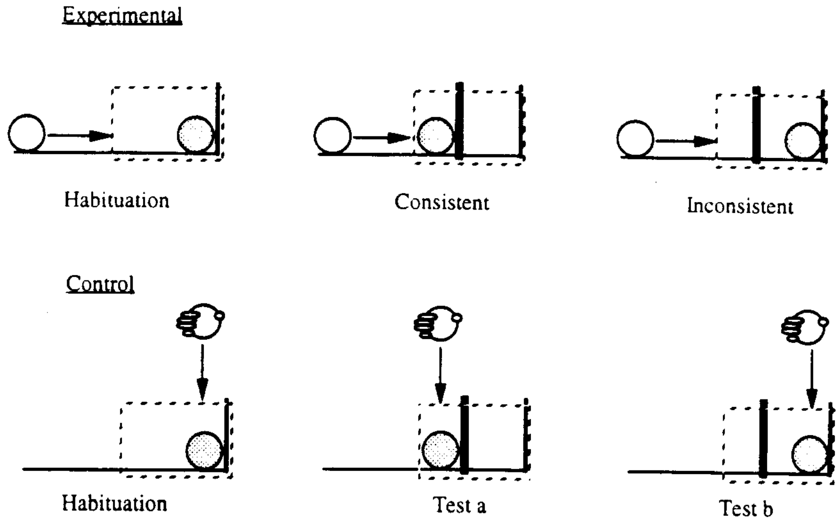

FIGURE 10.6 Displays for a study of infants' extrapolations of hidden object motion in accord with the continuity principle. (After Spelke et al., 1992) Dotted lines indicate the position of the screen; arrows indicate the path of visible object motion; the shaded figure indicates the final position of the object.

with the continuity principle (Sitskoorn and Smitsman, 1993) and that one object will not cause a change in the motion of a second object if the objects do not touch, in accord with the principle of contact (Leslie, 1988). Experiments suggest, however, that young infants are not sensitive to all the constraints on physical objects that are appreciated by adults. In particular, infants do not show consistent reactions to violations of the principle of inertia: They show no visual preference for an event in which a moving object spontaneously stops moving or changes direction (e.g., Leslie, 1988). These experiments suggest that young infants do not appreciate that objects move smoothly in the absence of obstacles.

OBSERVING EVENTS WITH HIDDEN OBJECTS Infants' inferences about the motions of hidden objects have been investigated by means of preferential-looking experiments in which critical object motions occur while the object is out of sight. These experiments provide evidence that infants infer that hidden objects will move in accord with the same principles of cohesion, contact, and continuity that guide their inferences about visible objects.

For example, Spelke and coworkers (1992) familiarized $2\frac{1}{2}$-month-old infants with an event in which a ball rolled behind a screen on an open stage, the screen was raised to reveal the object at rest at the end of the stage (figure 10.6), and looking time to this outcome display was recorded. Then infants were tested with events in which a barrier was introduced at the center of the stage in the path of the ball's motion, the ball was rolled behind the screen as before, and the screen was raised to reveal the ball either at a novel position on the near side of the barrier (consistent) or at its familiar position on the far side of the barrier (inconsistent with the continuity principle). Infants' looking times to the two event outcomes were compared to the looking times of infants in a control condition, who were presented with the same outcome displays preceded by equally consistent events. The infants in the experimental condition looked longer at the inconsistent event outcome. Because the ball could arrive at the inconsistent outcome position only by passing through or by jumping discontinuously over the barrier, the experiment provides evidence that the infants extrapolated the hidden object's motion on a connected and unobstructed path, in accord with the continuity principle (for further evidence, see Baillargeon, 1993).

Further experiments using similar methods provide evidence that infants extrapolate hidden object motion in accord with the principles of cohesion and contact: Infants infer that a hidden object will maintain its connectedness (Carey, Klatt, and Schlaffer, 1992) and that it will set a second object in motion only if the objects touch (Ball, 1973). Experiments nevertheless suggest that young infants do not infer that a hidden object will move in accord with inertia: Presented with events in which a linearly moving object rolled from view behind a screen, infants looked no longer at an event outcome in which the object reappeared at a position that was 90° displaced from the line of its previous motion than at an outcome in which the object reappeared on the line of its previous motion (Spelke et al., in press, b).

