The Epigenesis of Mind: Essays on Biology and Cognition

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5 Physical Knowledge in Infancy: Reflections on Piaget's Theory

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TWO PIAGETIAN THESES

This chapter focuses on two theses that are central to Piaget's theory of the development of physical knowledge (Piaget, 1954, 1969, 1974). One thesis concerns developmental changes in conceptions of the world. The other thesis concerns the relation of knowledge to perception.

First, Piaget proposed that conceptions of the physical world undergo revolutionary change in infancy and childhood. The most dramatic changes occur in infancy. In Piaget's view, young infants conceive of physical phenomena as emanating from their own actions. By the close of infancy, in contrast, children conceive the physical world as composed of objects, including themselves, whose behavior is governed by physical laws. For Piaget, this change was as radical as the conceptual changes that occur during scientific revolutions. In particular, Piaget and Inhelder (1969) likened the child's construction of a world of physical objects to the construction, in 16th-century astronomy, of the heliocentric universe. The conceptual revolution in infancy may be deeper than the Copernican revolution, however, because astronomers throughout history have shared a view of the self in relation to the external world: a view that is not shared, Piaget believed, by infants.

Second, Piaget proposed that children's conceptions are inextricably tied to their perceptions: Perception and thought are two aspects of a single developing capacity. In particular, the child who cannot conceive the world as composed of law-governed objects also cannot apprehend objects in his or her immediate surroundings: The child perceives a world of ephemeral appearances, not of stable and enduring bodies. Here again, a parallel is apparent between physical reasoning in infancy and in science. For example, the evolution of modern astronomy brought changes in scientists' perception of the stars and planets: What were once seen as an array of concentric spheres rotating about the center of the earth were later seen as an arrangement of separated bodies in space (e.g., Kuhn, 1959; Toulmin & Goodfield, 1961). Since spheres are enduring parts of the physical world, however, the perceptual changes that infants experience, according to Piaget, are again more fundamental.

Both of Piaget's theses have received considerable support. Concerning the first thesis, conceptual changes have been documented in the history of science (e.g., Crombie, 1952; Kitcher, 1988; Kuhn, 1962; Wiser & Carey, 1983), in studies of young adults learning science (White, 1988), and in studies of children's spontaneous reasoning about physical phenomena (Carey, 1988; this volume; Karmiloff-Smith, this volume; Smith, Carey, & Wiser, 1985; Vosniadou & Brewer, 1990), as well as in the experiments of Piaget and his successors (e.g., Bower, 1982; Gopnik, 1988; Harris, 1983). Concerning the second thesis, evidence for a linkage between perception and thought has come from studies in the history of science (e.g., Jacob, 1972; Kuhn, 1962) and from analyses of the apparently rational character of perception (Descartes, 1638; Helmholtz, 1926; Rock, 1983). Piaget's second thesis is also supported by (and springs from) arguments in philosophy concerning the impossibility of observation in the absence of some conceptual framework (Kant, 1929).

As noted, these theses suggest that the development of knowledge in children is similar to the historical development of knowledge in science and mathematics. Piaget viewed science and mathematics as human enterprises built upon abilities and activities that their practitioners share with ordinary adults and children. If that is true, then insights into the development of science and mathematics may shed light on the development of knowledge in children, and vice versa. Much of Piaget's life was devoted to exploring this possibility and its consequences: "When I reason in terms of genetic psychology, I always keep in the back of my mind something based on the history of sciences or the history of mathematics, because it is the same process" (Piaget, 1980, p. 151). To deny the parallel between children and scientists is both to forego the possibility of these insights and to reject what appears to be the simplest and most general account of the development of human knowledge.

Despite these considerations, it is now difficult to maintain Piaget's two theses jointly. Thirty years of research on the perceptual capacities of human infants provides evidence that infants' perceptions of physical objects do not differ fundamentally from the perceptions of adults (see Banks & Salapatek, 1983; Gibson & Spelke, 1983; Yonas, 1988, for reviews). In particular, young infants do not appear to experience the array of ephemeral appearances described by Piaget but a world of stable, three-dimensional objects (Gibson, 1969; Kellman, 1988; Leslie, 1988; Slater, Mattock, & Brown, 1990; Spelke, 1982). Infants even apprehend the persistence of objects that are fully

occluded (Baillargeon, 1987a, 1987b; Baillargeon, Spelke, & Wasserman, 1985). Although infants do not appear to perceive objects under all the conditions that adults do (see Spelke, 1990), the development of object perception would seem to be a process of enrichment, not of revolutionary change. This continuity in object perception is difficult to understand, if children's perceptions reflect their physical conceptions *and* if those conceptions differ radically and fundamentally from the conceptions of adults.

A second problem arises from Piaget's two theses: If infants perceive a radically different world from adults, it is not clear how children ever develop mature physical conceptions (see Kant, 1929; Koffka, 1935). A child whose conceptions led him or her to experience a succession of changing appearances rather than a layout of enduring objects might learn more and more about such appearances: when two appearances coincide, when one appearance follows another, and the like. The child's perceptions would not lead him or her to believe, however, that the ephemeral character of experience is an illusion. Thus, an inextricable linking of perception to thought appears to lead in a circle, in which the conceptions that determine initial perceptions can only perpetuate themselves. Piaget recognized this circularity: That recognition, I believe, lies behind his argument that true knowledge does not come from perception (e.g., Piaget, 1954; see also Putnam, 1980). He has been criticized, however, for failing to provide an account of conceptual development that avoids this circularity (see Piatelli-Palmarini, 1980).

If the preceding findings and arguments are correct, then at least one of Piaget's theses must be reconsidered. Many psychologists have proposed to abandon the second thesis and retain the first (Kellman, 1988; Leslie, 1988; Premack, 1990; for the guiding ideas behind this proposal, see Fodor, 1983; and Carey, 1985, 1988). According to this view, physical reasoning changes radically over development in ways that parallel conceptual change in science, but it is largely independent of the processes by which humans perceive objects. Object perception is based primarily on "modular" mechanisms: mechanisms that are largely innate and impervious to intention or belief. Thus, infants perceive objects in fundamentally the same ways as adults (and as scientists), but they reason about objects differently.

In this chapter, I suggest a different view. The processes by which humans perceive objects are inseparable from the processes by which humans reason about objects, just as Piaget believed (although other perceptual processes are distinct from physical reasoning). Physical reasoning and object perception do not, however, undergo revolutionary changes over human development. They develop through a process of enrichment around core principles that are constant. In these respects, the development of knowledge in infants and children may differ from the development of knowledge in science.

These suggestions are prompted by recent research on infants' inferences about hidden objects and their motions. Before turning to this research, however, I must say more about the nature of early-developing physical knowledge and of the tasks through which it may be revealed. This discussion begins again with Piaget.

SIGNS OF PHYSICAL KNOWLEDGE IN INFANCY

As children, humans gain knowledge of many physical phenomena. For example, children become sensitive to some of the properties and behavior of heat (e.g., Piaget, 1974; Strauss, 1982), fluids (e.g., Piaget & Inhelder, 1962), solid substances (e.g., Smith et al., 1985), light and shadow (e.g., Piaget, 1930, DeVries, 1987), and celestial bodies (e.g., Piaget, 1929; Vosniadou & Brewer, 1990). In infancy, however, studies of physical knowledge have focused primarily on the properties and behavior of middle-sized material bodies, such as cups, rocks, and apples. This domain of knowledge is my focus as well.

Piaget viewed human knowledge of physical objects as the implicit appreciation of physical laws, or constraints, governing objects' behavior. Although his writings contain no inventory of the constraints that humans come to appreciate, five constraints figure prominently in his experiments: *continuity* (objects exist continuously and move on connected paths), *solidity* (objects occupy space uniquely, such that no parts of two distinct objects coincide in space and time), *no action at a distance* (distinct objects move independently unless they meet in space and time), *gravity* (objects move downward in the absence of support), and *inertia* (objects do not change their motion abruptly in the absence of obstacles).[1]

In order to study infants' physical knowledge, Piaget focused on experimental tasks with two characteristics. First, his tasks require deliberate, coordinated action on the part of children. Second, his tasks require that children represent aspects of the world that are not currently manifest to their sensory systems and that they act on such representations to discover aspects of the world that they have never perceived directly. Physical knowledge is revealed, Piaget reasoned, only when children confront problems that cannot be solved by engaging in habitual actions or by responding to perceptible properties of events. The task that best exemplifies both requirements is the *invisible displacement object search task*, in which an object is moved from view and then undergoes some further, hidden motion. The child's task is to search for the object by engaging in novel actions on the objects that conceal

[1]Since the 17th century, classical mechanics has provided more general and precise statements of the principles of gravity and inertia, applicable to celestial as well as terrestrial motions, and it has all but abandoned the principle of no action at a distance. There is little reason to believe, however, that children or scientifically naive adults conceive of the motions of middle-sized terrestrial objects in these more general terms (see McCloskey, 1983; White, 1988). In this chapter, "gravity" and "inertia" are used in the more limited senses given above. They refer to aspects of object motion that are appreciated by adults and older children (e.g., Kaiser, McCloskey, & Proffitt, 1986; Kaiser, Proffitt, & McCloskey, 1985).

it. To search successfully, moreover, the child must deduce the object's location by drawing on knowledge of physical constraints on object motion.

In Piaget's experiments, 18-month-old infants were found to search for hidden objects by reaching only to positions that are consistent with constraints on object motion. In contrast, younger infants were found to violate all constraints on object motion when they were presented with invisible displacement tasks in which superficial aspects of the situation and habitual actions favored search at an impossible location. These findings suggested that a true appreciation of physical constraints on object motion develops at the end of infancy.

In recent years, Piaget's conclusions have been questioned, because of the observations on which they depend. Many investigations provide evidence that capacities to act in a coordinated manner are not constant over the infancy period (Diamond, this volume; Wellman, Cross, & Bartsch, 1986). Indeed, Piaget's own studies (1952) suggest that action capacities undergo extensive changes from birth to 18 months. If that is true, then tasks requiring coordinated search activity are not appropriate means to investigate young infants' physical reasoning. Rather, studies of young infants require tasks within the infants' behavioral repertoire. The challenge is to devise tasks that meet this requirement without sacrificing what is essential to Piaget's experiments: The tasks must not be solvable by engaging in habitual actions or by responding to superficial properties of events.

These requirements were first met, I believe, by experiments by Leslie (e.g., 1984) and Baillargeon (e.g., 1987a). Their experiments investigated infants' physical knowledge by means of a method that relies on infants' tendency to look less and less at increasingly familiar events and to look longer at novel events. This method centers on a behavior—looking time—and behavioral patterns—habituation and novelty preference—that are present and functional from birth (Friedman, 1972; Slater, Morison, & Rose, 1984) to adulthood (Spelke, Breinlinger, Macomber, Turner, & Keller, 1990). Thus, the method appears to be appropriate for studies of the cognitive capacities of infants of all ages. To investigate infants' physical knowledge, Leslie and Baillargeon adapted the method in different ways.

