5

Perceiving and reasoning about objects: Insights from infants

Elizabeth S. Spelke and Gretchen A. Van de Walle

Introduction

The human environment is populated by a rich variety of material objects, from rocks, to spoons, to pocket calculators, to animals and people. To act on our surroundings effectively, we must apprehend these objects and anticipate their behaviour. Some of this task appears to be accomplished by perceptual mechanisms: a cup stands before us and we see its shape, colour and texture. Even in this case, however, perception goes beyond the immediately visible, for we appear to 'see' the complete cup, not just the surfaces reflecting light to our eyes. To act on the cup, moreover, we must apprehend object properties that are not obviously visible at all, such as the cup's weight and centre of mass. As our encounters with objects become extended over time, object perception appears to become increasingly inferential in character. We look at the cup at different places and times and apprehend a body that has persisted between those encounters. We drop the cup and anticipate its behaviour. The cup falls from view, and we infer how it will continue to move and where, approximately, it will come to rest. These last activities seem to reflect not an ability to perceive visible objects but an ability to represent hidden objects and to reason about their behaviour.

How do humans perceive surrounding layouts of spatially extended, bounded objects? How do we reason about objects so as to anticipate their future behaviour or infer their unseen states and motions? Are object perception and physical reasoning related activities? How does each depend on, and illuminate, human conceptions of the physical world?

Studies in computational vision and philosophy suggest discouraging answers to these questions. There may be no basic process of object perception, dependent on general constraints on objects' behaviour. Rather, perception of objects may depend on processes of object recognition. Based on a computational analysis of human vision, for example, Marr (1982, pp. 270–1) suggests that perceptual mechanisms, attuned to general constraints on the arrangement and behaviour of the visible environment, cannot segment

Spelke, E. S., & Van de Walle, G. (1993). Perceiving and reasoning about objects: Insights from infants. In N. Eilan, R. McCarthy, & W. Brewer (Eds.), Spatial representation. Oxford: Basil Blackwell.

the surface layout into objects.[1] Based on an analysis of human intuitions about object persistence over change, Wiggins (1980) arrives at a similar conclusion.

Research in cognitive and educational psychology further suggests there is no basic process of physical reasoning, guided by knowledge of general constraints on objects' behaviour. High school and college students show striking inconsistencies in their common-sense reasoning about objects (e.g. Halloun and Hestenes, 1985; McCloskey, 1983). For example, one person may judge that a ball set in horizontal motion by striking will move both forward and downward after losing its support, whereas a ball set in motion by a carrier will move only downward (McCloskey, 1983). Similarly, one person may judge that water leaving a curved tube will follow a straight path, whereas a ball leaving a curved tube will follow a curved path (Kaiser, Jonides and Alexander, 1986). These and other findings suggest that humans reason about objects by exploiting a collection of expectations about the behaviour of particular kinds of objects in particular circumstances.

In philosophy and in psychology, little consensus has emerged concerning the relation between perception and reasoning, or concerning the existence and nature of general conceptions of the physical world. In the light of the above characterization of object perception and physical reasoning, the apparent intractability of these questions is not surprising. If perceiving and reasoning each depend on a wealth of acquired information about particular kinds of objects, then one would expect these processes to resemble one another in some respects (because the objects we must perceive and reason about are the same) and to diverge in other respects (because the appearance of an object, so useful for purposes of recognition, is not always the most useful guide to reasoning about its behaviour). One also would expect the quest for general conceptions of the physical world to remain unfulfilled, either because basic conceptions are buried under a wealth of more specialized conceptions, or because no basic conceptions exist.

Against these conclusions, we will sketch a different picture. There is a basic process of object perception, according with general and pervasive constraints on the behaviour of the material world. This process begins to operate before children have developed knowledge of particular kinds of objects; it enables children and adults to single out the things about which they develop knowledge. There is also a basic process of reasoning about objects, according with the same physical constraints. This process enables children and adults to trace objects through time and to anticipate their future states and positions. It provides a framework within which humans can gain further knowledge about the behaviour of objects of particular kinds.

If these suggestions are correct, then studies of early development may shed light on processes of object perception and physical reasoning. Studies of infants and young children could serve to reveal the operation of these processes at the time when the processes are most needed, and before they are overlaid by a wealth of specific knowledge.

In what follows, we review some research on infants' perception and reasoning about certain simple, inanimate objects.[2] For purposes of exposition, we consider studies of object perception and studies of physical reasoning separately, but we will suggest that this division is artificial. Neither perceiving objects nor reasoning about objects fits comfortably within the common-sense distinction between observing the world and thinking about it. They fit poorly within these categories, we believe, because object perception and physical reasoning are aspects of a single human competence, centring on a single system of knowledge.

1 Object perception in infancy

Psychologists' understanding of perception in infancy has grown greatly over the last three decades, owing in large part to the development of a set of useful experimental methods. In particular, preferential looking methods, focusing on systematic differences in infants' looking time to different visual patterns (Fantz, 1961), have served to assess a broad spectrum of perceptual abilities, including perception of hue (e.g. Teller and Bornstein, 1987), orientation (Atkinson, ch. 14, Braddick, ch. 15 of this volume), form (e.g. Schwartz and Day, 1979), depth (e.g. Kellman, Van de Walle, Hofsten and Condry, 1990; Slater, Mattock and Brown, 1990) and intermodal correspondences (e.g. Meltzoff, ch. 9 of this volume; Streri, 1990). A number of investigators have used these methods to investigate infants' ability to divide the perceived layout into unitary, bounded objects. Because these studies have been reviewed elsewhere, we summarize only a sampling of studies here (see Spelke, 1990, for a more detailed summary).

1.1 Infant perception of the unity and boundaries of visible objects Let us begin with a simple situation: A three-dimensional object is presented in front of a uniform background. Can infants perceive the unity of this object and its separateness from the background? Experiments using four different methods provide evidence that infants perceive object unity as early as three months of age (Spelke and Born, 1983; Spelke, 1985a; Hofsten and Spelke, 1985; Kestenbaum, Termine and Spelke, 1987; Spelke, Hofsten and Kestenbaum, 1989; Spelke, Breinlinger, Jacobson and Phillips, 1993a). The most recent of these studies (Spelke et al., 1993a) serves as an example.

In this experiment, three-month-old infants were presented with one of four conically shaped objects in an otherwise empty display (Figure 5.1, a and b). The experiment used a habituation of looking time method, in order to investigate whether infants perceived each of the objects as a unit that should move as a whole. On a series of trials, infants in an experimental condition saw a hand enter the display and tap the object, which remained at rest. Looking time was recorded until the infant looked away from the display, ending the trial. Trials continued until the infant's spontaneous looking time declined to half its initial level: the criterion of habituation.

A sequence of alternating test trials followed. On each trial, the hand entered the display and then grasped and lifted the top of the object. On the three whole-object test trials, the object rose as a single body; on the three half-object test trials, the object broke apart and only its upper half rose into the air (Figure 5.1, c and d). Looking time to the event outcomes was recorded, beginning when the display ceased to move and continuing until the infant looked away.

Looking times to the two event outcomes were compared to the looking times of infants in a separate baseline condition, who viewed the raised half- and whole-object displays with no prior exposure to the objects. Since the infants in the baseline condition viewed exactly the same displays as those in the experimental condition throughout the time that looking was recorded, the baseline condition controlled for differences in the intrinsic attractiveness of the two displays.

In habituation studies, infants tend to look longer at novel or surprising events (see Baillargeon, 1986; Bornstein, 1985; Spelke, 1985b; Atkinson, ch. 14, Braddick, ch. 15 of this volume). If the infants in the experimental condition perceived each of the four objects as a unit, then the event outcome in which the object broke apart should have

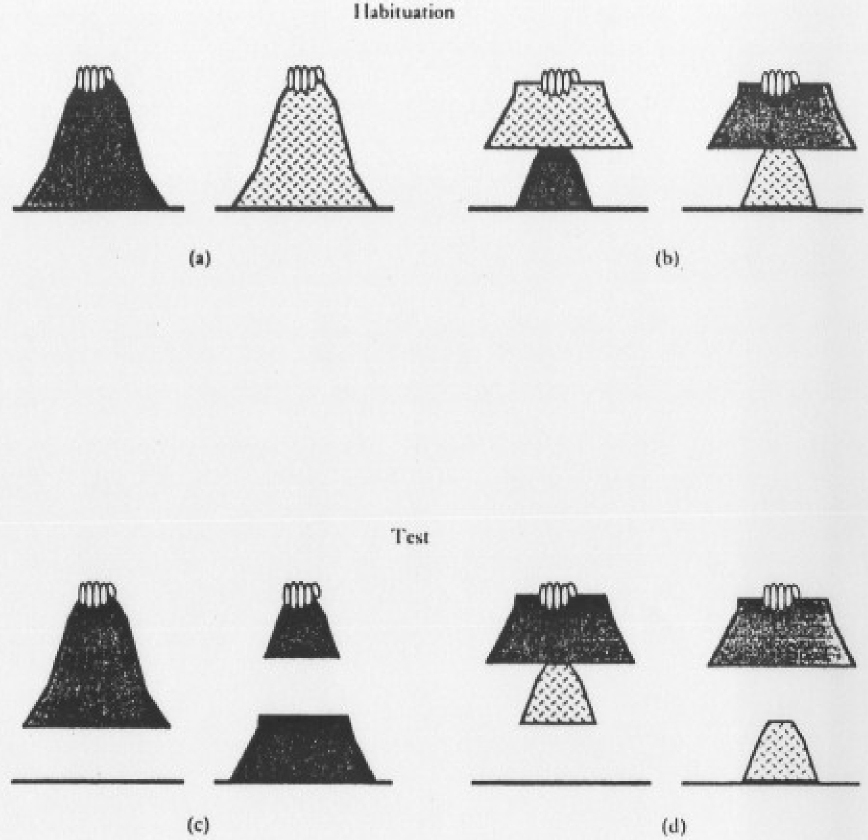

Figure 5.1 Schematic depiction of displays from an experiment on infants' perception of object boundaries. (After Spelke et al., 1993a.)

appeared more novel or surprising to them. The results supported this prediction: the infants in the experimental condition showed a significantly greater looking preference for the half-object display than those in the baseline condition, providing evidence that infants perceived the objects as unitary wholes.