Infants' extrapolations of hidden object motions closely resemble their extrapolations of visible object motions, and both kinds of extrapolations accord with the same principles that guide object perception. The existence of common principles underlying perception of visible objects, sensitivity to the naturalness of visible object motion, and inferences about the course of hidden object motion suggests that these abilities depend in part on common mechanisms, attuned to basic constraints on objects' arrangements and motions. This suggestion may appear surprising, given the obvious differences between the seemingly immediate and effortless process of perceiving objects and the often more lengthy and difficult process of reasoning about object motion. If the suggestion is correct, then cognitive scientists and neuroscientists may gain considerable insight into the mechanisms underlying reasoning processes by studying the mechanisms of object perception.

Object-directed action

Thus far, we have considered infants as observers but not as actors. Perceivers of all ages also act on objects, however, and successful action requires knowledge of how objects behave. To lift a cup, for example, one must know where and how to grasp it and where and how to apply force to raise and balance it. Casual observation suggests that much of this knowledge is lacking at early ages. Does any knowledge guide infants' actions on objects? We consider this question by focusing on the early development of object-directed reaching and visual tracking.

Reaching for Stationary Objects To manipulate their surroundings, infants must direct their reaching and grasping toward the edges of objects. Even newborn infants direct their reaching movements approximately toward an object that moves slowly and irregularly in front of them, but neonates typically do not grasp objects (Hofsten, 1982). At approximately 4 months of age, infants begin to succeed both at reaching for objects and at grasping them (e.g., White, Castle, and Held, 1964). Presented with an object that is suspended in front of a background, 4- to 6-month-old infants' reaching is roughly appropriate to the object's distance (e.g., Yonas and Granrud, 1985), and their grasping is roughly appropriate to the object's orientation (Hofsten and Fazel-Zandy, 1984). Furthermore, a large object is approached using both hands and a small one using only one hand (e.g., Clifton et al., 1991), although the adjustments of hand opening are not systematically related to object size (Hofsten and Ronnquist, 1988).

To reach effectively in scenes containing multiple objects, infants must reach for an object as a unit. Reaching is most successful if the hand closes on the edges of a single object; it is less effective if the hand contacts the center of an object or closes on the edges of distinct objects. Studies of infants' reaching for arrays of multiple objects provide evidence that infants direct their reaches to object edges (Hofsten and Spelke, 1985). For example, 5-month-old infants who were presented with two objects that were arranged in depth reached for the borders of the nearer and smaller object, usually without touching the farther object, provided that the objects were spatially separated or underwent distinct motions. In contrast, when the objects touched and either were stationary or moved together, infants reached for the borders of the two-object assembly, either contacting only the larger, more distant object, or contacting both objects. These studies provide evidence that infants direct their reaches to object boundaries that are specified spatially or kinematically.

Studies of the stimulus information guiding infants' reaching for objects converge with studies of the stimulus information underlying object perception. Five-month-old infants reach for an object that is specified by a pattern of common motion relative to its background (Arterberry, Craton, and Yonas, 1993), even in the absence of any static information for the figure-ground relationship (Craton and Yonas, 1990). Conversely, 5-month-old infants fail to reach appropriately for an object whose boundaries are specified only by discontinuities in surface orientation or edge alignment (Hofsten and Spelke, 1985). These findings suggest an early coordination between object perception and action.

Reaching for Visibly Moving Objects To catch a moving object, one must aim for the position that the object will occupy at the time the reach is completed. Successful reaching for moving objects therefore depends on capacities to extrapolate an object's motion (Hofsten, 1983). Experiments provide evidence that infants reach for moving objects as early as they reach for stationary objects and that they aim for future object positions. Infants appear to reach for objects by extrapolating their motions smoothly.

Evidence that reaching is guided by smooth extrapolations of object motion comes from a series of studies by Hofsten (e.g., 1983). Infants aged 4–8 months were presented with an object that moved at a constant speed on a semicircular trajectory. After observing several cycles of motion, infants began to reach for the object. Measurements of the direction of displacement of the infant's hands at the time a reaching movement began served to assess the infant's initial aiming for the object. Even on the first trial on which a reach occurred, infants aimed for a future object position by extrapolating a smooth, curvilinear path of motion.

More recent experiments obtained converging evidence for smooth extrapolations of object motion by measuring 8-month-old infants' reaching for an object that abruptly halted. When an object moving rapidly on a semicircular arc suddenly stopped while the infant was reaching for it, the reach continued ahead of the object's arrested position toward a position that the object would have attained if it had continued to move smoothly (see color plate 1). These reaching errors provide evidence that infants guide their reaching prospectively, at least 200 ms in advance of an object's currently perceived position (Hofsten and Rosander, 1993).