Leslie's research has focused on infants' apprehension of causal relationships between objects, in accord with the constraint of no action at a distance. Leslie investigated 6-month-old infants' sensitivity to this constraint by first habituating separate groups of infants to events in which changes in the motions of two objects coincided or failed to coincide in space and time. Then infants were presented with the mirror reversal of an event. If infants do not perceive causal relations among object motions, Leslie reasoned, then the reversals of both types of events should appear equally novel. If infants perceive causal relations among object motions in accord with the principle of no action at a distance, in contrast, then the reversal of the event in which the objects came into contact should be seen as more novel than the reversals of the other events, because it presented a reversal of causal relations. In the causal event he studied, one object (A) caused a second object (B) to begin moving, and B caused A to stop moving, whereas in the reversal of that event, A caused B to stop moving, and B caused A to begin moving.[2] Leslie's experiments provided evidence that infants apprehended the causal relations, in accord with the principle of no action at a distance. Further investigations, using other variants of the preferential looking method, have corroborated this finding (Ball, 1973; Leslie, 1988), although a few negative results have also been obtained (Leslie, 1988; Oakes & Cohen, 1990).

Baillargeon's research focused on infants' representations of hidden objects. Her studies (Baillargeon, Spelke, & Wasserman, 1985; Baillargeon, 1987a, 1987b), investigated whether infants represent the existence, location, orientation, shape, and rigidity of an object that stands behind an occluder. The critical events of her experiments presented a stationary object that disappeared behind a moving screen. The screen either stopped moving when it reached the location of the hidden object or it continued moving through that location, revealing empty space where all or part of the object had stood. These events were preceded by a familiarization period in which the screen appeared on an empty stage and moved as in the latter, impossible event.

Looking times to the two critical events were measured and compared. If infants represented the continued existence and location of the hidden object (and, in some studies, if they represented properties of the object such as its height and flexibility), then infants were expected to look longer at the event that was superficially more familiar, in which the screen passed through all (or part) of the object's location. This finding was obtained in every experiment conducted with infants aged 8 months or more (Baillargeon, 1987b). It was also obtained under a variety of conditions with infants as young as 3–4 months (Baillargeon, 1987a; Baillargeon, in press), although young infants did not succeed at all such tasks (Baillargeon, 1987b; see also Baillargeon & Graber, 1988, and Arterberry, 1989).

Baillargeon's experiments provide evidence that infants represent the continued existence of an object that is hidden from view. Her experiments also provide evidence that infants honor one aspect of the continuity constraint (objects continue to exist while hidden), one aspect of the inertia constraint (stationary objects do not change location spontaneously while hidden), and a rigidity constraint (visibly rigid objects do not change shape spontaneously while hidden). Finally, her studies provide evidence that

[2]My description of Leslie's experiments differs superficially from his own. Note that the experiment presupposes that infants perceive changes in object speed rather than changes in object velocity (i.e., rate of displacement in a particular direction). The effect of the motion of each object on the change in velocity of the other object is not altered by reversing the direction of object motion.

visual preference for novelty methods can be used to assess infants' understanding of events involving hidden objects. These findings provide the foundation for our research.

INFANT CONCEPTIONS OF OBJECT MOTION

Our investigations have focused on infants' inferences about object motion (Spelke et al., 1990; Katz, Spelke, & Purcell, 1990). For these studies, we have devised an invisible displacement task similar to that of Piaget (1954). In the critical events of the studies, infants are shown an object that moves out of view behind a screen. Then the screen is raised, revealing the object at rest in either of two positions. One resting position is consistent with all physical constraints on object motion; the other resting position is inconsistent with one or more constraints.

Prior to viewing these test events, infants are familiarized with a physically different event in which the same or a similar object moves from view and is revealed at a consistent resting position. In most of our studies, the familiarization event presents the object at the same final position as the inconsistent test event, such that the consistent test position is superficially more novel. Looking time to each event outcome is recorded, beginning when the object is revealed at its final position. If infants represent the continued existence and the continued motion of the hidden object, and if they are sensitive to the relevant constraints on object motion, then they are expected to look longer at the inconsistent test outcome.

I believe that this method meets all of Piaget's requirements for revealing true physical knowledge. It focuses on a behavior that would not arise from the detection of sensory novelty or from the activation of habitual activity. (In most of our studies, either process would lead infants to generalize habituation incorrectly, to the inconsistent test event.) Moreover, it presents a situation that can only be understood by representing a hidden object and inferring its hidden motion. Although the task does not require that the child engage in coordinated, overt activities such as object-directed reaching and manipulation, it does require operations that Piaget regarded as actions on the plane of thought. This task can serve to investigate the development of physical knowledge in infants too young to engage in object search.

The experiments described hereafter focused primarily on sensitivity to the constraints of continuity, solidity, gravity, and inertia. I begin with studies of infants' knowledge of the first two constraints.

Continuity and Solidity

Three experiments investigated whether young infants infer that a hidden object will move on a connected, unobstructed path (Spelke et al., 1990). In the first experiment, 4-month-old infants were familiarized with an event in which a ball fell behind a screen, the screen was raised, and the ball was revealed at rest on the floor of the display (Fig. 5.1). Then a second horizontal surface was added to the display above the floor, the screen was lowered over both surfaces, and the ball was dropped behind the screen as before. On alternating test trials the ball appeared on the new, upper surface or on the familiar, lower surface. The first of these positions was superficially novel but consistent with all constraints on object motion. The second position was superficially familiar but inconsistent with the continuity and solidity constraints: Because the upper surface extended outward to the walls of the display, the ball could not reach the lower surface by moving on any connected, unobstructed path. Adult subjects were presented with the three events and were asked to rate the "naturalness and expectedness" of each event outcome. They judged that the outcomes of the familiarization event and the consistent test event were natural and expected, whereas the outcome of the inconsistent test event was unnatural and unexpected.

Infants' reactions to these events were investigated by measuring looking

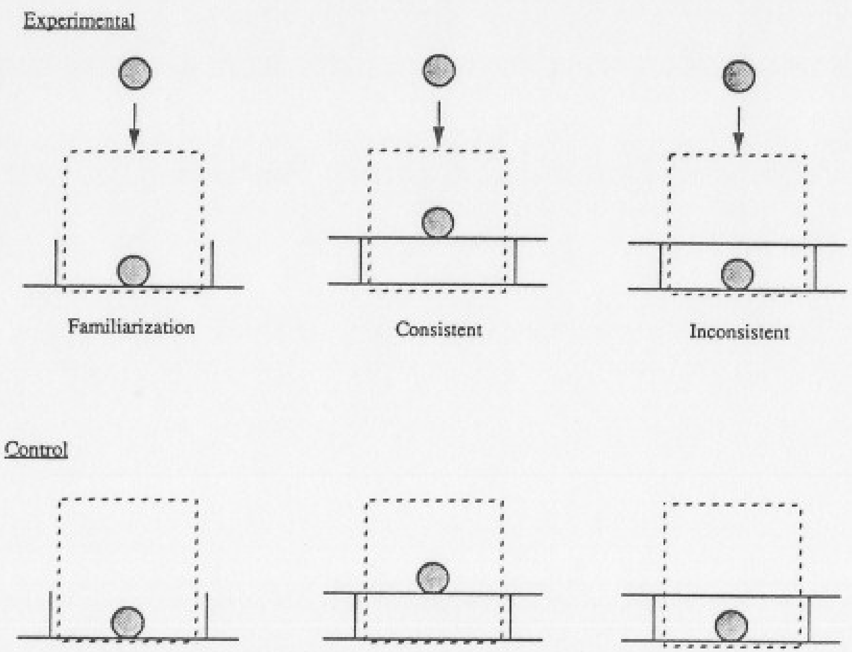

FIG. 5.1. Schematic depiction of the displays from a study of 4-month-old infants' knowledge of the continuity and solidity constraints. Each drawing depicts the initial and final position of the ball (filled circles), the path of the ball's visible motion (solid arrow), and the position of the screen when it was lowered into the display (dotted rectangle). (After Spelke et al., 1990, Exp. 1)

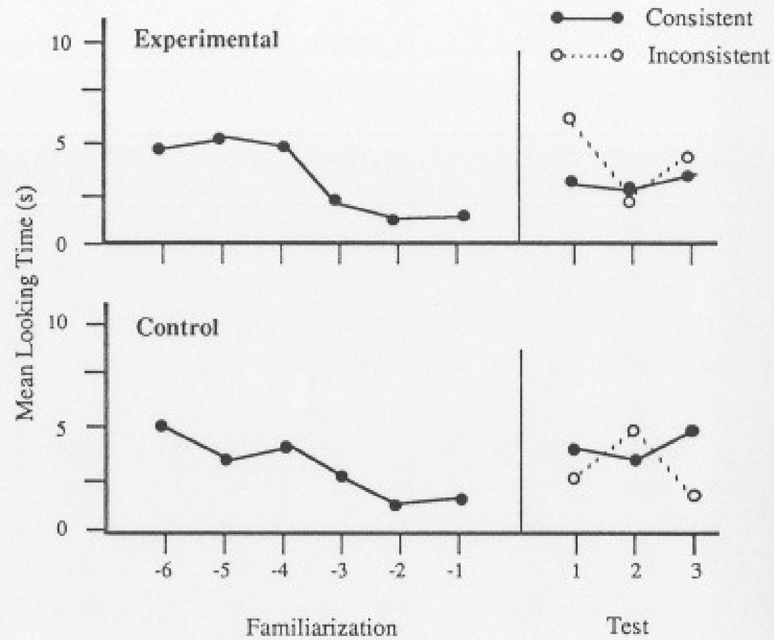

FIG. 5.2. Mean duration of looking at the event outcomes during the last six familiarization trials and the six test trials. (After Spelke et al., 1990, Exp. 1)

times to the displays after the screen was raised to reveal the ball in its final position. On each familiarization trial, looking time was recorded, beginning with the first look at the ball and ending when the infant looked away from the display. Familiarization trials continued until these looking times had declined to half their initial level. Then the test events were presented for 6 alternating trials, in counterbalanced order. Looking time was recorded on each test trial, beginning with the first look at either position that the ball could occupy (observers were unaware of the ball's position on any given trial) and ending when the infant looked away from the display.

Test trial looking times were compared to the looking times of infants in a control condition, in which the ball was simply placed in its final position, the screen was lowered and raised, and looking time was recorded as before. Because the control condition presented exactly the same displays as the experimental condition throughout the time that looking was recorded, that condition serves to assess any differences in the intrinsic attractiveness or superficial novelty of the test displays.