Let us now complicate the situation and ask whether infants perceive object boundaries of scenes containing several objects. Adults typically are able to perceive the distinctness of each object in a complex scene. Studies of young infants provide evidence that they also can perceive the distinctness of objects, under two conditions. First, young infants perceive two objects as distinct if the objects are spatially separated by a gap (Figure 5.2, a–c). Two objects are perceived as distinct not only when the objects are separated vertically so that the gap is visible (Spelke et al., 1989; Kestenbaum et al., 1987), but also when the objects are separated in depth, so that the gap cannot be seen directly (Hofsten and Spelke, 1985; Kestenbaum et al., 1987). Second, young

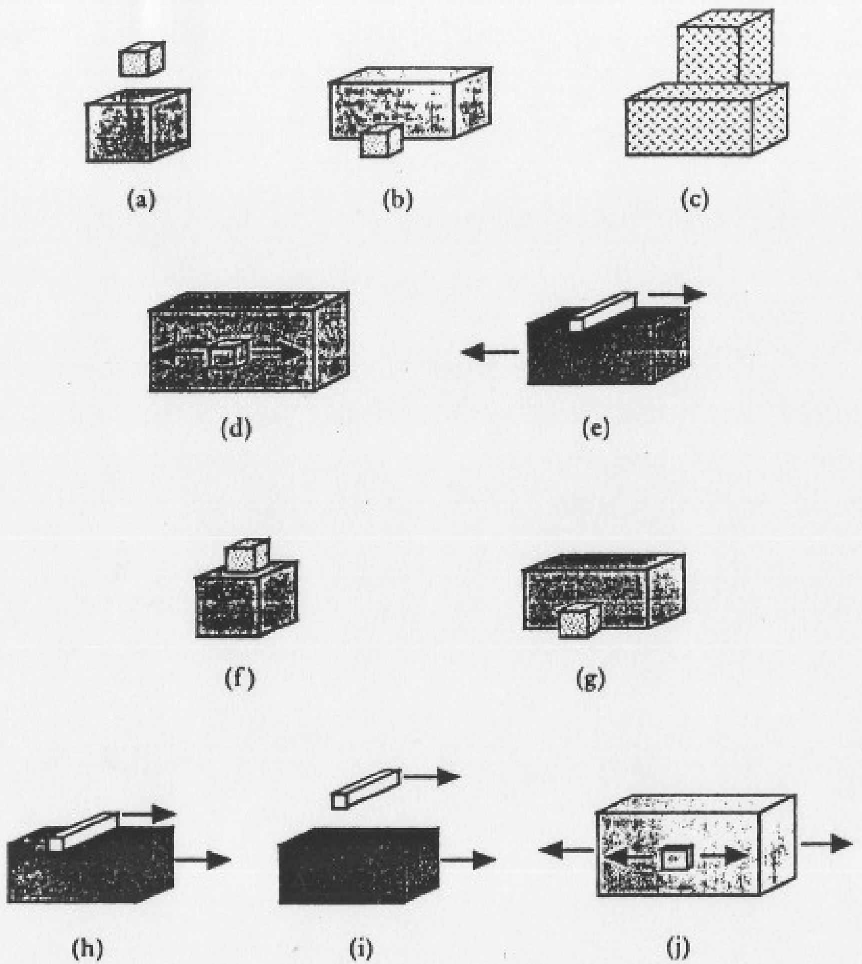

Figure 5.2 Schematic depiction of displays from experiments on object perception in infancy. Arrows indicate the direction and extent of object motion. The objects in (b), (c) and (j) were separated in depth; those in (d) and (g) were adjacent in depth. (After Hofsten and Spelke, 1985 (d, j); Kestenbaum, et al., 1987 (a, b, f, g); Prather and Spelke, 1982 (c); Spelke, et al., 1989 (e, h, i)).

infants perceive two objects as distinct if the objects undergo separate motions, even if the objects remain in contact throughout the time that they move (Figure 5.2, d and e). Two adjacent objects are perceived as distinct if one object moves while the other is stationary (Hofsten and Spelke, 1985) and also if each object moves rigidly in a different direction (Spelke et al., 1989).[3] In contrast, infants do not appear to perceive the boundary between two objects that are stationary and adjacent, even if the objects differ in colour, texture and form (Figure 5.2, f and g). In the experiment by Spelke et

al. (1991a), for example, three-month-old infants' perception of object unity appeared to be equally strong, regardless of whether infants viewed an object with a uniform colour and simple shape (Figure 5.1a) or an object with a top and bottom that differed in colour and were irregular in shape (Figure 5.1b). The Gestalt relationships that specify the boundaries of stationary objects for adults – colour similarity, smoothness of edges and figural goodness – do not appear to be effective for infants.

The above findings suggest that young infants are sensitive to two symmetrical constraints on object motion: *cohesion* and *boundedness*. First, a single object is a spatially connected body that retains its connectedness as it moves. When two surfaces can be seen *not* to be connected (because they are separated by a detectable gap or because their connectedness is broken as they move), the cohesion constraint dictates that the surfaces lie on different objects. Second, distinct objects are not connected, and they do not become connected when they move. When no spatial gap or relative motion can be seen to separate two surfaces, the boundedness constraint dictates that the surfaces lie on a single object. Infants' sensitivity to these two constraints can be encompassed by a single *principle of cohesion*: surfaces lie on a single object if and only if they are connected. This principle accounts for all the findings described above.

Let us turn to the case in which two objects undergo a common rigid motion. Infants' perception of commonly moving objects has been studied with configurations similar to those described above (Figure 5.2, h–j). Perception of object boundaries has been found to depend on how the objects are arranged in space.

When two objects are adjacent and move together, infants appear to perceive one connected body (Hofsten and Spelke, 1985; Spelke et al., 1989). This finding is not surprising, since the objects also are seen as one body when they are stationary. When two objects are separated by a visible gap and move together, infants appear to perceive two distinct bodies, despite the common pattern of motion (Spelke et al., 1989). This finding follows from the cohesion principle: two parts of a single object cannot be wholly unconnected. When two objects are separated in depth, however, a different finding is obtained. Although the objects are perceived as distinct when they are stationary, they are perceived as a single body when they move together (Hofsten and Spelke, 1985). This perception does not follow from the cohesion principle alone. What accounts for it?

One possible account is suggested by the intuitions of adults. If two partly hidden surfaces move rigidly together, we infer that the surfaces are in contact somewhere out of view. This inference follows from the physical constraint of *no action at a distance*: distinct objects do not move together if they are separated by a gap. Conversely, if two partly hidden surfaces move independently, adults infer that they are separated by a hidden gap. This inference follows from the physical constraint of *action on contact*: objects do not move independently when they are in contact. Both constraints can be captured by a single *principle of contact*: surfaces move together if and only if they are in contact. Once two partly hidden surfaces are inferred to be continuously in contact, the display is perceived as a single object, like the display in Figure 5.2h, in accord with the cohesion principle. Therefore, these cohesion and contact principles together specify that commonly moving, partly hidden surfaces lie on a single object.

Do infants perceive partly hidden objects in this way? This possibility may appear remote. In order for infants to perceive two commonly moving, partly hidden surfaces as adults do, they must perceive occlusion: infants must represent surfaces as hiding parts of other surfaces. In addition, infants must make inferences about the surfaces

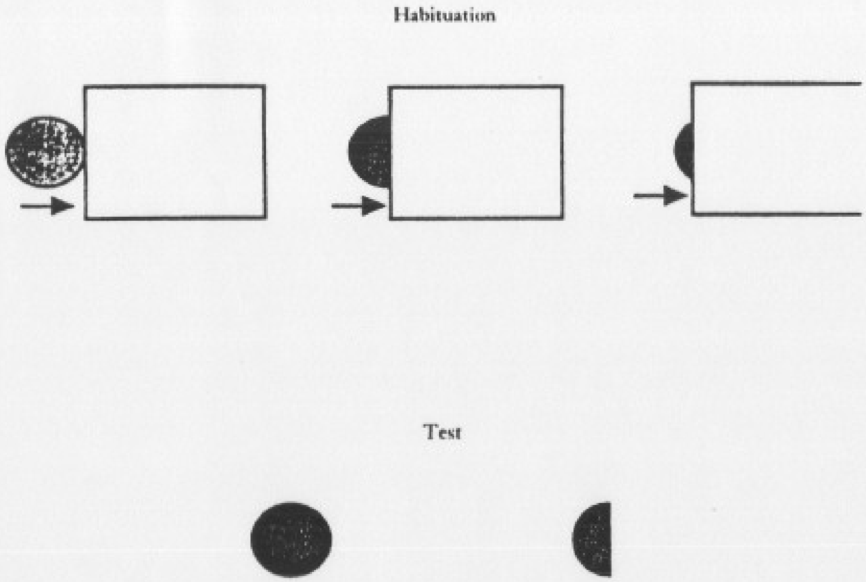

Figure 5.3 Schematic depiction of displays from an experiment on infants' perception of a progressively occluded object. Arrows indicate the direction of motion of the disk, which continued moving until it was fully hidden. (After Craton and Yonas, 1990.)

that lie in occluded parts of the layout. Finally, infants' inferences must follow from an analysis of the motions of visible surfaces, in accord with both the contact and the cohesion principles. We now turn to research that provides evidence for all these abilities.

1.2 Infant perception of partly occluded objects When a visible object moves partly out of view, young infants appear to perceive a persisting, unchanging body. Evidence for this ability comes from a variety of experiments (e.g. Baillargeon, 1987a; Bower, 1967; Craton and Yonas, 1990; Kellman and Spelke, 1983; Leslie, 1991; Spelke, Breinlinger, Macomber and Jacobson, 1992). An experiment by Craton and Yonas (1990) serves as an example. Four-month-old infants were habituated to a disk that moved in and out of view behind a screen (Figure 5.3). The disk underwent a fairly complex motion such that it was rarely fully visible or fully hidden: for most of the habituation period, the disk was partly occluded by the screen. Following habituation, the infants were shown test displays consisting of either a half disk or a whole disk. Four-month-old infants looked significantly longer at the half disk. This finding suggests that the infants did not perceive the occluding edge of the screen as a boundary of the disk, and that they did not perceive the disk to change shape as it moved from view. Rather, the infants appeared to perceive an object of constant form that was progressively hidden and revealed.

What do infants perceive when an object moves rigidly behind a surface that occludes its centre: can they infer that the visible surfaces are in contact behind the occluder throughout the event, and therefore perceive the object as one connected body? A number of experiments provide evidence for this ability. In one study (Kellman and Spelke, 1983), four-month-old infants in an experimental condition were habituated to a rod moving laterally behind a central occluding block. Following habituation, the infants were shown two test displays: a connected rod and a broken rod consisting of two aligned parts of the rod with a gap where the occluder had been (Figure 5.4). Their looking times were compared to those of infants in a baseline condition, who viewed the same test displays. The infants in the experimental condition looked significantly longer at the broken rod, relative to baseline. This experiment thus provided evidence that infants perceived the partly hidden rod as a connected object.

Subsequent experiments further investigated the conditions under which infants perceive the unity of a centre-occluded object. First, the object must move: infants do not infer contact between the visible surfaces of an object that is stationary (Kellman and Spelke, 1983). Second, any rigid motion in three-dimensional space leads infants to perceive object unity: motion in depth and vertical motion are as effective as lateral motion (Kellman, Spelke and Short, 1986). Third, retinal displacements produced by an object's motion are neither necessary nor sufficient for perception of object unity. If infants are in motion and view a centre-occluded object that moves conjointly with them, effectively eliminating any retinal displacement caused by the motion of the object, they infer contact between the object's partly occluded surfaces. Infants fail to infer contact between the surfaces of a stationary centre-occluded object during self motion, despite the fact that their own displacement produces substantial retinal displacement of the display (Kellman, Gleitman and Spelke, 1987). It appears that real, three-dimensional surface motion is necessary for perception of partly hidden objects. Fourth, in all the above studies, the Gestalt relations of colour similarity, smoothness of edges and figural goodness have no detectable influence on infants' perception of centre-occluded objects. In stationary displays, Gestalt relations fail to specify, for infants, that surfaces lie on one connected, partly hidden object (Kellman and Spelke, 1983; Schmidt and Spelke, 1984; Schmidt, 1985; Schwartz, 1982). In moving displays, these relations fail to influence either the strength of infants' perception of object unity (Kellman and Spelke, 1983) or the form of the objects that infants perceive (Craton and Baillargeon, personal communication). Infants' perception of centre-occluded objects accords only with the principles of contact and cohesion.

The above studies were conducted with infants at least three months old. It is interesting to ask whether younger infants would perceive partly occluded objects in the same way. Recent experiments by Slater, Morison, Somers, Mattock, Brown and Taylor (1990) suggest that they do not. Unlike four-month-olds, newborn infants may perceive the surfaces of a rigidly moving, centre-occluded object as separated by a gap.