Because the infants in the studies just cited typically viewed several cycles of object motion before they began reaching, it is possible that the infants learned that an object would move on a smooth path. A final study provides evidence that infants extrapolate smooth object motion even under conditions where such learning cannot occur (Hofsten et al., 1993). Six-month-old infants were presented with an object that moved on four trajectories with equal frequency: two linear trajectories that intersected at the center of the display and two trajectories with a sudden turn at the center (figure 10.7). Because linear and nonlinear trajectories were equally frequent, infants could not learn to predict, at the display's center, whether the object would continue in linear motion or turn. At the time the object reached the center, however, the infants' reaching movements were aimed to a position further along the line of the object's motion. Predictive reaching for moving objects evidently is guided by the principle that a linearly moving object continues in linear motion.

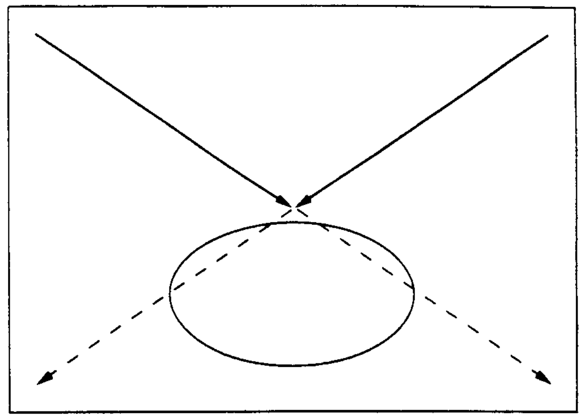

Figure 10.7 Displays for a study of infants' predictive reaching for linearly versus nonlinearly moving objects. (After Hofsten, Spelke, Vishton, and Feng, 1993) Solid arrows indicate the two paths of motion up to the intersection point of the paths, where predictive reaching was measured; dashed arrows indicate the two paths of motion after that point; the circle indicates the optimal area for reaching for the object.

Searching for Hidden Objects The most extensive studies of infants' reaching and visual following have focused on objects that leave the infants' view; the findings of such studies present a complex picture of the development of object-directed actions. In some respects, studies of infants' actions on hidden objects reveal sensitivity to the same constraints on object motion as studies of infants' perception of visible and hidden object motion. In other respects, studies of actions on hidden objects reveal different capacities and developmental patterns than any of the studies described earlier.

We first consider infants' reaching for objects obscured by darkness. If an object appears in a lighted room and then the lights are extinguished, 5-month-old infants reach reliably for the object, aiming for its previously visible borders (Hood and Willats, 1986). If a sound first is paired with a visible object and then is played in the dark, infants reach for the borders of the unseen object with which that sound had been associated (Clifton et al., 1991). These actions provide evidence that infants perceive an object as persisting when it ceases to be visible.

These reaching patterns contrast with infants' reactions to a visible object that moves out of view behind an occluder. Numerous studies, beginning with classical observations by Piaget (1954; see Harris, 1987, for a recent review), provide evidence that infants younger than 8 months do not reach for occluded objects and may not even follow such objects visually. Infants fail to retrieve hidden objects, even after they are trained to retrieve out-of-reach but visible objects (Munakata, 1992). Instead, infants act as if an occluded object is no longer obtainable or even of interest.

If an object moves in and out of view repeatedly on a smooth trajectory, infants as young as 3 months begin to adjust their visual tracking to the object's motion, looking toward its point of reappearance after occlusion (Nelson, 1971). The emergence of this tracking pattern suggests that infants have come to anticipate the object's reappearance. Research by Moore, Borton, and Darby (1978) investigated the principles guiding this anticipation, by presenting 5- and 9-month-old infants with events in which an object's occluded motion either was natural (as in figure 10.3c and 10.3e) or violated one of three constraints on object motion: the continuity constraint (as in figure 10.3d), the constraint that objects move smoothly (the object moved as in figure 10.3e but was occluded for an inappropriately brief duration), and the constraint that objects maintain constant appearances as they move (as in figure 10.3f). Visual tracking was recorded on both the natural and the violation trials, on the assumption that infants would track the event smoothly if the event proceeded as they had anticipated and that they would interrupt their tracking if it did not. At both ages, infants showed reliable disruptions of visual tracking when changes occurred in the speed of object motion or in the object's size, shape, and color (Moore, Borton, and Darby, 1978). In contrast, only the older infants showed a disruption of visual tracking when they viewed an event in which the object motion was spatially discontinuous. These findings are exactly opposite to the findings of preferential-looking experiments (Spelke et al., in press, c; Xu and Carey, 1992): Young infants' visual search appears to be guided by the principle that objects move smoothly and the principle that objects maintain constant visual appearances and not by the principle of continuity.