If 4-month-old infants represent the existence of an object that moves from view, and if they infer that the hidden object will continue to move on a

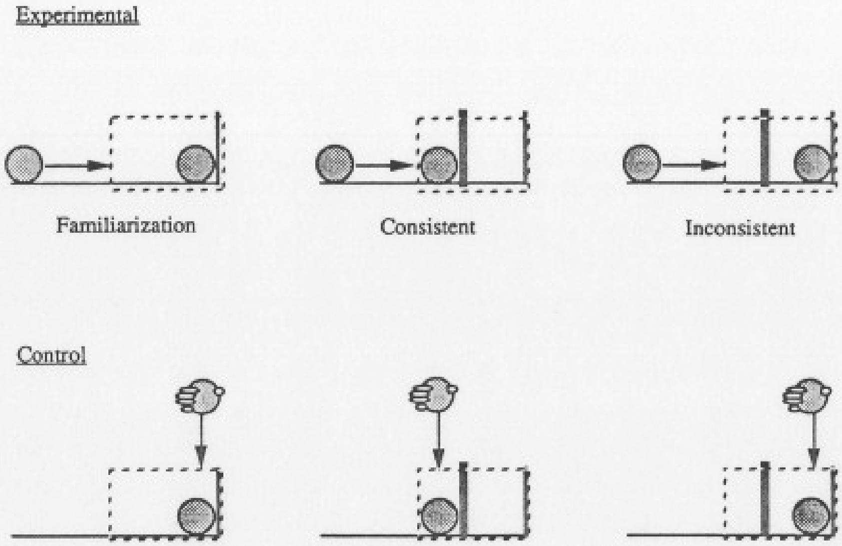

FIG. 5.3. Displays from a study of 2½-month-old infants' knowledge of the continuity and solidity constraints. (After Spelke et al., 1990, Exp. 3)

connected, unobstructed path, then the infants in the experimental condition were expected to look longer at the outcome of the test event in which the ball appeared on the lower surface, relative to controls. That event outcome should have commanded longer looking, despite its superficial familiarity, because it is inconsistent with the continuity and solidity constraints.

The findings accorded with this prediction (Fig. 5.2): Infants in the experimental condition looked reliably longer at the inconsistent event than at the consistent event, and their preference for the inconsistent event reliably exceeded that of infants in the control condition. Our first experiment provides evidence that 4-month-old infants infer that a hidden object will move on a connected, unobstructed path.

The next experiment began to investigate both the generality of this ability and its earlier development. Participants were infants in the third month (range, 2;9 to 2;29). Infants in the experimental condition were familiarized with events in which a ball was introduced on the left side of the display and was rolled rightward on a horizontal surface, disappearing behind a screen. The screen was raised to reveal the ball at rest on the right side of the display, beside the only object that stood in its path (Fig. 5.3). After habituation, the infants were tested with events in which a second object was placed in the center of the display behind the screen, the ball was rolled as before, and the ball was revealed either at a new position next to the new object (consistent) or at its familiar position—a position it could not reach without passing

through or jumping discontinuously over the first object (inconsistent). Adult subjects judged that the familiarization and consistent test outcomes were natural and expected, whereas the inconsistent test outcome was unnatural and unexpected.

Looking times were compared to the looking times of infants in a control condition, who were presented with familiarization and test events with exactly the same outcomes, in which the ball was held by a hand and was lowered vertically to its final position (see Fig. 5.3). The findings were similar to those of the first experiment (Fig. 5.4): Infants in the experimental

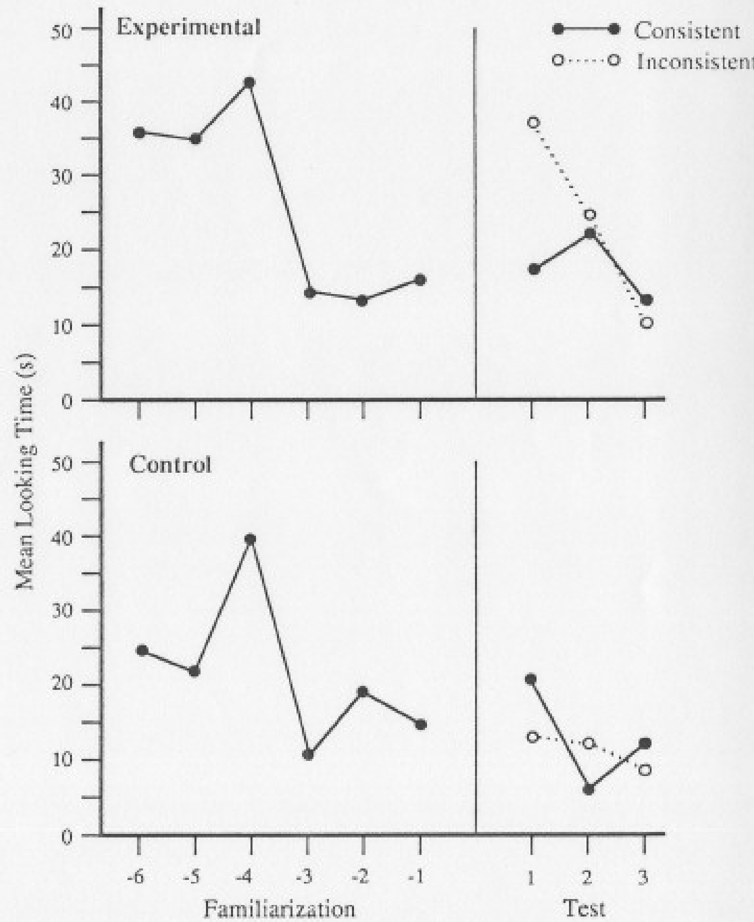

FIG. 5.4. Mean duration of looking at the event outcomes during the last six familiarization trials and the six test trials. (After Spelke et al., 1990, Exp. 3)

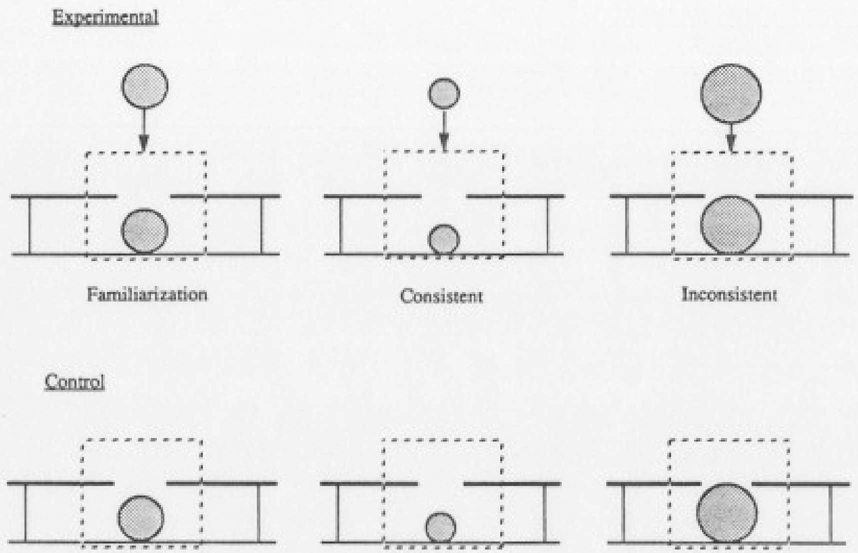

FIG. 5.5. Displays from a study of 4-month-old infants' knowledge of the continuity and solidity constraints. (After Spelke et al., 1990, Exp. 2)

condition looked reliably longer at the inconsistent test event, relative to those in the control condition. The experiment provides evidence that $2^1/_2$-month-old infants represent hidden objects and infer their motions in accord with the continuity and solidity constraints.

The last experiment in this series probed further infants' sensitivity to the continuity and solidity constraints. It investigated whether 4-month-old infants, like adults, infer that *no part of* one object can jump over, or pass through, any part of another object. The experiment also investigated whether infants infer that a hidden object will maintain a constant size and shape as it moves.

Four-month-old infants were presented with events in which a ball fell behind a screen toward a surface with a gap and then the screen was raised to reveal the ball below the gap on a lower, continuous surface (Fig. 5.5). In the familiarization event, the diameter of the ball was slightly smaller than the gap. In the test events, the ball was either smaller still (consistent) or larger than the gap (inconsistent). Adults judged that the familiarization and consistent test event outcomes were natural and expected, and that the inconsistent test event outcome was unnatural and unexpected.

Looking times were recorded as in the first experiment and were compared to the looking times of infants in a control condition analogous to that

of the first experiment. The findings were clear (Fig. 5.6): Infants in the experimental condition looked reliably longer at the test event with the large ball than did those in the control condition. This preference provides evidence that the infants inferred that no part of the ball would pass through the surface in its path.

The findings of this experiment corroborate Baillargeon's findings that infants represent the size of a hidden object and honor a rigidity constraint, inferring that a hidden object will maintain a constant shape and size. In the

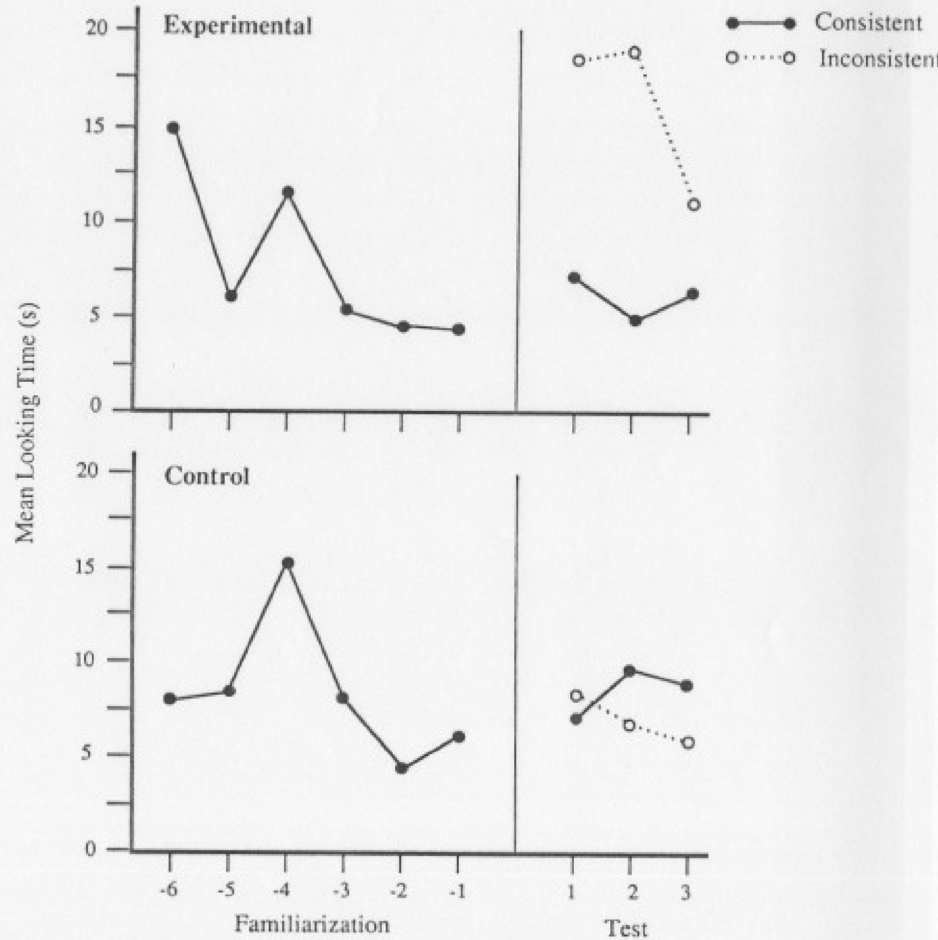

FIG. 5.6. Mean duration of looking at the event outcomes during the last six familiarization trials and the six test trials. (After Spelke et al., 1990, Exp. 2)

absence of a rigidity constraint, the large ball could have reduced its size as it arrived at the surface with the gap and then reached its final position by moving through the gap on a connected, unobstructed path.[3]