In these studies, newborn infants were habituated to a rigidly translating, centre-occluded object (either an outline square or a rod). Following habituation, the infants were presented with paired test stimuli consisting of a broken and a connected figure. With both the outline square and the rod, newborn infants showed a significant preference for the connected rather than the broken test display, suggesting that they perceived the centre-occluded object as two spatially separated bodies bounded by the occluder. Additional studies provided evidence that these looking patterns were not produced either by a preference for a familiar object or by a failure of attention to the occluder

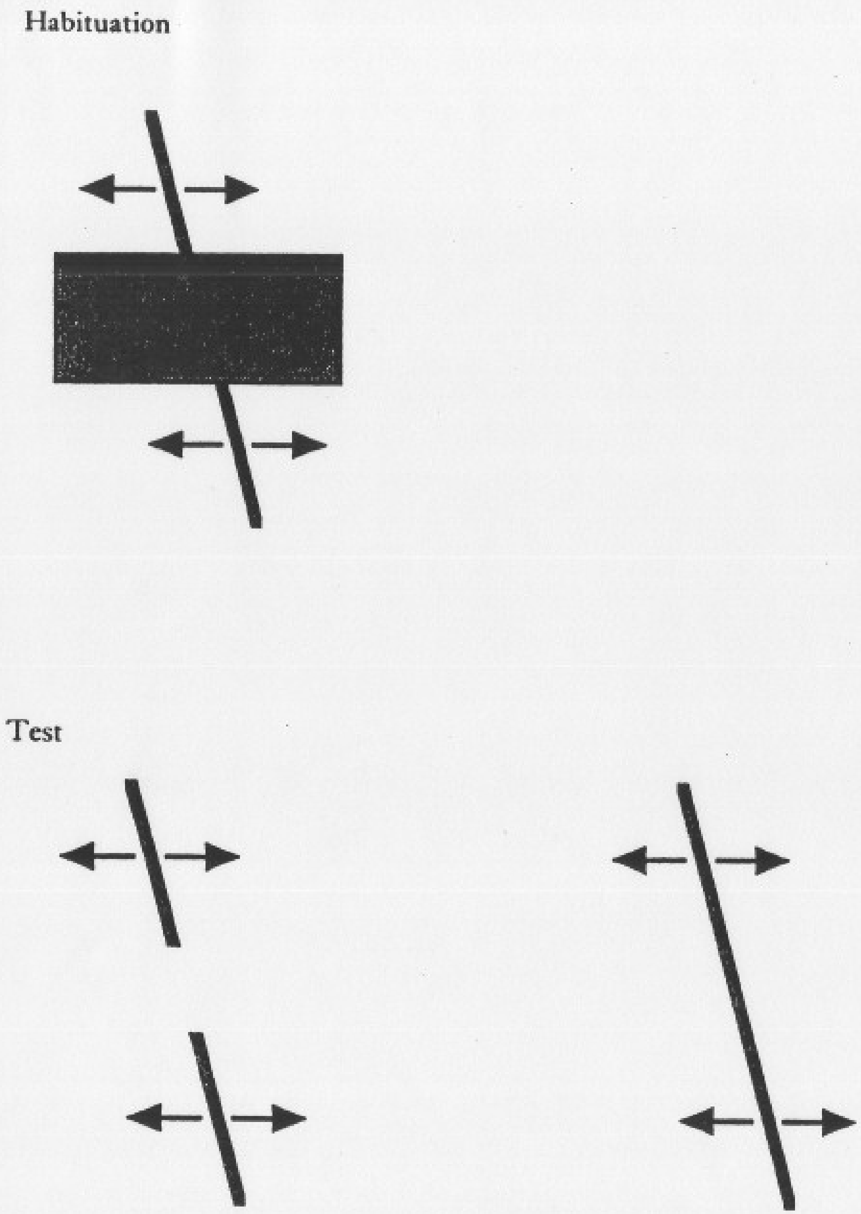

Figure 5.4 Schematic depiction of displays from an experiment on infants' perception of partly occluded objects. Arrows indicate the direction and relative extent of the rod's motion. (After Kellman and Spelke, 1983.)

during habituation. A final study directly compared newborn and four-month-old infants' performance using displays differing only in size. This study replicated Kellman and Spelke's (1983) original findings with four-month-old infants; newborns again exhibited the opposite visual preferences.

The above findings could be interpreted in at least four ways. First, newborn infants may be insensitive to the motion relations that are critical to the perception of partly occluded objects in infancy. This possibility is consistent with research on the neural mechanisms of motion processing and their development in infancy (Johnson, 1990). Second, developmental changes in depth perception may allow four-month-old infants, but not newborns, to perceive the correct depth relations between the occluder and the partly hidden object. Very young infants may fail to see a centre-occluded object as occluded because they fail to perceive its surfaces as standing behind the occluder. Consistent with this possibility, a wealth of research provides evidence that sensitivity to depth increases dramatically over the first four months (e.g. Held, Birch and Gwiazda, 1980; Kellman et al., 1990). Third, the neural pathways allowing cognitive control over visual attention may mature over the first four months. Newborn infants therefore may fail to exhibit, in their looking preferences, cognitive capacities that are present and otherwise functional (Johnson, 1990). Fourth, young infants may perceive occlusion, depth and motion relations correctly but may fail to perceive object unity in accord with the contact and cohesion principles. Current research is attempting to test these possibilities.

Whatever processes account for developmental changes in the first months of life, it appears that three- and four-month-old infants perceive visible objects in accord with the principles of cohesion and contact. For such infants, perception of visible objects evidently depends on processes that operate quite late in perceptual analysis. These processes take as input a representation of arrangements and motions of surfaces in the three-dimensional visible layout, not lower level representations of arrangements and displacements of images in the two-dimensional visual field. We now ask whether these processes are more central still: does object perception depend on distinct visual mechanisms, haptic mechanisms and the like, or does it depend on a single mechanism operating on representations of the layout obtained from any perceptual mode? If perception of objects depends on an amodal mechanism, then infants might perceive objects when they encounter surfaces through other perceptual modes, and their perception should accord with the same principles as perception of visible objects.

1.3 Infant perception of haptically presented objects Research on haptic perception provides evidence that infants perceive object unity and boundaries from active touch (Streri and Spelke, 1988). Infants aged four and a half months were given two rings to hold, one in each hand, under a bib that blocked their view of the rings and of their bodies. In one condition, the rings were constrained to move rigidly together; in another condition, the rings could be moved independently.[4] Infants explored the rings at will, without touching the area between the rings or bringing the rings into view. The experiments investigated whether, in each condition, infants perceived one connected object or two separate objects.

Perception of the unity or distinctness of the objects was tested through a haptic habituation and visual transfer test (Figure 5.5). In past research, infants were found to look more at a visible object that differed from the object they had felt during habituation (Streri and Pêcheux, 1986; Streri, 1987). After exploring the rings haptically to a

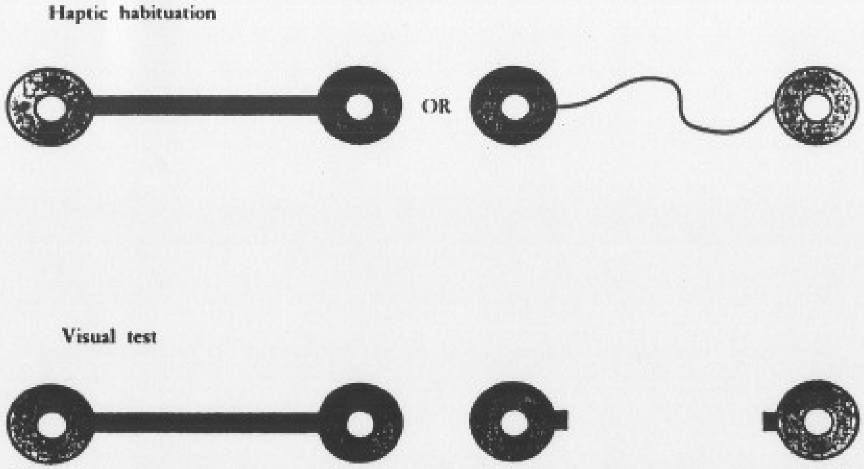

Figure 5.5 Schematic depiction of displays from an experiment on infants' haptic perception of object boundaries. (After Streri and Spelke, 1988.)

criterion of habituation, infants were presented with two visual displays consisting of two rings that were either connected or separated by a gap. Their looking preferences between the displays were compared to the preferences of infants in a separate baseline condition, who were presented with the same visual displays after no habituation sequence. The infants who had explored the rigidly movable rings looked significantly longer at the separated rings, providing evidence that they perceived the haptically presented rings as connected. Conversely, the infants who explored the independently movable rings looked longer at the connected rings, providing evidence that they perceived the rings as distinct. These perceptions accord with the contact principle and with the findings of studies of object perception in the visual mode.

Further experiments varied properties of the rigidly movable assembly such as the similarity of the two rings in form, texture and weight, and the simplicity of the overall shape of the assembly (Streri and Spelke, 1989). In contrast to adults, infants' perception of the rings was not affected by these properties. As in the case of vision, Gestalt relations evidently fail to influence infants' perception of haptically presented objects.

Most recently, experiments have investigated infants' perception of haptically presented objects that remain in contact but that undergo distinct rigid motions (Streri, Spelke and Rameix, 1993). In different conditions, the two rings either underwent separate horizontal motions (they could by pushed together and pulled apart) or separate vertical motions (they could be slid up and down with respect to one another). Infants either explored the rings actively, producing the relative motions, or they held the rings passively while an experimenter produced the motions. Like adults (Gibson, 1962), infants perceived the objects effectively only when they manipulated the assembly actively. In the active motion conditions, infants' looking preferences provided evidence that each haptic assembly was perceived as two distinct objects. These findings accord with the cohesion principle and with the findings of studies of visual object perception (Hofsten and Spelke, 1985; Spelke et al., 1989).

Experiments on haptic object perception therefore provide evidence that infants perceive haptically presented objects in accord with the cohesion and contact principles and not in accord with the Gestalt principles of similarity and figural goodness. Object perception appears to accord with the same principles in the haptic and the visual modes. It may depend on a single, amodal mechanism.

1.4 Principles of object perception In summary, infants appear to organize the perceived layout into bodies that are cohesive, that are bounded, that move independently of bodies from which they are spatially separated, and that move together with bodies with which they are in contact. Infants' perception of objects can be encompassed by two principles: the principle of cohesion (surfaces lie on one object if and only if they are connected) and the principle of contact (surfaces move together if and only if they are in contact).[5]

The above studies suggest that object perception accords with physical constraints on objects' behaviour. The research described in the next section investigated whether sensitivity to such constraints also allows infants to reason about objects. We ask whether infants can use knowledge of physical constraints in objects' behaviour to make sense of the motions of objects that are visible, and to make inferences about the motions of objects that are hidden.

2 *Physical reasoning in infancy*

2.1 Infants' representations of hidden objects Perceptual encounters with objects are sporadic: objects enter and leave the field of view whenever the perceiver, or other objects, move. Adults nevertheless represent each object as existing and moving continuously over space and time. These representations partly reflect our sensitivity to a basic physical constraint on object motion. According to the *continuity constraint*, objects move only on connected paths from one place and time to another. We now ask whether infants represent hidden objects in accord with this constraint.

First, consider whether infants represent the continued existence of an object that leaves their view, in accord with one aspect of the continuity constraint: objects exist continuously. Studies using three different methods, and quite different situations, provide evidence for this ability. In one series of studies, Clifton, Rochat, Litovsky and Perris (1991) presented six-month-old infants with two visible objects that differed in size and made distinctive sounds. Infants were allowed to reach for the objects. As is often observed (e.g. Bruner and Koslowski, 1972), infants reached in different ways for the large and small objects. After this familiarization, the room lights were extinguished, such that no object could be seen, and the sounds that had accompanied the large and small objects were presented in alternation. Presented with each sound, subjects tended to engage in the reaching movements elicited by an object of the appropriate size. Analyses of the reaching patterns of individual infants suggested that these reactions were not attributable to response learning during the period when the object was visible. Rather, infants appeared to represent each object's position and size, and these representations guided infants' reaching.