Finally, numerous experiments have investigated the principles that guide older infants' manual search for hidden objects. (Piaget [1954] and Harris [1987] offer psychological analyses of infants' developing search patterns; Goldman-Rakic [1987], offers a neurobiological analysis.) After infants begin to reach for hidden objects at approximately 8 months of age, their search is subject to striking errors. Infants can be induced to search for an object at places to which the object could not move on any connected, unobstructed path: Object search fails to accord with the continuity principle. When an object moves in succession behind two occluders, infants sometimes look for the object behind the first occluder or behind both occluders at once, as if the object could have left parts of itself in both locations: Object search fails to accord with the cohesion principle. Finally, manual search for hidden objects is not appropriately guided by the contact principle: If a hidden object stands inside a visible object that moves, infants fail to search for the hidden object in a position that is appropriate to the motion of the visible object. In each of these cases, infants' failure to search for hidden objects contrasts with their successful extrapolations of the motions of objects that they observe but on which they do not act (see Baillargeon, 1993).

Studies of infants' search for hidden objects suggest two patterns of dissociation in infants' knowledge. First, there is a dissociation between patterns of manual search for hidden objects and patterns of visual search for hidden objects. At 8 months, for example, visual search accords with the continuity principle but manual search does not (compare Piaget, 1954, to Moore, Borton, and Darby, 1978). Second, there is a dissociation between patterns of manual search for objects and perceptions and inferences about objects that are observed but not manipulated. When infants begin to search for hidden objects at 8 months, their search does not appear to accord with any of the principles that guide their inferences about the motions of hidden objects in events that they observe without overt action (compare Piaget, 1954, to Baillargeon, 1993).

SUMMARY: OBJECT-DIRECTED ACTION Although studies of infants' reaching for stationary, visible objects reveal a close convergence between object-directed reaching and object perception, studies of infants' reaching for visibly moving objects and infants' looking and reaching for hidden objects suggest discrepancies between the knowledge guiding various actions and the knowledge guiding perception. Of the numerous attempts to explain infants' developing action patterns, none appears fully successful. In particular, infants' errors of reaching for and visually tracking hidden objects cannot plausibly be explained by limitations on infants' abilities to represent unseen objects (Clifton et al, 1991), to engage in coordinated action (Munakata, 1992), to remember past events (Baillargeon, 1993), or to understand how objects move (Spelke et al., in press, b). These explanations may fail, because all assume that a single body of knowledge underlies human actions on objects. In contrast, the findings of the studies cited suggest that multiple representational systems guide infants' actions on objects and that these systems are distinct, in part, from the systems by which infants perceive objects and make sense of physical events.

Themes and prospects

A number of themes emerge from the studies we have reviewed. First, human infants appear to share some of the human adult's capacities to perceive, reason, and act; these cognitive capacities trace back to an early point in human life. Like studies of the developing brain (see Rakic, this volume), studies of perceptual and cognitive development cast doubt on the view that psychological capacities and their underlying neural structures develop from the periphery inward, such that infants first sense and respond reflexively to external events and only later come to perceive and reason about the significance of such events. Perception, action, and reasoning all appear to emerge early in infancy and to develop in synchrony thereafter.

Second, young infants' abilities to perceive, act on, and reason about objects appear to be sharply limited, relative to the abilities of adults. Because infants possess only a subset of mature abilities, detailed studies of object perception, object-directed action, and physical reasoning may shed light on the nature of these capacities in their mature state by revealing associations and dissociations among different abilities. Studies of infants already suggest that capacities to perceive and reason about objects are closely related to one another and that both these capacities are surprisingly distinct from capacities to act on objects. These findings may serve as guides for investigations of the neural mechanisms subserving perception, reasoning, and action in the young human brain.

Third, infants' perceptions of objects and reasoning about object motion appear to accord with the constraints on objects that are most fundamental and reliable. Although not all objects are regular in shape and substance, move on smooth paths, or maintain constant shapes, colors, and textures throughout their existence, all objects move cohesively and continuously. Before the rise of modern technology, moreover, all inanimate objects interacted only on contact. Kellman (1993) has suggested that perceptual and cognitive mechanisms that are attuned to the most reliable environmental constraints provide the firmest foundation for learning, because the information they deliver, although incomplete, is rarely in error. Studies of object perception appear to conform to Kellman's principle.