The present findings also support an important assumption behind my interpretation of all these studies: The studies reveal pre-existing conceptions of object motion and do not "teach" such conceptions over the course of familiarization. In the familiarization period of this experiment, infants were presented with a ball that fell behind a screen and reappeared below a surface with a gap. This presentation may have led infants to learn about aspects of the motion of the ball: Infants might have learned, for example, that the ball would move so as to pass through the gap in the upper surface and land on the lower surface. If infants did not already honor the solidity and continuity constraints, however, then generalization of that learning to the test events should have depended only on the similarity of each test ball to the familiar ball (because the events were otherwise the same). The obtained looking patterns are not consistent with such generalization: Whereas the infants in the control condition generalized habituation equally to the two test events, the infants in the experimental condition generalized habituation more to the event with the smaller ball. We conclude that infants are predisposed to generalize whatever they learn about one object's motion only to new objects that can undergo the same motion *by moving on a connected, unobstructed path.* The looking preferences obtained in this experiment make sense only if infants were already sensitive to the solidity and continuity constraints.[4]

In summary, the experiments provide evidence that young infants are sensitive to certain constraints on object motion. Before 3 months of age, human infants represent hidden, moving objects and infer that such objects will continue to move on connected, unobstructed paths. Infants' inferences accord with the solidity and continuity constraints across a fairly broad range of circumstances. Young infants infer that a hidden object will move on a

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[3]The rigidity constraint does not imply that infants are incapable of perceiving or representing nonrigid objects, but only that infants (like adults) infer that perceptible bodies will move rigidly in the absence of information for nonrigidity. Evidence for the default nature of this constraint comes from an experiment by Baillargeon (1987b). In one condition, infants were presented with an object that underwent no visible motion or change. When the object disappeared behind a moving screen, the infants inferred that it would remain rigid while hidden. In a second condition, infants were allowed to manipulate a deformable object. When that object subsequently disappeared behind a moving screen, the infants did not infer that it would remain rigid. It is not clear whether, for infants, other constraints on object motion have this default character.

[4]The same arguments apply, with modifications, to the findings of the preceding experiments. The findings of these experiments also support other critical assumptions behind the use of the present method, such as the assumption that infants will look longer at event outcomes that fail to accord with their inferences about hidden object motion. See Spelke et al. (1990) for discussion.

connected, unobstructed path whether its motion is vertical or horizontal, accelerating or decelerating, through open space or against a supporting surface, and whether the obstacle to further motion is a delimited object, an extended surface, or two surfaces separated by a gap. It is possible that the continuity and solidity constraints are applicable to all solid body motions for infants, as they are for adults.

Concerning Piaget's theory, the present findings, along with the findings of Leslie (1988) and Baillargeon (1987a), provide evidence that the capacity to represent and reason about the world develops long before the attainment of major sensorimotor coordinations. Infants under 3 months do not reach effectively for visible objects, coordinate actions into means–ends relationships, or even look at their hands systematically (Piaget, 1952, 1954). Nevertheless, such infants appear to represent hidden objects and infer their motions in accord with two constraints that are central to the object concept, in Piaget's theory. These findings suggest that the sensorimotor coordinations described by Piaget are not a prerequisite for the emergence of physical knowledge. I return in the concluding discussion to other suggestions raised by these findings.

Gravity and Inertia

The next studies investigated whether infants appreciate that objects move downward in the absence of support and that objects continue in motion in the absence of obstacles. An initial experiment (Spelke et al., 1990) tested for sensitivity to both constraints by means of the same method and nearly the same displays as the first study of continuity and solidity. Four-month-old infants were familiarized with an event in which a ball fell behind a screen and was revealed at rest on the first of two surfaces in its path (Fig. 5.7). For the test, the upper surface was removed, the ball was dropped as before, and it was revealed either in a new position on the lower surface or in its former position in midair. In the first of these events, the ball's final position was superficially novel but consistent with gravity and inertia: The falling ball continued falling until it arrived at a surface that served both as a support and as an obstacle to further motion. In the second event, the ball's final position was superficially familiar but apparently inconsistent with gravity (the ball appeared to be unsupported) and inertia (the ball appeared to have stopped moving in the absence of obstacles). Adults judged that the familiarization and consistent test event outcomes were natural and expected, whereas the inconsistent outcome was not; judgments were as strong as for the events of the first experiment.

Looking times were compared to those of infants in a control condition, who viewed events with outcomes similar to those in the experimental condition: A hand-held ball was introduced at its final position, it was covered

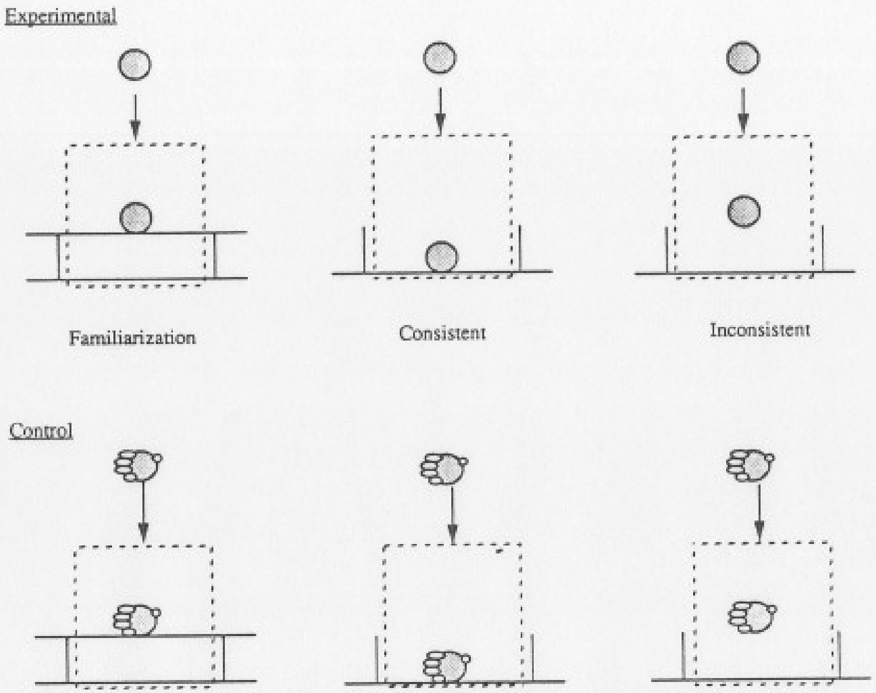

FIG. 5.7. Displays from a study of infants' knowledge of the gravity and inertia constraints. (After Spelke et al., 1990, Exp. 4)

and uncovered by a screen, and it was held motionless until the infant looked away. The control events were consistent with the effects of gravity and inertia, because the ball was stationary and supported by the hand both before and after it was occluded.

The findings of this experiment differed markedly from those of its predecessors (Fig. 5.8). Infants in the experimental condition looked longer at the outcome of the *consistent* test event. The experiment therefore provided no evidence that 4-month-old infants were sensitive either to the effect of gravity or to the effect of inertia on the motion of the falling object.

The experiment was then repeated with a sample of 6-month-old infants, with the more familiar pattern of findings (Fig. 5.9): Infants in the experimental condition looked longer at the outcome of the inconsistent test event, relative to controls. Comparisons across the two ages indicated that the reversal in preferences was reliable. Between 4 and 6 months, infants evidently began to infer that the hidden, falling object would continue falling to a surface.

These experiments do not reveal what aspects of object motion 6-month-

old infants have begun to appreciate. Between 4 and 6 months, infants may develop a general conception that objects require support or a general conception that objects do not stop moving abruptly in the absence of obstacles. As a third possibility, infants may develop more specific expectations about the behavior of falling bodies. The remaining experiments explored these possibilities.

The next studies (Spelke et al., 1990; Spelke & Keller, 1989) focused on the conception that objects require support. The experiments used the same displays as the preceding study (Fig. 5.10). In the familiarization event, a hand-held ball was introduced into the display with two surfaces, it was placed on the upper surface, the hand released the ball, and the ball remained at rest. The upper surface was removed for the test events, and the hand placed and

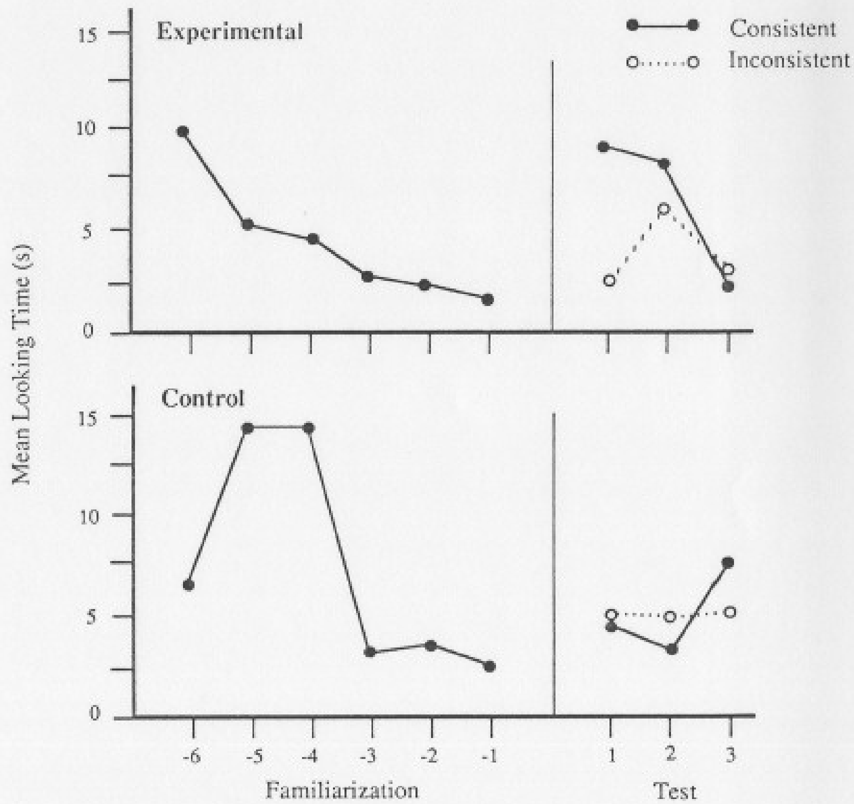

FIG. 5.8. Four-month-old infants' mean duration of looking at the event outcomes during the last six familiarization trials and the six test trials. (After Spelke et al., 1990, Exp. 4)