Further evidence for object representations comes from research using preferential looking methods and objects that move fully from view behind an occluder. Although we have already described one such study (Craton and Yonas, 1990), the most extensive studies come from the laboratory of Baillargeon (1986; 1987a; 1987b; Baillargeon, Spelke and Wasserman, 1985). In Baillargeon's first experiments, infants were familiarized with a screen that rotated 180° on a table, in the manner of a drawbridge. After habituation to this event, a stationary object was placed behind the screen. The position and dimensions of the object were such that the object was fully visible when the screen lay flat on the table, was progressively occluded as the screen rose and was fully hidden by the time the screen had rotated 60°. The screen's rotation then continued. On alternating trials, the screen stopped when it reached the place occupied by the object (a novel but possible motion) or it rotated 180° through the place occupied by the object, revealing nothing in its path (a familiar but impossible motion). Infants as young as four and a half months looked longer at the latter motion (Baillargeon, 1987a). This finding provides evidence that infants represented the existence and location of the hidden object.

Given only the above findings, one could question the richness, robustness and accessibility of young infants' representations (Fischer and Biddell, 1991). Further studies by Baillargeon provide evidence that five- to seven-months-old infants' representations of objects are quite rich, incorporating information not only about the existence of a hidden object, but also about its location, size and rigidity (Baillargeon, 1987b; Baillargeon and Graber, 1987). In one series of studies, infants were presented with objects of different heights behind a rotating screen. Preferential looking to screen rotations of different extents depended reliably on the height of the hidden object: the taller the object, the less extensive the screen rotation that elicited a novelty reaction (Baillargeon, 1987b). This finding, like the findings of Clifton et al. (1991), of Craton and Yonas (1990) and of a further experiment by Baillargeon (Baillargeon and Graber, 1987), provides evidence that infants represented the size and shape of the hidden object and inferred that these properties would not change while it was hidden. In other studies, infants were presented with objects differing in rigidity. An extensive screen rotation evoked novelty reactions only for the rigid object (Baillargeon, 1987b). This finding suggests that infants can represent the permissible transformations of a hidden object: in this case, change in shape (see also Baillargeon, Graber, DeVos and Black, 1990).

If an object moves fully out of view in one location and returns to view in another location, it must have traced a connected path from the first location to the second. An experiment by Spelke and Kestenbaum (1986) suggests that four-month-old infants, like adults, represent the identity or distinctness of successively hidden objects in accord with this aspect of the continuity constraint.

Infants were presented with a display in which two objects passed successively behind two spatially separated screens (Figure 5.6): an object that stood to the left of the left screen moved behind it, and after a pause, an object emerged to the right of the right screen. At the right end of the display, the second object changed direction and the same motions were presented in reverse. This event occurred repeatedly, as long as the infant looked at it. Although only one object is visible at a time in this event, adults describe the event as containing two objects moving in succession, one on each side of the gap between the screens. This perception follows from the continuity constraint: objects move only on connected paths.

To investigate infants' perception of this event, a group of infants was habituated to it. Other infants were habituated to an event in which a single object moved continuously behind the two screens, to an event in which one or two objects moved behind a single wide screen, or to no event (baseline condition). Then all the infants were presented, on alternating trials, with displays of either one or two fully visible objects. Infants

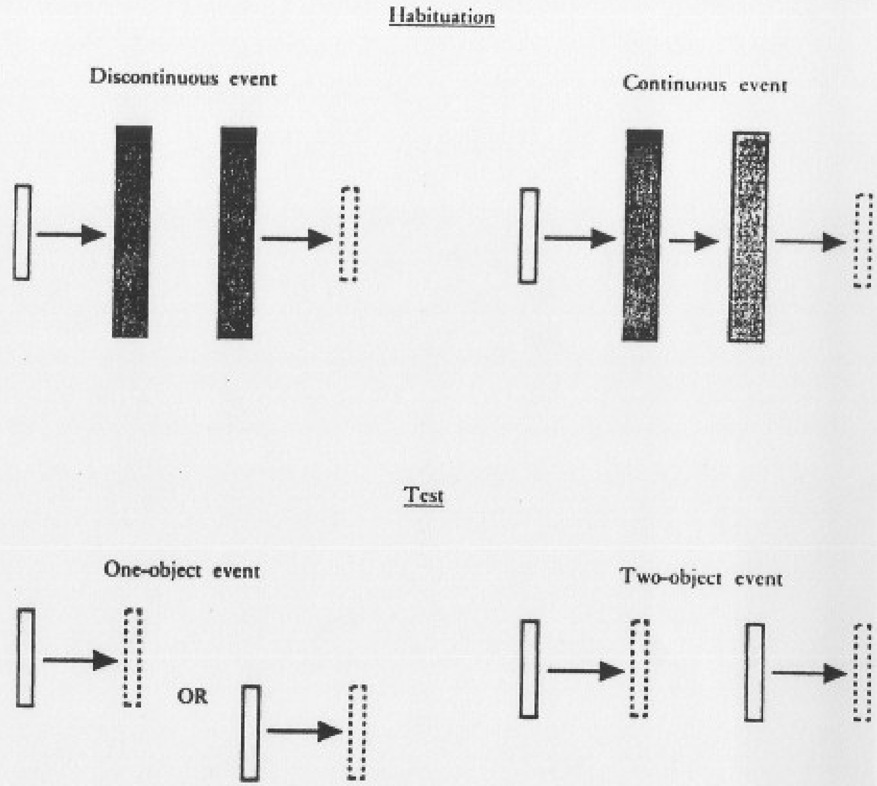

Figure 5.6 Schematic depiction of displays from an experiment on infants' apprehension of object identity. Arrows indicate the path of the object's motion from its initial position (solid lines) to its final position (broken lines). (After Spelke and Kestenbaum, 1986.)

habituated to the discontinuous motion showed a preference for the one-object event. This preference differed reliably from the preferences of infants habituated to continuous motion and from baseline. The experiment provides evidence that infants apprehended two continuously moving objects in the discontinuous event, in accord with the constraint that objects move only on connected paths. Research by Baillargeon and Graber (1987) supports the same conclusion.

2.2 Infants' inferences about hidden object motion The above experiments suggest that infants represent hidden objects and their motions, and that their representations accord with the continuity constraint. The next experiments extend these findings in two directions (Spelke et al., 1992; 1993b). First, they investigate whether infants are able to infer how a hidden, moving object continues to move and where it comes to rest. Second, they investigate whether infants' representations of the motions of hidden objects accord with a second physical constraint on object motion. The *solidity*

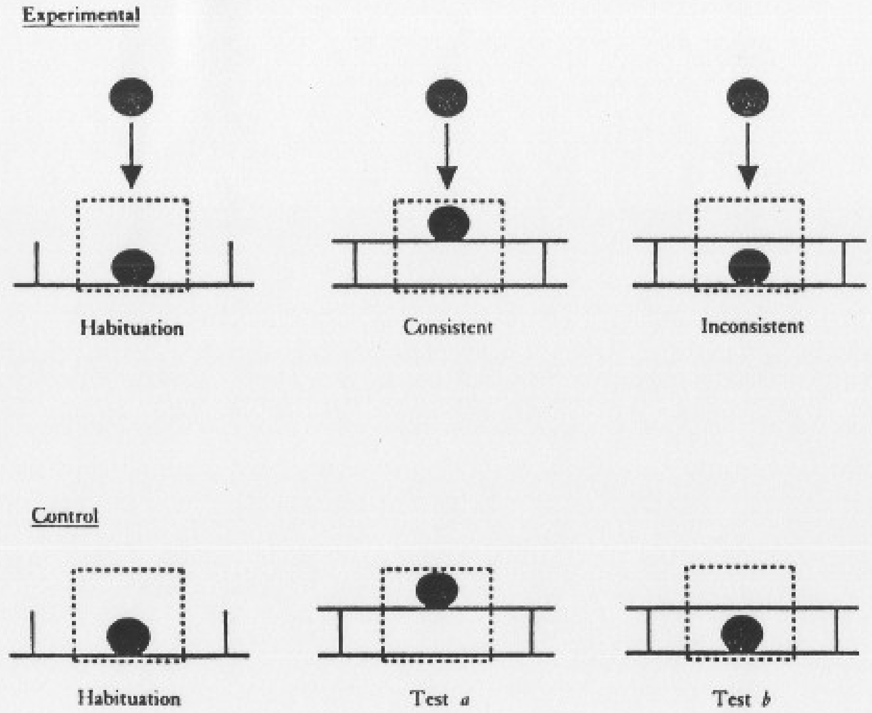

Figure 5.7 Schematic depiction of displays from an experiment on infants' inferences about hidden object motion. Broken lines indicate the position of the screen. Arrows indicate the direction and path of visible motion in the experimental condition. In the control condition, the ball was moved forward in depth to its final position. (After Spelke et al., 1992.)

constraint dictates that objects move only on non-intersecting paths, such that no parts of distinct objects ever coincide in space and time. If infants represent hidden object motion in accord with the continuity and solidity constraints, then they should infer that a hidden moving object will neither 'jump over' nor 'pass through' any obstacle in its path.[6]

These experiments used a modified preferential looking method so as to present young infants with a task devised by Piaget: an 'invisible displacement task'. In the first experiment (Spelke et al., 1992), four-month-old infants were first presented with an open stage with a brightly coloured floor (Figure 5.7). A screen was lowered to cover the lower half of the stage, including the floor, a ball was introduced above the screen and dropped behind it, and then the screen was raised to reveal the ball on the floor: an expected outcome for adults. Looking time to this event outcome was recorded, beginning with the raising of the screen. The event was repeated on a series of trials, until looking time declined by 50 per cent.

After this habituation sequence, a second, brightly coloured surface was introduced

into the display above the floor, the screen was lowered to cover both surfaces and the ball was dropped as before. On alternating test trials, the screen was raised to reveal the ball at rest either in a new position on the upper surface or in its familiar position on the floor. Whereas the new position was consistent with all constraints on object motion, the familiar position was inconsistent with the continuity and solidity constraints. Given that the upper surface neither moved nor ruptured, the ball could only have reached the lower surface by 'jumping over' or 'passing through' the upper surface, in violation of the continuity or solidity constraints.

Looking times to the two test outcomes were recorded, beginning with the raising of the screen, and were compared to the looking times of infants in a control condition. In the control condition, infants were presented with the same outcome displays, preceded by events in which the ball was moved forward in depth to its final position, and then the screen was lowered and raised. As in the studies of Spelke et al. (1993a), therefore, infants in the two conditions viewed exactly the same displays throughout the time that looking was recorded.

If infants inferred that objects would move in accord with the continuity and solidity constraints, then the infants in the experimental condition were expected to look longer at the inconsistent event, relative to those in the control condition. The findings confirmed this prediction. The experiment thus provided evidence that four-month-old infants inferred that the hidden object would move on a connected path that intersected no other object, in accord with solidity and continuity constraints.

This finding complements the findings of research by Baillargeon (1986), using a different preferential looking method. It was replicated and extended by Spelke et al. (1992; 1993b) in four further studies. In these studies, reasoning in accord with the continuity and solidity constraints was tested with events in which an object fell through the air toward a surface with a gap, rolled on a horizontal surface in the frontal plane or rolled on a horizontal surface in depth. Experiments were conducted at four ages: two and a half months, four months, six months and ten months. At all these ages and for all the events, infants looked longer at event outcomes that were inconsistent with the continuity and solidity constraints.