If the earliest-developing knowledge encompasses the most reliable constraints on objects, then knowledge of these constraints is likely to remain central to human perception and reasoning throughout life. Indeed, the principles of cohesion, continuity, and contact appear to be central to mature conceptions of objects: As adults, we hesitate to consider something an object if it fails to move cohesively and continuously on contact with other objects. Object perception and physical reasoning therefore appear to develop by enrichment around constant core principles. Further studies of infants may serve to probe both the detailed nature of core mature knowledge and the physical embodiment of this knowledge in the brain.

Fourth, infants' object-directed actions do not appear to be guided by the same fundamental constraints on objects as object perception. It is not the principles of cohesion, continuity, and contact that guide infants' actions on moving objects but the principle that objects move smoothly. According to the principle of inertia in classical mechanics, a moving object will continue to move in the same direction and at the same speed unless acted on by external forces. In addition, forces applied to a moving object will only gradually change the object's speed or direction. Although the inertia principle does not appear to guide either infants' or adults' reasoning about object motion (diSessa, 1983;

McCloskey, Washburn, and Felch, 1983; Spelke et al., in press, b), smooth changes in object motion are of crucial importance when one tries to coordinate one's action with events in the world. The inertial constraints on the body and the processing constraints on neural activity introduce a time lag between external events and internal adjustments to those events: It takes time to transmit information through the nervous system and further time before the contraction of a muscle has an effect. By smoothly extrapolating object motion, it is possible to overcome these time lags in action systems. The knowledge guiding object-directed actions may diverge from that guiding object perception and physical reasoning, therefore, because the demands on a knowledge system underlying action differ from the demands on a knowledge system underlying perception (Kellman, 1993).

The divergence between the knowledge guiding perception and reasoning about objects and that guiding object-directed tracking and reaching highlights our final theme. It is tempting, in view of the integrated and flexible cognitive performance of human adults, to assume that human cognition rests on a single, complex system of knowledge. Studies of infants, like studies of neurologically impaired adults (e.g., Shallice, 1987), studies of animals (e.g., Gallistel, 1990), and studies of neural development (e.g., Neville, this volume) cast doubt on this assumption: Cognition does not appear to depend on a single, homogeneous knowledge system but rather on a set of distinct systems for representing the world. The studies reviewed in this chapter suggest that the representational system underlying object perception and physical reasoning is distinct from the representational system or systems underlying many object-directed actions. Multiple, largely autonomous systems of knowledge may underlie human cognitive functioning.

In adults, distinct systems of knowledge may work together, such that a wide range of distinct beliefs can jointly influence our thinking and deliberate action (Fodor, 1983; Sperber, in press). In infancy, distinct knowledge systems may be less interconnected: Infants' actions on objects do not appear to be guided by the knowledge guiding infants' perceptions of objects, or the converse. This contrast suggests that cognitive systems become increasingly interactive over the course of human development (see Rozin, 1976; Karmiloff-Smith, 1992; Hermer, 1993). Linking different knowledge systems together may constitute a major cognitive task for the developing child.

If these suggestions are correct, then studies of human development, both in psychology and in neuroscience, may help shed light on the functional organization and the neural basis of human knowledge in two ways. First, studies of infants may serve to probe the nature and organization of a single system of knowledge under conditions that are relatively free from the interactive effects of other knowledge systems. Second, studies of cognitive development may serve to probe the processes by which humans come to relate different cognitive systems to one another. These processes, in turn, may provide a key to understanding the flexibility and productivity of mature human thinking.

ACKNOWLEDGMENTS This work was supported by grants to Elizabeth Spelke from the National Institutes of Health (HD-23103) and the National Science Foundation (INT-9214114), by a fellowship to Elizabeth Spelke from the James McKeen Cattell Foundation, by a fellowship to Peter Vishton from Cornell University, and by grants to Claes von Hofsten from the Swedish Research Council. We thank Jean-Pierre Lecanuet, Henriette Bloch, the Laboratoire de Psychobiologie du Developpement (EPHE-CNRS), and the Laboratoire de Psychologie du Developpement et de l'Education de l'Enfant (Universite Rene Descartes/CNRS) for their assistance in preparing this manuscript.

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