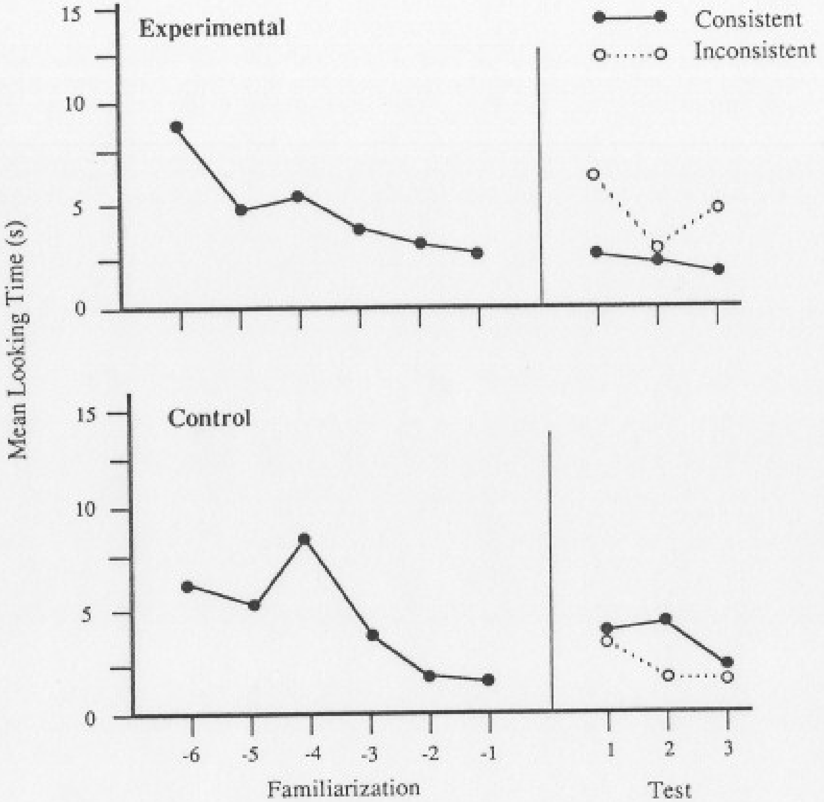

FIG. 5.9. Six-month-old infants' mean duration of looking at the event outcomes during the last six familiarization trials and the six test trials. (After Spelke et al., 1990, Exp. 5)

released the ball in the same position, now in midair (familiar but inconsistent), or on the lower surface (novel but consistent). Looking times were recorded, beginning when the hand released the ball and continuing as in the previous experiments. These looking times were compared to the looking times of infants in a control condition, who viewed identical events except that the hand never released the ball. If infants appreciate that a stationary object released by a hand should remain at rest only if it stands on a supporting surface, then the infants in the experimental condition should have looked longer at the outcome of the inconsistent event.

Unlike any previous experiment, this experiment was preceded by a lengthy period of piloting, during which the events and procedure were modified (Spelke & Keller, 1989). We first presented the events with an

occluding screen, as in the preceding studies. When the preliminary findings were negative, we removed the screen in order to present events that were more compelling. Then we experimented with a number of different object motions prior to the release of the ball: In different pilot experiments, the hand waved the ball from side to side, moved it up and down, moved it minimally to avoid confusing the infants (the ball was introduced from behind and moved forward) and moved it maximally to avoid boring the infants (the ball was introduced, moved forward, waved from side to side, lifted, and then lowered to its final position). Adult subjects responded similarly to all these latter variations, judging that the consistent outcome was natural and expected and that the inconsistent outcome was unnatural and unexpected. Adults' judgments of these events did not differ in strength or consistency from their judgments for the events of the preceding experiments.

All the pilot experiments yielded the same results with 6-month-old infants: no evidence of differential looking to the consistent and inconsistent events. In the end, we conducted experiments with infants of two ages—6 and 9 months—and with events that were fully visible. All the younger infants were presented with the minimal motion event to maximize the simplicity of the experiment; half the older infants were presented with the minimal and half with the maximal motion events (findings for these two subgroups of infants did not differ).

The findings are presented in Figs. 5.11 and 5.12. Six-month-old infants in both conditions looked equally at the consistent and inconsistent test out-

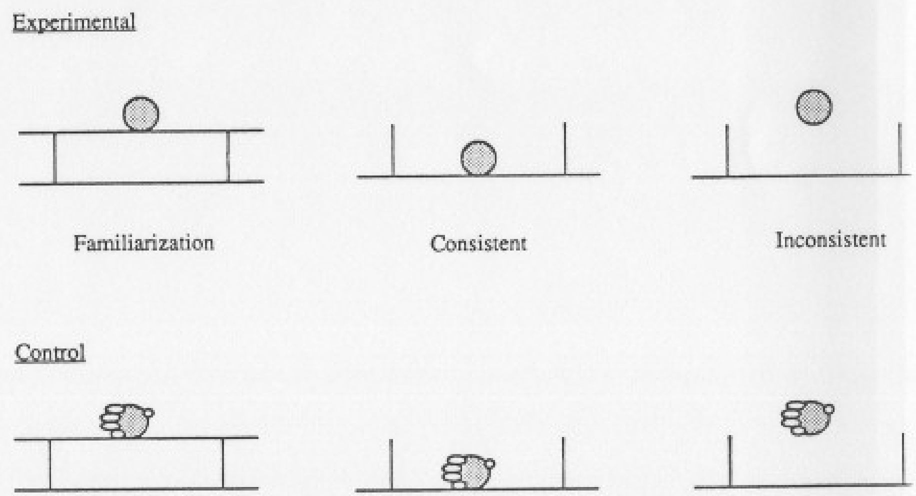

FIG. 5.10. Displays from a study of infants' knowledge of gravity. (After Spelke et al., 1990, Exp. 6)

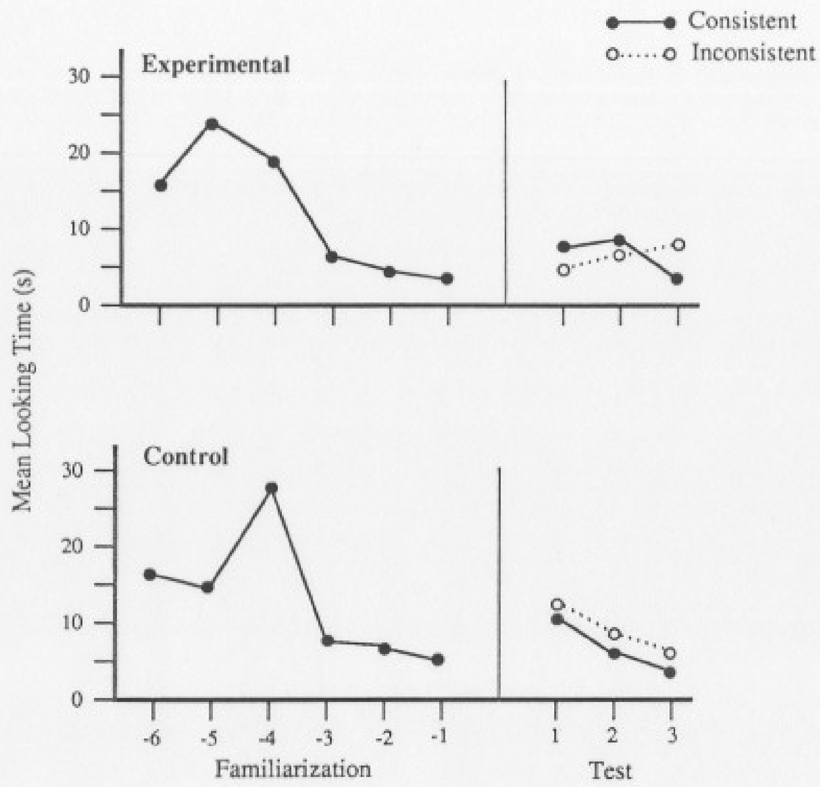

FIG. 5.11. Six-month-old infants' mean duration of looking at the event outcomes during the last six familiarization trials and the six test trials. (After Spelke et al., 1990, Exp. 6)

comes. Although 9-month-old infants in the experimental condition appeared to look longer at the inconsistent outcome, that preference did not differ significantly either from the preference of infants in the control condition or from the preference of the younger infants.

The findings of this experiment provide no evidence that 6-month-old infants have developed a general appreciation that objects require support. Although such infants evidently infer that a falling object will continue falling until it reaches a supporting surface, they do not appear to infer that a stationary object will begin to fall when it loses its support.

We cannot conclude, from the present studies, that infants have no knowledge of object support relations—only that they do not exhibit such knowledge in the present situation. Indeed, research by Baillargeon and her colleagues (Baillargeon, 1990; Baillargeon & Hanko-Summers, 1990;

Needham, 1990) provides evidence that infants are sensitive to the certain aspects of object support. Nevertheless, the failure of infants to respond to support relations in the present experiment is striking, in light of the findings of the previous studies. The support experiment used the same preferential looking method, similar events, and the same outcome displays as the study that preceded it. The divergent findings of these two experiments suggest that 6-month-old infants have developed no general conception that object mo-

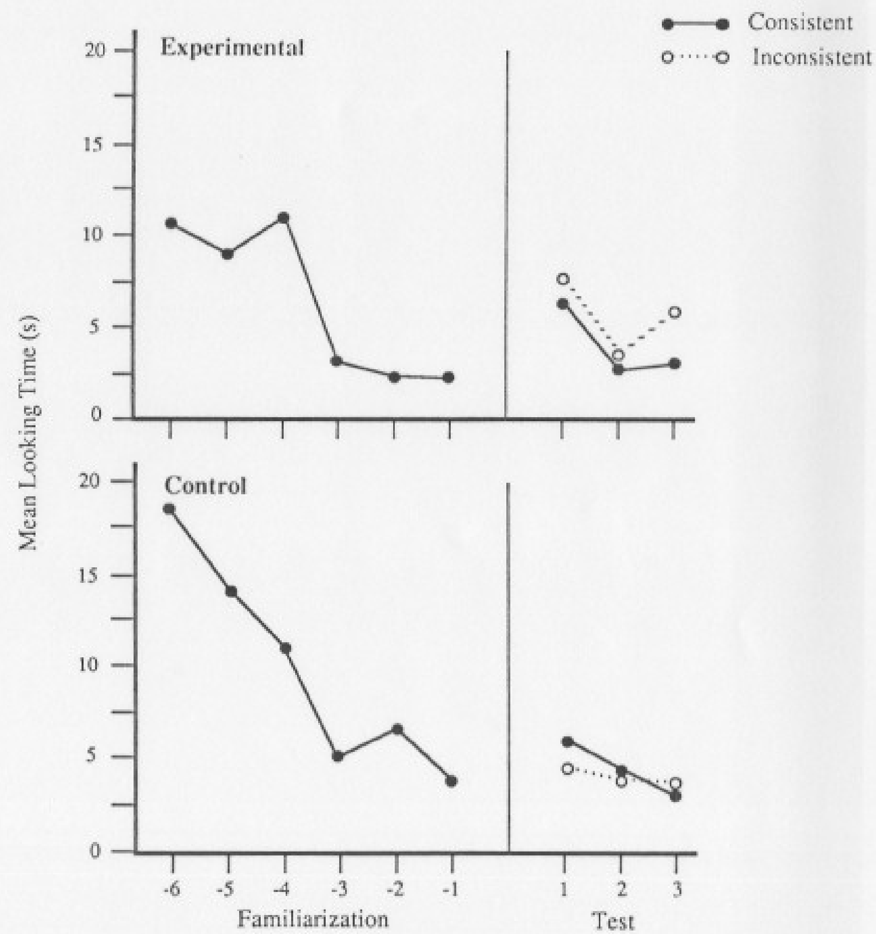

FIG. 5.12. Nine-month-old infants' mean duration of looking at the event outcomes during the last six familiarization trials and the six test trials. (After Spelke & Keller, 1989)

tion is subject to gravity. We next investigated whether they have developed a general conception that object motion is subject to inertia.