Continuity and solidity are symmetrical constraints on object motion. The continuity constraint dictates that a single object travels on a connected path over space and time: its path can contain no gaps (Figure 5.8b). The solidity constraint dictates that distinct objects travel on separate paths over space and time: paths cannot intersect such that the objects coincide in space at any moment in time (Figure 5.8c). These two constraints, therefore, can be encompassed by a single *principle of continuity*: an object traces exactly one connected path over space and time. The above research provides evidence that this principle guides young infants' reasoning about hidden objects.

The continuity principle does not permit fully specific predictions about the motion or the final position of a hidden object. For example, an object that falls from view toward an obstacle might cease moving before reaching the obstacle. If the object does reach the obstacle, it might come to rest, rebound, displace the obstacle, break the obstacle or itself be broken. All these event outcomes are consistent with the continuity and solidity constraints:[7] adults distinguish between these outcomes by applying knowledge of other constraints on object motion and knowledge of the behaviour of objects of particular kinds. The next experiments have begun to investigate whether infants distinguish among some of these outcomes, and infer that objects will move in accord with two further physical constraints on object motion: gravity and inertia.

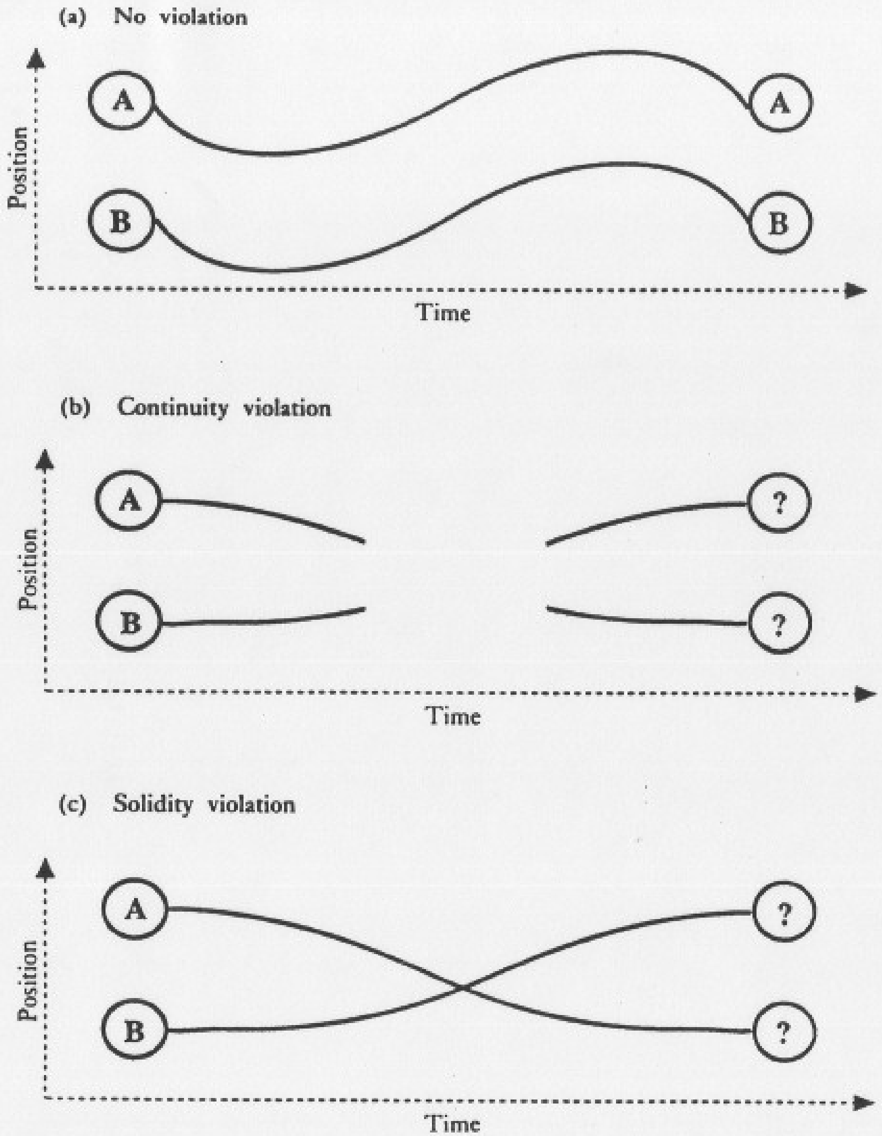

Figure 5.8 Schematic depiction of events that accord with, or violate, the continuity and solidity constraints. Solid lines indicate each object's path of motion, expressed as changes in its position over time. Each object traces (a) exactly one connected path over space and time, (b) no connected path over space and time or (c) two connected paths over space and time.

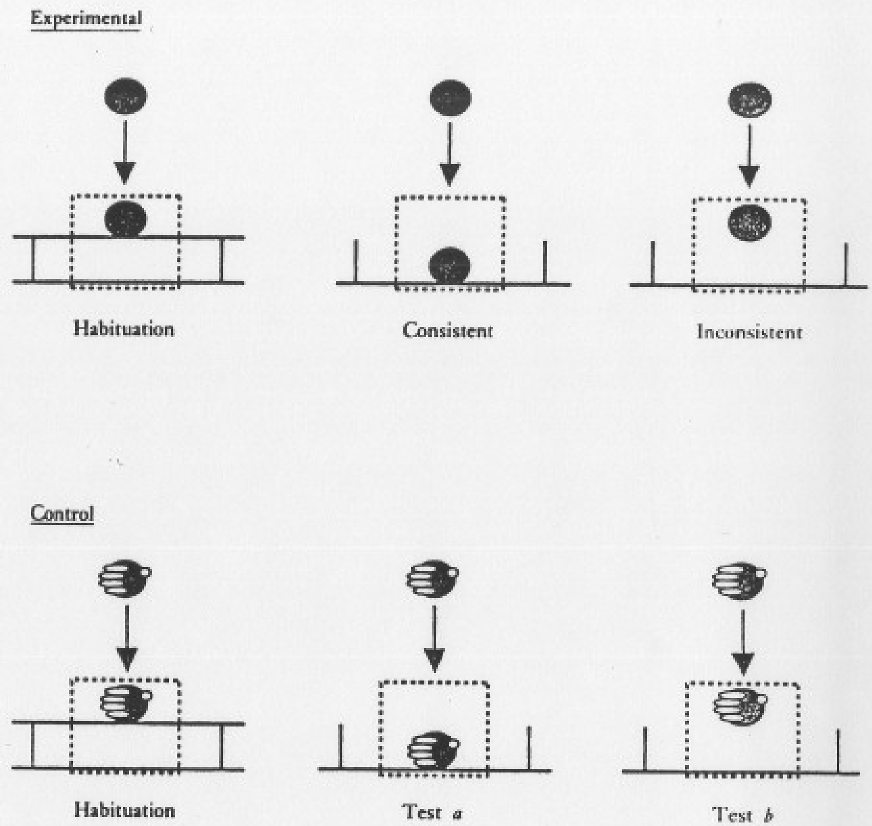

Figure 5.9 Schematic depiction of displays from an experiment on infants' inferences about hidden object motion. Arrows indicate the direction and path of visible motion in the experimental and the control condition. In the control condition, the hand held the ball throughout the event. (After Spelke et al., 1992.)

A number of experiments have tested whether infants infer that an object that moves from view will move downward to a supporting surface on a smooth path, in accord with the constraints of gravity and inertia (Spelke et al., 1992; 1993b; 1993c). One experiment by Spelke et al. (1992) serves as an example. This study used the same method and nearly the same events as the above studies of continuity and solidity (Figure 5.9). Four-month-old infants were habituated to a ball that fell behind a screen covering two surfaces and was revealed at rest on the first surface in its path. Then the upper surface was removed, the ball was dropped behind the screen as before, and it was revealed either in a new position on the lower surface or in its former position, now in midair. The latter position was inconsistent with gravity and with inertia: the ball appeared to stop falling in the absence of support and to change its motion in the absence of obstacles.

Looking time to these two outcomes was compared to the looking time of infants in a control condition, presented with a hand-held ball that was lowered to its resting position before the lowering and raising of the screen. Except for the hand, the infants in the control condition viewed the same outcome displays as those in the experimental condition, but with outcomes that were consistent with gravity and inertia. Infants in the experimental condition looked non-significantly longer at the *consistent* outcome. Their preferences differed reliably from the preferences of infants in the corresponding studies of continuity and solidity. These findings provide no evidence for sensitivity either to gravity or to inertia.

In further experiments using the invisible displacement method, sensitivity to gravity and inertia has been tested with other events and at other ages, ranging from three to twelve months. Infants under six months of age have shown no sign of sensitivity to either constraint in any situation tested. Sensitivity to both constraints appears to emerge at older ages, although it appears to emerge in a piecemeal fashion, with considerable variability across infants (Spelke et al., 1992; 1993b; 1993c). Comparisons across experiments have revealed that infants respond more strongly and consistently to the violations of the continuity and solidity constraints than to violations of the gravity and inertia constraints (Spelke et al., 1992; 1993b). These studies suggest that infants do not make fully specific inferences about the motion of hidden objects. They suggest, moreover, that sensitivity to continuity and solidity is more deeply rooted in human development than sensitivity to gravity and inertia. Sensitivity to gravity may not, however, be fully absent in early infancy (see Baillargeon, 1990; Baillargeon and Hanko-Summers, 1990; Needham and Baillargeon, 1991).

The next experiments investigate whether infants represent the motions of hidden objects in accord with one more physical constraint on objects' behaviour: no action at a distance. Experiments by Ball (1973), Borton (1979) and Baillargeon, DeVos and Black (in Baillargeon, 1992) provide evidence that they do. Infants reason about hidden interactions between objects in accord with the constraint that surfaces move together only on contact.

Ball's (1973) experiment may have been the first to use a preferential looking method to investigate young infants' inferences about hidden object motion. Infants ranging in age from nine to 122 weeks were familiarized with an event in which one object moved behind an occluding screen and, after an appropriate temporal delay, a second object emerged from the other side of the screen (Figure 5.10). Separate groups of infants then were presented with a fully visible display in which one of two events occurred. In one condition, the first object came to a halt on contact with the second object, and the second object immediately began to move in the same direction. In the second condition, the first object came to a halt before it reached the second object, and after a delay, the second object began to move. Looking times to the two event outcomes were recorded and compared to the looking times of infants in a no-habituation baseline condition.

Ball's analysis treated all the infants in each condition as a single group. He found that the infants in the experimental condition looked significantly longer at the display in which the objects were separated by a spatial and temporal gap, relative to baseline. Because Ball reported the data for each subject in an appendix to his paper, we were able to re-analyse his data separately for the youngest infants. The looking preference for the display in which the object motions were spatially and temporally separated differed significantly between the two conditions, among the subset of infants tested

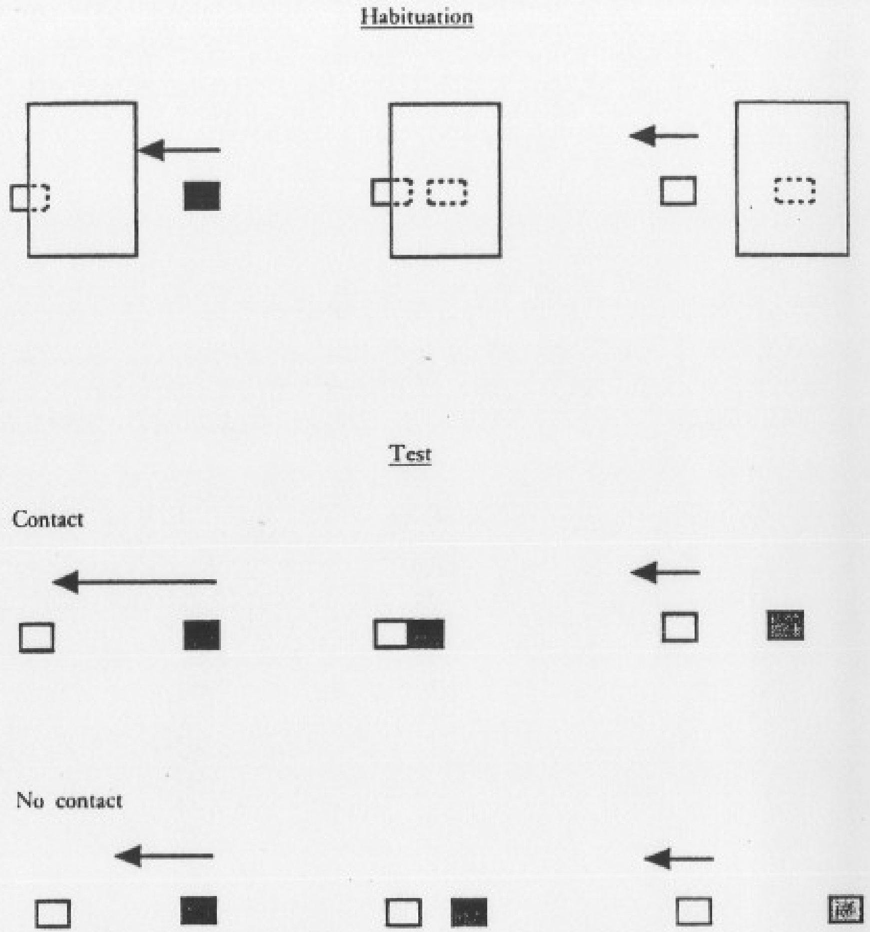

Figure 5.10 Schematic depiction of displays from an experiment on infants' inferences about hidden object motion. Each arrow indicates the direction and extent of motion of the object below it. (After Ball, 1973.)

at less than 28 weeks of age (Wilcoxon-Mann-Whitney $z = 2.48$, $p < .01$). Ball's experiment therefore provides evidence that by six and a half months of age, infants infer contact between the surfaces of the hidden objects, in accord with the constraint of no action at a distance.[8]

Two further experiments provide additional evidence for this ability (Baillargeon et al., 1991; in Baillargeon, 1992; Borton, 1976). In Baillargeon et al.'s study, six-month-old infants were shown a long narrow platform with a toy bear that either sat on the left end of the platform or sat next to the platform without touching it. The display was then hidden from view by a screen, a hand reached behind the screen and pulled the platform to the right and the bear moved rightward into view through an aperture in the screen. Infants looked longer at the event in which the bear had been shown sitting next to the platform. This finding suggests that infants understood that the bear would move together with the platform only if it was in contact with the platform's surface.

2.3 Infants' apprehension of causal relations between objects When adults view two objects that collide and immediately change their motion, we tend to experience each object as causing the other object's change in motion (Michotte, 1963). This impression accords with the constraint of action on contact. Adults' impression of a causal relation is removed, moreover, if a spatial gap or a temporal delay separates the two objects' motion (Michotte, 1954). The absence of an impression of causality between spatially or temporally separated objects accords with the constraint of no action at a distance. As noted above, these geometrical constraints can be captured by a single principle of contact.

We conclude this section by considering whether infants infer causal relations in accordance with this principle. Using preferential looking methods, Alan Leslie (1988; Leslie and Keeble, 1987) presented infants with animated film sequences in which two objects moved in succession (Figure 5.11). In one condition, the first object came into contact with the second object, and the second object immediately began to move in the same direction. The objects therefore moved together at the moment of contact. In other conditions, the motions of the two objects were separated in space or in time. To assess whether infants apprehended a causal relation in any of these events, Leslie familiarized separate groups of infants with one of the events and then presented the same event in reverse. He reasoned that in conditions where the familiarization event was perceived as causal, a reversal of that event would reverse not only the direction of the objects' motion, but also the causal relation between the objects. The infants who perceived a causal relation in the familiarization event therefore should recover their looking to the reversal of that event more than the infants who saw an event evoking no impression of a causal relation.

Leslie's experiments provided evidence that infants perceive causal relations as adults do. The infants presented with the objects that moved together at the moment of contact reacted to the event reversal with reliably longer looking than those presented with the objects whose motions were separated by a spatial or temporal gap.

In one respect, Leslie's findings go beyond the scope of this chapter: we offer no account of the mechanisms underlying impressions of causality in infants or adults (see Leslie, 1988; Michotte, 1954).[9] We believe it is significant, nevertheless, that infants' causal impressions accord with the contact principle. This finding converges with the findings from studies of infants' inferences about hidden object motion (Baillargeon et al., 1991; Ball, 1973; Borton, 1976). Infants may make sense both of visible and of hidden object motions in accord with a small set of general constraints on the behaviour of material bodies.

2.4 Principles guiding physical reasoning In summary, young infants appear to reason about the existence and the motions of both visible and hidden objects. Under certain conditions, infants represent the persistence of an object that is fully hidden, they trace object identity over successive encounters, they infer how a hidden, moving object continues to move and where it comes to rest, and they apprehend the causes of an object's motion. Early reasoning about object motion appears to accord with four

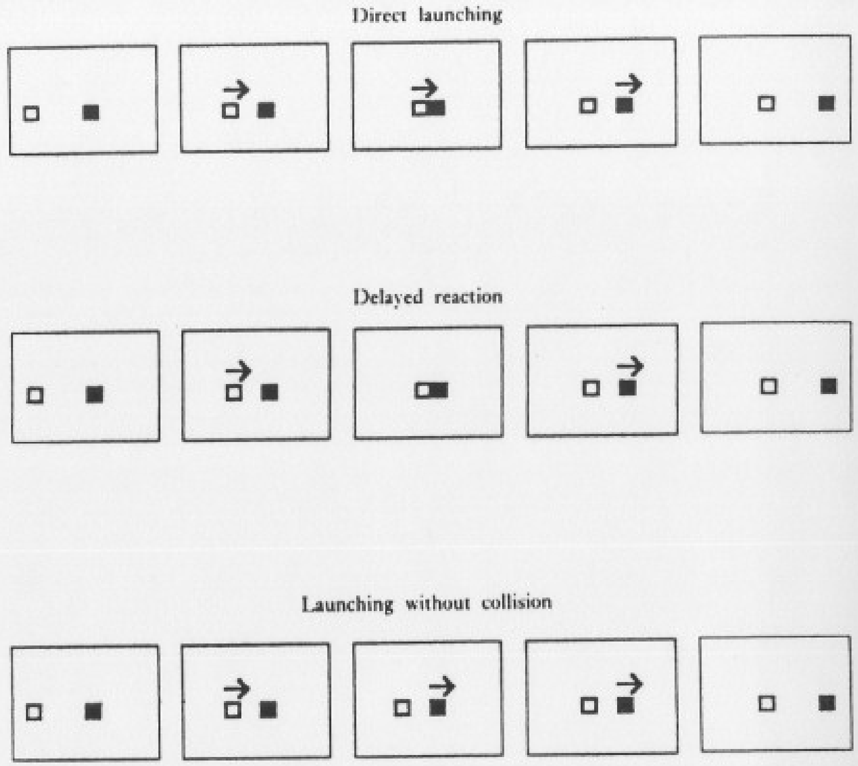

Figure 5.11 Schematic depiction of displays from an experiment on infants' impressions of causal relations between object motions. Arrows indicate the presence and direction of motion of the object(s) below. (After Leslie and Keeble, 1987.)

constraints: continuity, solidity, action on contact and no action at a distance. These constraints, in turn, can be captured by the principle of continuity (an object moves on a unique, connected path) and the principle of contact (objects move together if and only if they are in contact). How do these principles relate to the principles guiding object perception?

3 Object perception and physical reasoning in infancy

Infants' abilities to reason about objects resemble their abilities to perceive objects. First, object perception and physical reasoning both depend on an analysis of how surfaces are arranged in space, and how surface arrangements change over time. Second, the relevant spatio-temporal arrangements apply in both cases to surfaces in the three-dimensional layout, not to images in the two-dimensional visual field. Third, processes of object perception appear to depend on amodal mechanisms. It seems very likely that the same is true for the process of physical reasoning, although to our knowledge, this issue has not been investigated directly. We suggest now that there is a stronger relation between object perception and physical reasoning: the principles that encompass object perception and physical reasoning are closely connected, and possibly identical. This relation suggests that a single system of knowledge guides perceiving and reasoning about objects.

Consider first the contact principle. One could propose distinct and relatively restricted principles to encompass infants' perception of the simultaneously moving ends of one centre-occluded object, infants' inferences about the hidden motions of two successively moving objects, infants' impression of a causal relation between two objects that make contact, and infants' impression of no causal relation between two objects that do not make contact. The contact principle could, however, figure in all these abilities. When two surfaces move together, either throughout an event or at one point in an event, this principle dictates that the surfaces are in contact. When two surfaces move independently, this principle dictates that the surfaces are not in contact. Conversely, when two surfaces come into contact, this principle dictates that their motions are not independent. When two surfaces are separated by a spatial or temporal gap, finally, this principle dictates that their motions are independent; neither motion therefore could cause the other.

We now turn to the relation between the cohesion principle, specifying the conditions for object unity over space, and the continuity principle, specifying the conditions for object persistence over time. These principles are not identical: non-solid substances such as sand and water behave in accord with the continuity principle (a pile of sand moves on a connected, unobstructed path) but not in accord with the cohesion principle (a sand pile does not retain either its connectedness or its boundaries as it moves in relation to other objects and substances). Nevertheless, the principles are related. The necessary and sufficient condition for object unity, over space and time, is that the (spatial) parts and (temporal) appearances of an object be connected. Moreover, cohesion implies continuity: only continuously movable bodies could behave in accord with the cohesion principle.

The relation between the cohesion principle and the continuity principle can be discerned if one focuses on the separate constraints of boundedness and solidity, on one hand, and cohesion and continuity, on the other. According to the boundedness constraint, no parts of two distinct objects are connected. That is, every path from a part of one object to a part of the other object contains one or more boundary points, where at least one of the objects ends. This condition cannot be satisfied if points on distinct objects occupy the same location: no boundary separates a point from itself. It follows that no parts of distinct objects ever coincide in space and time, and therefore that the paths of two distinct, persisting objects can never intersect. Boundedness can only be satisfied by bodies whose behaviour accords with the solidity constraint.

Consider next the constraints of cohesion and continuity. According to the cohesion constraint, the parts of a single object are linked by enduring connections: connections that persist as the object moves. This condition cannot be met if there are gaps in the object's path through space or time. Cohesion can only be satisfied by bodies whose behaviour accords with the continuity constraint.

These considerations suggest that there is a close relationship between object perception and physical reasoning. It is possible, indeed, that the same principles govern perception and reasoning. Infants may infer that a hidden object moves not only continuously but also cohesively; infants may infer that two hidden, moving objects not only do not intersect but also do not merge. Ongoing research supports both these possibilities (Carey, personal communication). During infancy, object perception and physical reasoning may depend on a single system of knowledge.[10]

If object perception and physical reasoning are based on a single system of knowledge, then it is fair to ask whether this knowledge is embedded in 'perceptual' or 'reasoning systems'. We question both characterizations.