Our first study (Spelke et al., 1990) presented nearly the same displays as the second solidity/continuity experiment (Fig. 5.13). Infants were familiarized with an event in which a ball was introduced on the left side of a horizontal surface, rolled rightward behind a screen, and was revealed at rest next to the first of two objects in its path. For the test, the first obstacle was removed, the ball was rolled as before, and it was revealed either in a new position against the second obstacle or in its former position. In the latter case, the rapidly moving ball appeared to have halted spontaneously, contrary to the inertia constraint. Adults judged that the familiarization and the first test event were natural, whereas the second test event was unnatural.

These events were presented to 6-month-old infants. Looking times to the two test outcomes were compared to the looking times of infants in a control condition identical to that of the corresponding continuity/solidity experiment. The findings of the experiment were negative: Infants in the two conditions looked equally at the two test events (Fig. 5.14). This looking pattern suggested that 6-month-old infants do not appreciate that object motion is subject to inertia.

The next experiments (Katz et al., 1990) tested this possibility further with different events, and they investigated the later development of sensitivity to inertia. These experiments focused on what may be a more compelling manifestation of the inertia principle. When an object moves on a horizontal

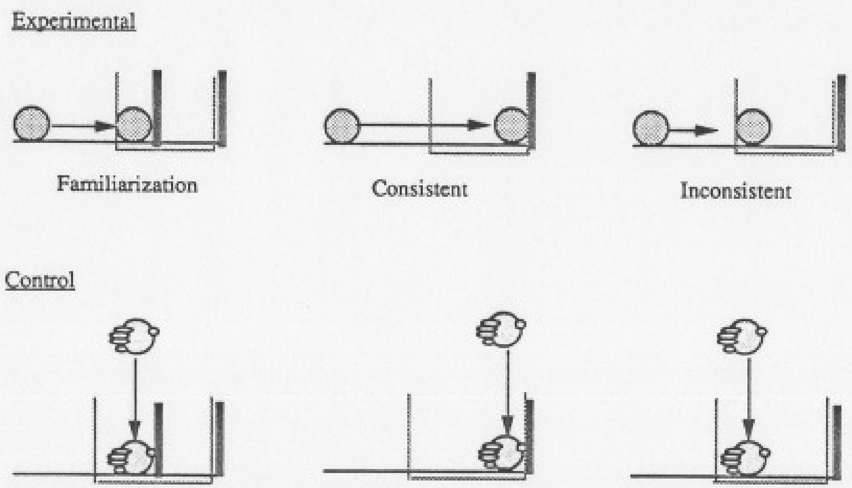

FIG. 5.13. Displays from a study of infants' knowledge of inertia. (After Spelke et al., 1990, Exp. 7)

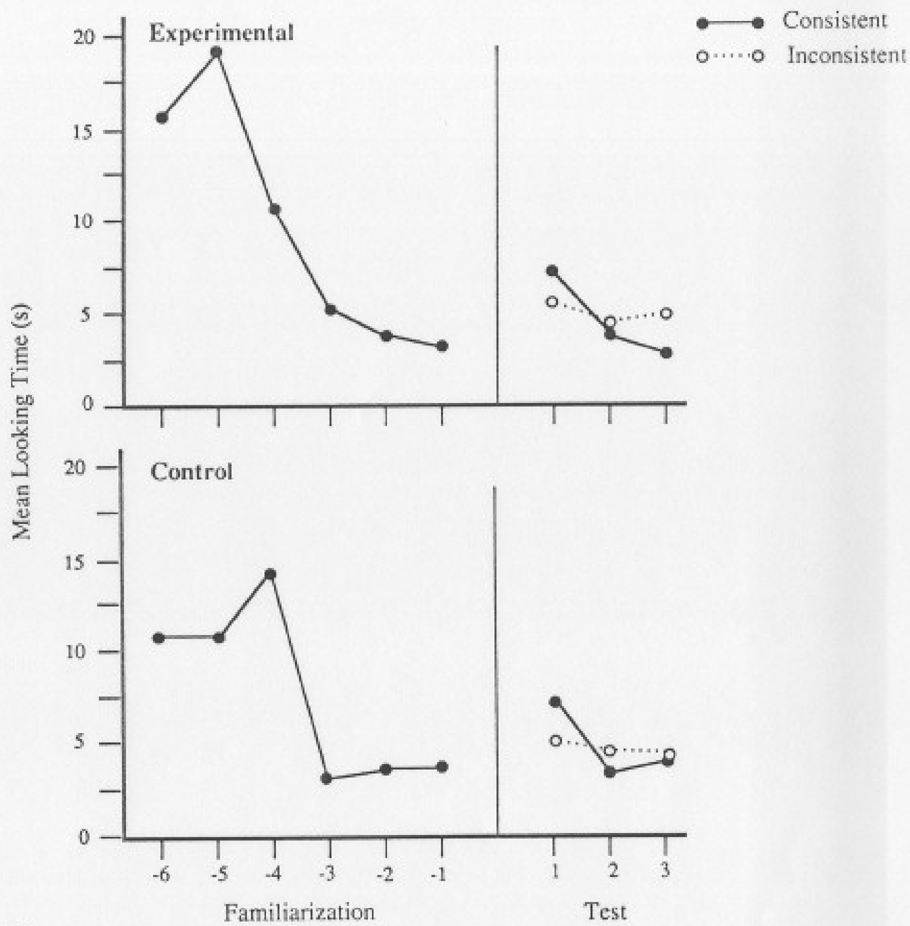

FIG. 5.14. Six-month-old-infants' mean duration of looking at the event outcomes during the last six familiarization trials and the six test trials. (After Spelke et al., 1990, Exp. 7)

surface, it does not change direction spontaneously: In the absence of obstacles, it continues moving in a straight line. The experiments investigated whether infants are sensitive to this aspect of object motion.

The events took place on a display similar to a billiard table. Each infant sat in front of the table, held in a booster seat by a parent, and viewed the events by looking ahead and down. The events involved a ball that was rolled diagonally across the table, disappearing behind a screen when it reached the table's center. When the screen was raised, the ball was revealed at rest in one of the corners of the table (Fig. 5.15). Half the infants were familiarized with an event in which the ball began at the back right corner, disappeared at the center, and reappeared at the front left corner. Then they were tested with events on the opposite diagonal: The ball was presented in the front right corner, it disappeared at the center, and it reappeared either in a novel position on a line with its new motion (consistent) or in its familiar position: a position it could reach only by turning more than 90 degrees while hidden beneath the screen (inconsistent). The remaining infants in the experiment were presented with the same events on the reverse diagonals. Thus, each test outcome was consistent for half the subjects and inconsistent for the remaining subjects.

Adults judged that the familiarization and consistent test events were natural and expected, whereas the inconsistent test events were unnatural and unexpected. To assess infants' reactions to the events, looking times to the outcomes of the test events were compared. If infants inferred that the linearly moving object would continue in linear motion, they were expected to look longer at the outcome of the inconsistent event.

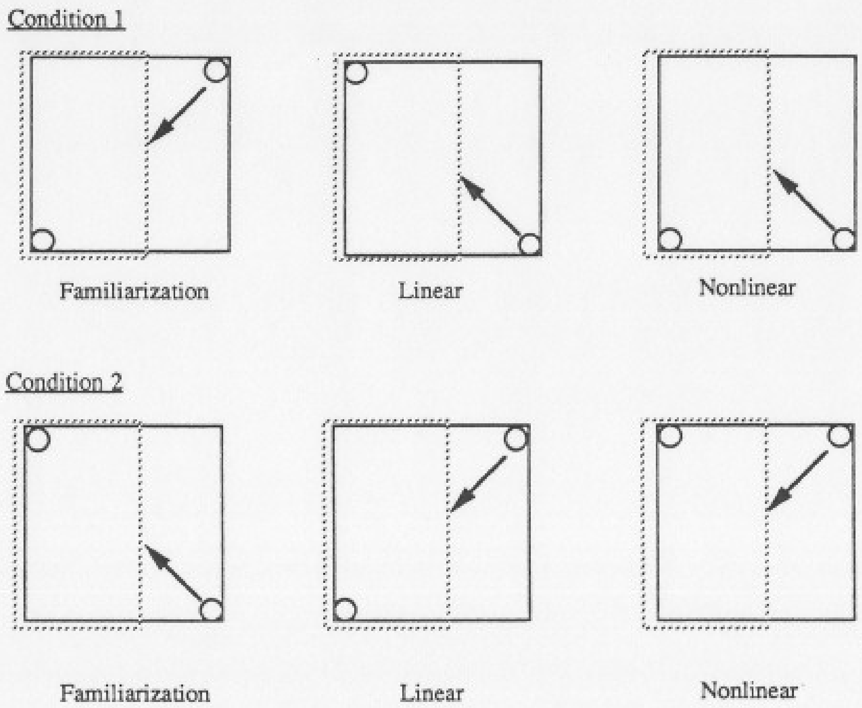

FIG. 5.15. Displays from a study of infants' knowledge of inertia. (After Katz et al., 1990, Exp. 1)