One of us has suggested that apprehending objects does not depend on 'perceptual processes' akin to those underlying the apprehension of colour, distance or motion (Spelke, 1988). This suggestion was based on a consideration of three aspects of object perception: the nature of its input, its amodal character and its accordance with physical constraints on objects' behaviour. The suggestion contrasted with the common view that object representations are produced by input systems operating independently of reasoning (e.g. Fodor, 1983; see also Gibson, 1966; 1979; Koffka, 1935; Michotte, Thinès and Crabbé, 1964) and echoed Marr's (1982) proposal that in moving from the representation of surfaces to the representation of objects, one passes the limits of 'pure perception' (see footnote 1). We believe the findings of the present studies cast strong doubt on the view that object perception depends on an input system operating independently of physical reasoning. Indeed, perceiving and reasoning about objects appear to be inseparable processes. In this respect, the present findings support Marr's view.[11]

Nevertheless, representing hidden objects and inferring their motions do not appear to depend on 'reasoning processes' akin to the processes involved in calculating one's income tax or solving crossword puzzles. For adults, inferences in accord with the constraints of continuity and contact appear to be immediate, effortless and unconscious. In some cases, these inferences are unaffected by specific knowledge of the objects being viewed: they occur even when such knowledge indicates that they are inappropriate (Michotte, 1963). Prototypical reasoning processes, in contrast, tend to be slow, effortful, deliberate and responsive to knowledge from any source (Fodor, 1983). These considerations led Michotte to propose that humans *perceive* the motions of hidden objects and the causal relations among visible objects. The present findings support aspects of Michotte's view (see also Leslie, 1988). Contrary to Michotte, however, the findings suggest that object perception and physical reasoning are based on a system of knowledge of physical objects, not on general perceptual principles such as those proposed by the Gestalt psychologists.

The processes that underlie perceiving and reasoning about objects therefore appear to lie at the border of what is traditionally considered 'perception' and what is traditionally considered 'thought'. An appreciation of the unique position of these processes may shed light both on the nature and on the development of physical knowledge.

4 *Physical conceptions in infancy and adulthood*

The above experiments suggest answers to the four questions that began this chapter, as those questions apply to infants. There appears to be a general process of object perception in infancy, applicable to all material bodies. Infants perceive the unity and boundaries of objects by analyzing the spatial arrangements and motions of surfaces, in accord with the principles of cohesion and contact. There also appears to be a general process of physical reasoning in infancy. Infants reason about the behaviour of material bodies in accordance with the principles of contact and continuity. The close relation between the principles guiding object perception and those guiding physical reasoning suggests a connection between these psychological processes. In infancy, perceiving and reasoning about objects may be guided by one system of knowledge: a single conception of material bodies comprising, at least in part, the principles of cohesion, contact and continuity.

What might these findings with infants suggest about object perception, physical reasoning and physical knowledge in adults? It is conceivable that studies of infants reveal nothing about mature perception, reasoning or knowledge. Studies of infants could be uninformative for either of two reasons. First, mature processes of object perception and physical reasoning might depend on mechanisms that emerge after infancy. Second, mature processes of perception and reasoning may result from developmental processes that bring radical change to physical conceptions (Carey, 1991; Gopnik, 1988; Kuhn, 1977; Piaget, 1954).

Contrary to these possibilities, we suggest that the principles guiding perception and reasoning in infancy are central to the physical conceptions of adults. This suggestion arises from a consideration of how one learns spontaneously about the physical world. It is supported, we believe, by a variety of observations, both from psychology and from philosophy, concerning adults' physical conceptions.

Insofar as humans develop knowledge by learning, and learn about objects by observing their behaviour, we suggest that the system of physical knowledge found in infants will tend to be enriched, not overturned, by the further development of knowledge (Spelke, 1991). This suggestion hinges on the claim that a single system of knowledge underlies infants' physical reasoning and object perception. If the principles of cohesion and contact underlie object perception, then infants will single out objects whose behaviour accords with those principles. As children learn about the bodies they single out, their learning may well enrich their initial conceptions. Children may learn, for example, that material bodies tend to have simple shapes, to move smoothly and to fall when unsupported. Children will not learn, however, that the behaviour of material bodies violates the cohesion and contact principles, even if the world that surrounds them contains myriad violations of the principles. Such learning will not occur, because entities that violate the cohesion and contact principles will not be singled out as objects.[12] Spontaneous learning will tend to deepen, not dislodge, the initial conception of material bodies.

A number of observations in philosophy and in psychology appear to support the view that cohesion, contact and continuity are central to mature conceptions of material bodies. Consider mature, common-sense intuitions about object identity over change. Intuitions about the persistence of a material body are clearest when the body's behaviour accords with all of these constraints; intuitions about the non-persistence of a body are clearest when the body's behaviour violates all the constraints. In contrast, intuitions about physical identity appear to become least certain, and decisions most problematic, when the behaviour of a body accords with some constraints and violates others: for example, when two particles fuse or one object is disassembled and reassembled (see Hirsch, 1982).

Consider next the sortal concepts that children acquire: concepts such as 'chair' or 'tiger'. These concepts tend strongly, although not universally, to apply to bodies whose behaviour accords with the principles guiding object perception and physical reasoning. In English, there are sortal terms such as 'lock', 'cup', 'bolt' and 'bee', but not one term for 'lock-and-key', 'cup and saucer', 'nut-and-bolt' or 'bee colony', despite the functional coherence of the latter notions. The accordance of sortal concepts

with the principles guiding object perception and physical reasoning may not be accidental. Initial conceptions of material bodies may underlie the acquisition of sortal concepts and sortal terms (see Markman, 1989; Mervis, 1987; Shipley and Shepperson, 1990; Soja, Carey and Spelke, 1991).

In contrast, the constraints on material bodies that infants fail to recognize may be weaker and less central to the physical conceptions of adults. To be sure, adults recognize that objects tend to have simple and regular shapes, that objects tend to fall when unsupported and that objects tend to move smoothly. Nevertheless, adults quite readily perceive, reason about and learn sortal terms for objects that are irregular in shape (e.g. rocks), that can rest without apparent support (e.g. kites) and that can change direction abruptly and spontaneously (e.g. animals). Moreover, adults' sensitivity to physical constraints such as gravity and inertia is incomplete, at best (McCloskey, 1983; Proffitt and Gilden, 1989).

These observations suggest that the earliest developing conceptions of physical objects are the most central conceptions guiding mature object perception and physical reasoning. For adults, such conceptions are overlaid by a wealth of knowledge about the appearances and the behaviour of particular kinds of objects. Even this more specific and limited knowledge, however, reflects the core knowledge from which it grew. Both for adults and for children, cohesion, contact and continuity may be central to our understanding of the material world. Through studies of early development, psychologists may investigate the nature of this core knowledge.

ACKNOWLEDGEMENTS

We thank the editors of this volume for their insightful comments on an earlier version of this manuscript. Supported by a grant, to ESS, from the National Institutes of Health (HD23103) and by a graduate fellowship, to GAV, from the National Science Foundation.

NOTES

1 More specifically, Marr suggests that perceptual mechanisms recover from retinal images a description of the visible surface layout: the '2.5D sketch'. This description does not indicate where an object ends and the next begins. According to Marr, it is likely to mark 'the limits of what one might call pure perception – the recovery of surface information by purely data-driven processes without the need for particular hypotheses about the nature, use or function of the objects being viewed' (Marr, 1982, p. 269).

2 We intend our account of object perception and physical reasoning to apply to all material bodies, including machines, animals and persons. Unfortunately, few studies exist concerning infants' perceiving or reasoning about objects in the latter categories. The chapter therefore focuses on objects such as balls and blocks.

3 We do not know what infants perceive when visible objects undergo non-rigid motions that preserve their connectivity, such as uniform bending or rotation around a joint. Current research is investigating some of these situations.

4 The rings were connected by a long and highly flexible elastic band that in all likelihood was not detectable by the infants.

5 Although the present account of object perception is substantially in agreement with the account in Spelke (1990), the bi-directional cohesion principle now replaces Spelke's uni-directional principles of cohesion and boundedness, and the bi-directional contact principle

replaces and revises Spelke's (1990) uni-directional principles of no action at a distance and rigidity.

6 The terms in quotations should not be interpreted as in ordinary language. When an object hits an obstacle, it may rupture the obstacle and thus move beyond it. Although this event may be described as one object passing through another, it does not violate the solidity constraint, because the two objects never coincide in space at any time. Similarly, an object that hits an obstacle may alter its motion and bounce over it. Although this event may be described as one object jumping over another, it does not violate the continuity constraint, because each object exists continuously and moves on a connected path. It is significant, we believe, that the English language has no term for events that violate the continuity and solidity constraints, even though such events are ubiquitous (for example, in the motions of shadows). People do not ordinarily communicate about such events, we suggest, because they do not really apprehend or understand them.

7 Infants may rule out the last two outcomes if their inferences about hidden object motion are guided by the cohesion constraint, because events in which the object or obstacle breaks apart violate that constraint. Two recently completed experiments provide evidence in favour of this possibility (S. Carey, personal communication).

8 Because the surfaces moved together only at the moment of impact and were otherwise both spatially separated and independently moving, the cohesion principle dictates that the surfaces comprised two separate objects.

9 The contact principle formulated here – *objects move together if and only if they are in contact* – must be combined with other premises in order to yield the inference that one object has *caused* another object's motion.

10 In our usage, a 'system of knowledge' is a set of principles that characterize the entities in a domain and underlies inferences about those entities (see Chomsky, 1980). We do not imply that this knowledge is explicit or conscious in infants or adults.

11 Contrary to Marr, however, studies of infants suggest that both object perception and physical reasoning depend in part on sensitivity to *general* constraints on the behaviour of material bodies. They do not depend exclusively on 'particular hypotheses' about objects of particular kinds.

12 Shadows provide an interesting test case for this thesis. Both infants and young children detect shadows, and they may be predisposed to consider shadows as objects, subject to the cohesion and contact principles (Piaget, 1960; deVries, 1987; Rubenstein, 1991). With development, children discover that shadows do not behave in accordance with these constraints. This discovery does not, however, lead to a change in conceptions of material bodies. Rather, children come to view shadows as non-material (see Carey, 1991)

REFERENCES

Baillargeon, R. 1986: Representing the existence and the location of hidden objects: Object permanence in 6- and 8-month-old infants. *Cognition*, 23, 21–41.

Baillargeon, R. 1987a: Object permanence in 3.5- and 4.5-month-old infants. *Developmental Psychology*, 23, 655–64.

Baillargeon, R. 1987b: Young infants' reasoning about the physical and spatial material characteristics of a hidden object. *Cognitive Development*, 2, 179–200.

Baillargeon, R. 1990: The development of young infants' intuitions about support. Paper presented at the 7th International Conference on Infant Studies, Montreal, Canada.

Baillargeon, R. 1992: The object concept revisited: New directions in the investigation of infants' physical knowledge. In C. E. Granrud (ed.), *Visual Perception and Cognition in Infancy*. Carnegie-Mellon Symposia on Cognition, Volume 23. Hillsdale, NJ: Erlbaum.

Baillargeon, R. and Graber, M. 1987: Where's the rabbit? 5.5-month-old infants' representation of the height of a hidden object. *Cognitive Development*, 2, 375–92.

Baillargeon, R., Graber, M., DeVos, J. and Black, J. C. 1990: Why do young infants fail to search for hidden objects? *Cognition*, 24, 255–84.

Baillargeon, R. and Hanko-Summers, S. 1990: Is the top object adequately supported by the bottom object? Young infants' understanding of support relations. *Cognitive Development*, 5, 29–54.

Baillargeon, R., Spelke, E. S. and Wasserman, S. 1985: Object permanence in five-month-old infants. *Cognition*, 20, 191–208.

Ball, W. A. 1973: The perception of causality in the infant. Paper presented at the Society for Research in Child Development, Philadelphia, PA.

Bornstein, M. H. 1985: Habituation of attention as a measure of visual information processing in human infants: Summary, systematization, and synthesis. In G. Gottlieb and N. A. Krasnegor (eds), *Measurement of Audition and Vision in the First Year of Postnatal Life*. Norwood, NJ: Ablex.

Borton, R. W. 1979: The perception of causality in infants. Paper presented at the Society for Research in Child Development, San Francisco, CA.

Bower, T. G. R. 1967: The development of object permanence: Some studies of size constancy. *Perception and Psychophysics*, 2, 411–18.

Bruner, J. S. and Koslowski, B. 1972: Visually preadapted constituents of manipulatory action. *Perception*, 1, 3–14.

Carey, S. 1985: *Conceptual Change in Childhood*. Cambridge: Bradford/MIT.

Carey, S. 1991: Knowledge acquisition: Enrichment or conceptual change? In S. Carey and R. Gelman (eds), *Epigenesis of Mind: Studies in biology and cognition*. Hillsdale, NJ: Erlbaum.

Chomsky, N. 1980: *Rules and Representations*. New York: Columbia University Press.

Clifton, R. K., Rochat, P., Litovsky, R. and Perris, E. 1991: Representation guides infant reaching in the dark. *Journal of Experimental Psychology: Human Perception and Performance*, 17, 323–9.

Craton, L. and Yonas, A. 1990: The role of motion in infant perception of occlusion. In J. Enns (ed.), *The Development of Attention: Research and theory*. North-Holland, Elsevier Science Publishers, B.V.

deVries, R. 1987: Children's conceptions of shadow phenomena. *Genetic Psychology Monographs*, 112, 479–530.

Fantz, R. L. 1961: The origins of form perception. *Scientific American*, 204, 66–72.

Fischer, K. W. and Biddell, T. 1991: Constraining nativist inferences about cognitive capacities. In S. Carey and R. Gelman (eds), *Epigenesis of Mind: Studies in biology and cognition*. Hillsdale, NJ: Erlbaum.

Fodor, J. 1983: *The Modularity of Mind*. Cambridge, Mass: Bradford/MIT.

Gallistel, C. R. and Gelman, R. 1990: The what and how of counting. *Cognition*, 34, 197–9.

Gelman, S. 1989: Children's use of categories to guide biological inferences. *Human Development*, 32, 65–71.

Gibson, J. J. 1962: Observation on active touch. *Psychological Review*, 69, 447–91.

Gibson, J. J. 1966: *The Senses Considered as Perceptual Systems*. Boston: Houghton-Mifflin.

Gibson, J. J. 1979: *The Ecological Approach to Visual Perception*. Boston: Houghton-Mifflin.

Gopnik, A. 1988: Conceptual and semantic development as theory change. *Mind and Language*, 3, 197–216.

Halloun, I. A. and Hestenes, D. 1985: Common sense concepts about motion. *American Journal of Physics*, 53, 1056–65.

Held, R., Birch, E. and Gwiazda, J. 1980: Stereoacuity of human infants. *Proceedings of the National Academy of Science*, 77, 5572–4.

Hirsch, E. 1982: *The Concept of Identity*. New York: Oxford.

Hofsten, C. von and Spelke, E. S. 1985: Object perception and object-directed reaching in infancy. *Journal of Experimental Psychology: General*, 114, 198–212.

Johnson, M. H. 1990: Cortical maturation and the development of visual attention in early infancy. *Journal of Cognitive Neuroscience*, 2, 81–95.

Kaiser, M. K., Jonides, J. and Alexander, J. 1986: Intuitive reasoning about abstract and familiar physics problems. *Memory and Cognition*, 14, 308–12.

Keil, F. 1979: The development of the young child's ability to anticipate the outcomes of simple causal events. *Child Development*, 50, 455–62.

Kellman, P. J., Gleitman, H. and Spelke, E. S. 1987: Object and observer motion in the perception of objects by infants. *Journal of Experimental Psychology: Human Perception and Performance*, 12, 586–93.

Kellman, P. J. and Spelke, E. S. 1983: Perception of partly occluded objects in infancy. *Cognitive Psychology*, 15, 483–524.

Kellman, P. J., Spelke, E. S. and Short, K. R. 1986: Infant perception of object unity from translatory motion in depth and vertical translation. *Child Development*, 57, 72–86.

Kellman, P. J., Van de Walle, G. A., Hofsten, C. von and Condry, K. F. 1990: Perception of motion and stability during observer motion by pre-stereoscopic infants. Poster presented at the International Conference on Infant Studies, Montreal, Canada.

Kestenbaum, R., Termine, N. and Spelke, E. S. 1987: Perception of objects and object boundaries by three-month-old infants. *British Journal of Developmental Psychology*, 5, 367–83.

Koffka, K. 1935: *Principles of Gestalt Psychology*. New York: Harcourt, Brace and World.

Kuhn, T. S. 1977: A function for thought experiments. In his *The Essential Tension*. Chicago: University of Chicago Press.

Leslie, A. M. 1987: Pretense and representation: The origins of 'Theory of Mind'. *Psychological Review*, 94, 412–26.

Leslie, A. M. 1988: The necessity of illusion: Perception and thought in infancy. In L. Weiskrantz (ed.), *Thought and Language*. Oxford: Oxford University Press.

Leslie, A. M. 1991: Infants' understanding of invisible displacement. Paper presented at the Society for Research in Child Development, Seattle, WA.

Leslie, A. M. and Keeble, S. 1987: Do six-month-old infants perceive causality? *Cognition*, 25, 265–88.

Markman, E. M. 1989: *Categorization and Naming in Children*. Cambridge, Mass: Bradford/MIT.

Marr, D. 1982: *Vision*. San Francisco: Freeman.

McCloskey, M. 1983: Naive theories of motion. In D. Gentner and A. L. Stevens (eds), *Mental Models*. Hillsdale, NJ: Erlbaum.

Mervis, C. M. 1987: Child-basic object categories and lexical development. In U. Neisser (ed.), *Concepts and Conceptual Development: Ecological and intellectual factors in categorization*. Cambridge: Cambridge University Press.

Michotte, A. 1954: *The Perception of Causality*. New York: Basic Books.

Michotte, A., Thinès, G. and Crabbé, G. 1964: Les compléments amodaux des structures perceptives. *Studia Psychologica*. Louvain: Presses Universitaires de Louvain.

Needham, A. and Baillargeon, R. 1991: Reasoning about support in 3-month-old infants. Unpublished manuscript.

Piaget, J. 1954: *The Construction of Reality in the Child*. New York: Basic Books.

Piaget, J. 1960: *The Child's Conception of Physical Causality*. Paterson, NJ: Littlefield, Adams and Co.

Prather, P. and Spelke, E. S. 1982: Three-month-old infants' perception of adjacent and partly occluded objects. Paper presented at the International Conference of Infant Studies, Austin, TX.

Proffitt, D. R. and Gilden, D. L. 1989: Understanding natural dynamics. *Journal of Experimental Psychology: Human Perception and Performance*, 15, 384–93.

Rubenstein, J. 1991: Just me and my shadow: Infant conceptions of shadow phenomena. Unpublished honours thesis, Cornell University, Ithaca, NY.

Schmidt, H. 1985: The role of Gestalt principles in perceptual completion: A developmental approach. Unpublished doctoral dissertation, University of Pennsylvania, Philadelphia, PA.

Schmidt, H. and Spelke, E. S. 1984: Gestalt relations and object perception in infancy. Paper presented at the International Conference on Infant Studies, New York.

Schwartz, K. G. 1982: Perceptual knowledge of the human face in infancy. Unpublished doctoral dissertation, University of Pennsylvania, Philadelphia, PA.

Schwartz, M. and Day, R. H. 1979: Visual shape perception in early infancy. *Monographs of the Society for Research in Child Development*, 44 (Serial No. 182).

Shipley, E. F. and Shepperson, B. 1990: Countable entities: Developmental changes. *Cognition*, 34, 109–36.

Slater, A., Mattock, A. and Brown, E. 1990: Size constancy at birth: Newborn infants' responses to retinal and real size. *Journal of Experimental Child Psychology*, 49, 314–22.

Slater, A., Morison, V., Somers, M., Mattock, A., Brown, E. and Taylor, D. 1990: Newborn and older infants' perception of partly occluded objects. *Infant Behavior and Development*, 13, 33–49.

Soja, N. N., Carey, S. and Spelke, E. S. 1991: Ontological categories guide young children's inductions of word meanings: Object terms and substance terms. *Cognition*, 38, 179–211.

Spelke, E. S. 1985a: Perception of unity, persistence, and identity: Thoughts on infants' conceptions of objects. In J. Mehler and R. Fox (eds), *Neonate Cognition*. Hillsdale, NJ: Erlbaum.

Spelke, E. S. 1985b: Preferential looking methods as tools for the study of cognition in infancy. In G. Gottlieb and N. Krasnegor (eds), *Measurement of Audition and Vision in the First Year of Postnatal Life*. Norwood, NJ: Ablex.

Spelke, E. S. 1988: Where perceiving ends and thinking begins: The apprehension of objects in infancy. In A. Yonas (ed.), *Perceptual Development in Infancy*. Minnesota Symposium on Child Psychology (vol. 20). Hillsdale, NJ: Erlbaum.

Spelke, E. S. 1990: Principles of object perception. *Cognitive Science*, 14, 29–56.

Spelke, E. S. 1991: Physical knowledge in infancy: Reflections on Piaget's theory. In S. Carey and R. Gelman (eds), *Epigenesis of Mind: Studies in biology and cognition*. Hillsdale, NJ: Erlbaum.

Spelke, E. S. and Born, W. S. 1983: Visual perception of objects by three-month-old infants. Unpublished manuscript.

Spelke, E. S., Breinlinger, K., Jacobson, K. and Phillips, A. 1993a: Gestalt relations and object perception: A developmental study. Unpublished manuscript.

Spelke, E. S., Breinlinger, K. Macomber, J. and Jacobson, K. (1992): Origins of knowledge. *Psychological Review*, 99, 605–32.

Spelke, E. S., Hofsten, C. von and Kestenbaum, R. 1989: Object perception and object-directed reaching in infancy: Interaction of spatial and kinetic information for object boundaries. *Developmental Psychology*, 25, 185–96.

Spelke, E. S., Katz, G., Purcell, S. E., Ehrlich, S. M. and Breinlinger, K. 1993b: Early knowledge of object motion: Continuity, solidity, and inertia. Unpublished manuscript.

Spelke, E. S. and Kestenbaum, R. 1986: Les origines du concept d'objet. *Psychologie Française*, 31, 67–72.

Spelke, E. S., Simmons, A., Breinlinger, K., Jacobson, K. and Macomber, J. 1993c: Developing knowledge of gravity I: Infants' sensitivity to hidden object motion. Unpublished manuscript.

Streri, A. 1987: Tactile discrimination of shape and intermodal transfer in 2- to 3-month-old infants. *British Journal of Developmental Psychology*, 5, 213–20.

Streri, A. 1990: *Voir, atteindre, toucher*. Paris: Presses Universitaires de France.

Streri, A. and Pêcheux, M. G. 1986: Cross-modal transfer of form in 5-month-old infants. *British Journal of Developmental Psychology*, 4, 161–7.

Streri, A. and Spelke, E. S. 1988: Haptic perception of objects in infancy. *Cognitive Psychology*, 20, 1–23.

Streri, A. and Spelke, E. S. 1989: Effects of motion and figural goodness on haptic object perception in infancy. *Child Development*, 60, 1111–25.

Streri, A., Spelke, E. S. and Rameix, E. 1993: Modality-specific and amodal aspects of object perception in infancy: The case of active touch. Unpublished manuscript.

Teller, D. Y. and Bornstein, M. H. 1987: Infant color vision and color perception. In P. Salapatek and L. Cohen (eds), *Handbook of Infant Perception, vol. 1, From sensation to perception*. Orlando, FL: Academic Press.

Wellman, H. M. 1990: *The Child's Theory of Mind*. Cambridge, Mass: Bradford/MIT.

Wiggins, D. 1980: *Sameness and Substance*. Cambridge, Mass: Harvard University Press.