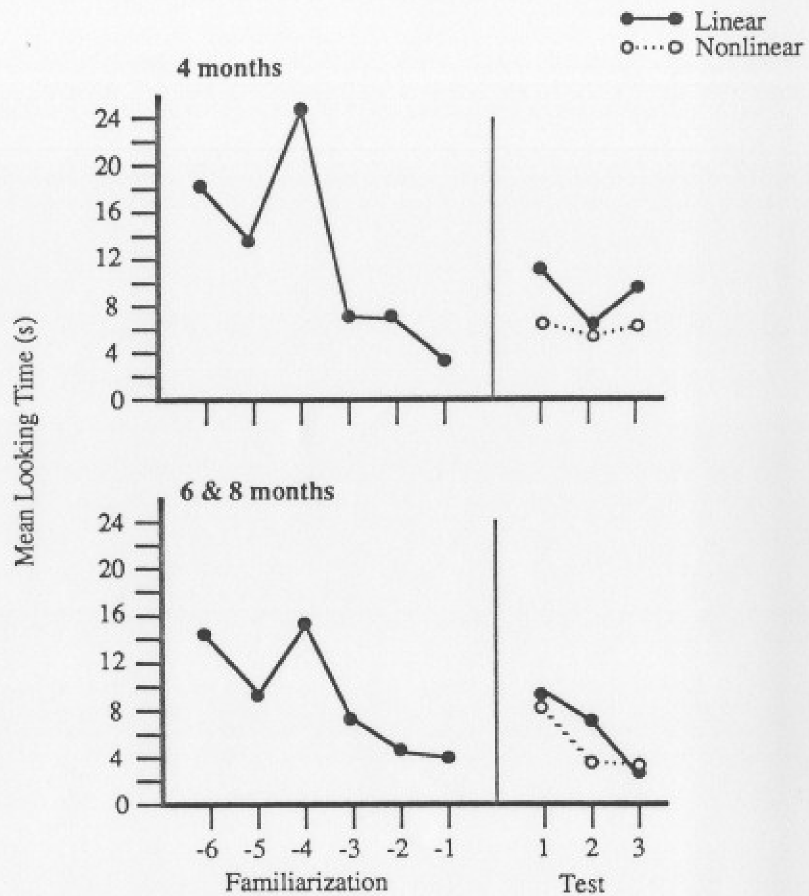

FIG. 5.16. Mean duration of looking at the event outcomes during the last six familiarization trials and the six test trials. (After Katz et al., 1990, Exp. 1)

This experiment was conducted first with 4-month-old infants, with striking results (Fig. 5.16): Infants looked reliably longer at the superficially novel *consistent* event, contrary to the inertia constraint. The experiment was repeated, therefore, with 6- and 8-month-old infants (Fig. 5.16). Like the 4-month-olds, the older infants looked reliably longer at the consistent test event. Infants aged 4 to 8 months thus appeared to dishabituate to a change in the object's final position, not to a change from apparently linear to apparently nonlinear motion. The experiment provides no evidence that infants infer that a linearly moving object will continue in linear motion.

The last experiment in this series, suggested by Michael McCloskey, investigated infants' expectation of linear motion in a situation in which the consistent and inconsistent event outcomes were equally novel. Infants were presented with the same billiard table display (Fig. 5.17). In the familiarization event, this display contained a barrier that stopped the ball's motion at the center of the table. For the test, the barrier was removed, the ball was rolled as before, and it was revealed on alternating trials in the two corners of the display. Because the two corners were equidistant from the center, the two test positions were equally novel. One position would be reached by a continued linear motion, whereas the other required a 90-degree turn. Looking times to the test outcomes were recorded as before.

The experiment was conducted with 6- and 8-month-old infants (Fig. 5.18). It revealed a significant shift between these ages: Whereas the 6-month-old infants looked equally at the linear and nonlinear test outcomes, the 8-month-old infants looked reliably longer at the nonlinear outcome. The difference between looking preferences at the two ages was reliable. In this situation, sensitivity to inertia began to be manifest between 6 and 8 months of age.

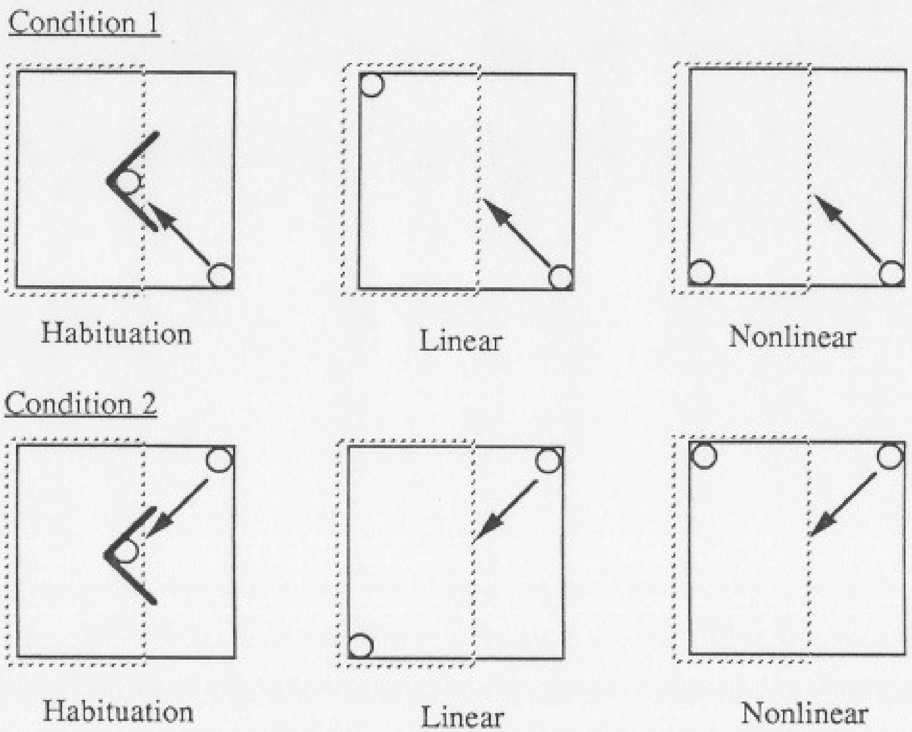

FIG. 5.17. Displays from a study of infants' knowledge of inertia. (After Katz et al., 1990, Exp. 2)

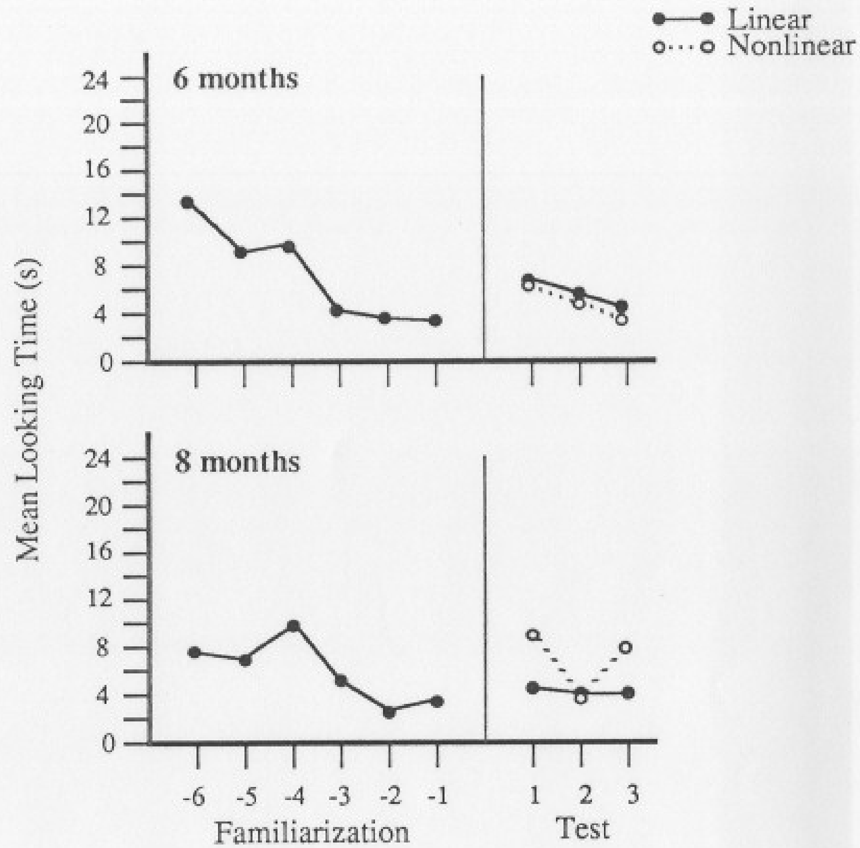

FIG. 5.18. Mean duration of looking at the event outcomes during the last six familiarization trials and the six test trials. (After Katz et al., 1990, Exp. 2)

These two experiments suggest that knowledge of one aspect of inertia has begun to develop, but is still fragile, at 8 months of age. In contrast to 6-month-old infants, 8-month-old infants inferred that an object would move to a new position on a linear path rather than to a new position on a nonlinear path. Nevertheless, neither 6- nor 8-month-old infants appeared to infer that an object would move to a new position on a linear path rather than to a familiar position on a nonlinear path. The last finding contrasts with the findings of the solidity/continuity experiments, in which infants dishabituated to familiar but inconsistent event outcomes.

As always, the negative conclusions suggested by the inertia experiments must be offered cautiously. It is possible that studies using different methods or events would provide evidence that younger infants are sensitive to the inertia constraint. Nevertheless, the findings of these studies contrast with the positive findings of the preceding experiments. This contrast suggests that young infants have no general conception that object motion is subject to inertia.

In summary, the present studies provide no evidence that 4-month-old infants are sensitive to any effect of gravity or inertia on object motion. Six-month-old infants have become sensitive to one such effect: They evidently infer that a falling object will land on a supporting surface rather than in midair. Nevertheless, the inferences made by 6-month-old infants are limited. Such infants do not appear to infer that an object will begin to fall if it loses its support or that an object will move in a constant direction in the absence of obstacles. These findings suggest that 6-month-old infants have developed local knowledge of the behavior of falling objects, rather than any general appreciation that object motion is subject to gravity or inertia. Finally, the experiments suggest that conceptions of gravity and inertia are still fragile at 8 or 9 months of age, although aspects of these conceptions appear to be developing. I now consider possible implications of these findings.

Summary and Suggestions

The preceding experiments suggest several differences between the development of knowledge of continuity and solidity, on one hand, and the development of knowledge of gravity and inertia, on the other. First, humans appear to appreciate that objects move on connected, unobstructed paths before we appreciate that object motion is subject to gravity and inertia. Sensitivity to the continuity and solidity constraints is manifest at the youngest age yet tested: $2^1/_2$ months. Sensitivity to gravity or inertia does not begin to be manifest in our studies until 6 months. Although future research with different methods or displays may suggest otherwise, it now seems that knowledge of continuity and solidity is more deeply rooted in human development than is knowledge of gravity and inertia.

A second difference between performance in the continuity/solidity experiments and performance in the gravity/inertia experiments concerns the consistency of infants' reactions. Infants' responses to violations of the solidity and continuity constraints were consistent across subjects and across situations. In contrast, responses to violations of the gravity and inertia constraints were inconsistent in both respects: Variability in looking preferences within an experiment was high, and changes in the events presented to infants led, in some cases, to striking changes in infants' responses to inconsistent event outcomes.

One possible explanation for these differences is as follows. Knowledge of continuity and solidity may derive from universal, early-developing capacities to represent and reason about the physical world. These capacities may emerge in all infants whose early growth and experience fall within some normal range. They may enable children to infer how any material body will move in any situation.

In contrast, knowledge of gravity and inertia may derive from the child's growing acquaintance with particular kinds of events involving physical objects. This knowledge may be relatively local, enabling the child to make inferences, for example, about events in which a stationary object is released and falls, but not about other events involving moving objects. The development of this knowledge may be highly dependent on the child's specific experiences, such that it arises at somewhat different times for different children.

This account may appear puzzling. Gravity and inertia are pervasive constraints on behavior of perceptible material bodies, including the behavior of children themselves. Given the limited perceptual and exploratory capacities of young infants, the perceptual evidence for the effects of gravity and inertia would appear to be at least as great as the evidence for solidity and continuity, and probably greater (see Spelke, et al, 1990, for discussion; see also Piaget, 1954; Harris, 1983). Adults, moreover, recognize the effects of gravity and inertia in the present events: Subjects judged that the events that were inconsistent with gravity and inertia appeared as unnatural as the events that were inconsistent with continuity and solidity (Spelke et al., 1990; Katz et al., 1990). Why, then, are young infants predisposed to infer that object motion will accord with continuity and solidity but not with gravity or inertia? What, moreover, are the implications of this predisposition for the course of later development?

THREE PIAGETIAN THEMES

To approach these questions, I return to three themes at the center of Piaget's work. First, I consider whether development brings radical change in understanding the physical world. I suggest, in contrast, that early conceptions are central to later development. Then, I ask whether reasoning is tied to perception. I suggest that a single process, built in part on the continuity and solidity constraints, underlies perceiving and reasoning about objects. These discussions lead to a third Piagetian theme, concerning the place of developmental studies within what is now cognitive science.

Physical Knowledge and Conceptual Change

The present experiments, with those of Leslie and Baillargeon, provide evidence that young infants represent physical objects and reason about object motions in accord with the constraints of continuity, solidity, rigidity, and no action at a distance. Once children are able to act on objects in a coordinated manner, then studies focusing on such actions provide evidence for the same abilities at the end of infancy. Taken together, these findings cast doubt on the thesis that conceptions of physical objects undergo radical change during the infancy period. One may ask, nevertheless, whether conceptions change more radically with later development. Do conceptions of physical objects undergo fundamental changes when children acquire language or begin formal instruction, or when adults study or practice science?

Because research on infants cannot address this question, I offer only a few observations and speculations about the later development of physical understanding. First, the constraints of solidity and continuity appear to be honored uniformly and without question in adults' commonsense reasoning about object motion. In a number of experiments, adults have been asked to judge the path that a moving object will follow under a variety of conditions (e.g., McCloskey, 1983). Subjects tend to judge strongly that objects will move on connected, unobstructed paths. Indeed, no subject in McCloskey's experiments ever judged that an object's path would contain a gap or intersect another object, even when subjects were asked about situations that were unfamiliar or that elicited other errors (McCloskey, personal communication). These observations suggest that solidity and continuity are core principles of human reasoning about physical objects: principles that emerge early in development and remain constant over the lives of most humans.

The uniformity of adherence to the continuity and solidity constraints contrasts with the errors and inconsistencies in adults' judgments about the effects of gravity and inertia on object motion. When adults were asked to judge the path of a moving object in the same experiments by McCloskey (1983), many subjects chose paths that were inconsistent with the effects of gravity or inertia. Their judgments, moreover, were often uncertain, variable across individuals, and variable across situations (see also Clement, 1972; Halloun & Hestenes, 1985; Kaiser, Jonides, & Alexander, 1986; Shanon, 1976). These observations suggest that no general conceptions of gravity or inertia guide the commonsense reasoning of adults. Abilities to reason about the effects of gravity and inertia may depend instead on a wealth of accumulated knowledge about how objects move under particular conditions. This knowledge may begin to accumulate during the later months of the first year of life.

If these suggestions are correct, then there is considerable invariance over cognitive development: The physical knowledge that emerges first in infancy remains most central to the commonsense conceptions of adults. Nevertheless, this knowledge cannot be extended to the quantum level, where particles may violate all the above constraints on object motion. The development of quantum mechanics suggests that initial conceptions of object motion place no absolute limits on the physical theories that humans construct. It also suggests that commonsense physical reasoning differs from scientific physical reasoning in certain respects. What are the implications of these suggestions for Piaget's theses about conceptual change and about the relation between common sense and scientific knowledge?

In some respects, the development of common sense knowledge clearly differs from the development of scientific knowledge. Common sense knowledge of physical objects may develop rapidly and spontaneously with little effort or reflection; scientific physical knowledge often develops more slowly and effortfully, stimulated by instruction, reflection, and mathematical abstraction (e.g., Duhem, 1954). Common sense physical conceptions may be tacit and unquestioned, whereas scientific conceptions usually can be made explicit and subjected to scrutiny. As ordinary thinkers, humans may tolerate considerable inconsistencies among their beliefs (e.g., Kaiser et al., 1986; McCloskey, 1983). Scientists strive for consistency more explicitly, albeit only with partial success (e.g., Kuhn, 1977). Finally, common sense and scientific conceptions may conflict with one another even in scientists and science educators, who remain prey to errors when they reason intuitively about certain aspects of object motion (Proffitt, Kaiser, & Whelan, 1990).

Despite these differences, there appear to be important common features to the development of common sense and scientific understanding. When scientists have been led to abandon constraints that are central to human thought, they appear to have done so only with great difficulty and reluctance. This difficulty was evident in the 17th century, when the simplest and most general laws of motion appeared to violate the principle of no action at a distance. It may be manifest in the present century by the resistance of many scientists to the introduction of quantum theory, and also by the difficulty physics students may experience when they first encounter entities that are both material and immaterial, entities that occupy two locations at once, and entities that lack any spatiotemporally connected history. The turmoil that accompanies these changes in scientific conceptions may stem as much from the incompatibility of new scientific theories with intuitive conceptions as from the incompatibility of new theories with prior theories.

In these last respects, common sense reasoning and scientific reasoning may indeed resemble one another. All humans, including scientists, may seek primarily to extend their understanding by building on core conceptions that are universal and unquestioned. Through their experiments, systematic observations, and reflections, scientists may be more apt than ordinary humans to confront situations in which the inadequacies of those conceptions appear. Conceptual changes thus may occur more often in scientific reasoning than in common sense reasoning. Nevertheless, the same core principles may influence human reasoning throughout development.

Perception and Thought

If central conceptions of the physical world are largely constant over human development, then the major objections to Piaget's thesis of the inseparability of perception and thought are eliminated. That thesis is compatible with the evidence that infants perceive the world much as adults do. Moreover, it no longer leads to an impasse in which a child's distorted perceptions lock him or her into a conceptual system that is distinct from the adult's. The truth of that thesis can be evaluated, however, only by comparing the detailed nature of perceptual processes to processes of physical reasoning. Before this can be accomplished, "perception" must be further analyzed.

There is abundant evidence that perception does not result from a single process but from a host of relatively separable processes, each operating in accord with distinct principles (see, e.g., Rock, 1983; Hochberg, 1978; Marr, 1982). If different perceptual processes are separable from one another, then all of perception cannot be inseparable from thinking and reasoning. We may ask, however, whether any perceptual achievements are linked to physical reasoning. I consider two such achievements: perception of a three-dimensional layout of surfaces, and perception of unitary and bounded objects.

Mechanisms of surface perception appear to differ from mechanisms of physical reasoning in important ways. First, the two kinds of mechanisms operate on different inputs: surface perception results from an analysis of two two-dimensional, changing arrays of light, whereas physical understanding evidently results from an analysis of one three-dimensional layout surface. Second, mechanisms of surface perception appear to be modality-specific (different mechanisms serve to construct representations of surfaces from visual information, auditory information, and haptic information), whereas mechanisms of physical reasoning appear to be amodal. Third, the mechanisms of surface perception do not appear to operate in accord with the solidity, continuity, or rigidity constraints. Humans can readily perceive forms that interpenetrate (such as shadows), forms that go in and out of existence (such as reflections on water), and forms that move nonrigidly. Indeed, nonrigid and interpenetrating forms may be perceived even in situations where a perception that is consistent with the rigidity and solidity constraints is possible (Bruno, 1990; Hochberg, 1986; Leslie, 1988; but see Ullman, 1979; Wallach & O'Connell, 1953). These considerations suggest that processes of perceiving surfaces are distinct from processes of physical reasoning.

In contrast, mechanisms for perceiving objects appear to be strikingly similar to mechanisms for physical reasoning. Like physical reasoning, object perception appears to take as input a three-dimensional representation of surfaces (Kellman, Spelke, & Short, 1986; see Spelke, 1988). Object perception also appears to depend on amodal mechanisms (Streri & Spelke, 1988, 1989).

Most important, object perception and physical reasoning appear to accord with similar principles. A review of research on infants' perception of objects suggested that infants perceive objects in accord with four principles: cohesion, boundedness, rigidity, and no action at a distance (Spelke, 1990). The latter two principles are the same as those that guide physical reasoning in Leslie's and Baillargeon's experiments. Moreover, the cohesion and boundedness principles were found to imply, respectively, the principles of continuity and solidity (Spelke, 1990): Only continuous, solid bodies could satisfy those principles.[5] These findings suggest that object perception and physical reasoning are closely linked abilities. They may be reflections of a single capacity.

Although continuity and solidity may follow from the principles by which infants perceive objects, gravity and inertia do not. This difference could account for the earlier emergence of knowledge of the former constraints. If continuity, solidity, rigidity, and no action at a distance figure in infants' capacities to apprehend objects, then infants will honor these constraints as soon as they can perceive objects at all. The connection between physical reasoning and object perception might also explain why scientific theories that do not accord with the principles continuity, solidity, or no action as a distance are difficult for adults to construct or understand. Adults may not easily question these constraints on object motion because the constraints are built into the very processes by which we apprehend the material bodies whose behavior we ponder.

Thus, research on infancy provides support for one part of Piaget's second thesis. At least in early infancy, object perception and physical reasoning may be manifestations of a single underlying capacity. That capacity may be based on sensitivity to certain fundamental constraints on the behavior of material bodies.

Genetic Epistemology

It is sometimes said that recent research on perceptual and cognitive development has undermined Piaget's theory of cognitive development; psychologists must seek other frameworks for understanding knowledge and its growth. Indeed, recent research has cast doubt on a number of Piaget's claims. Capacities to perceive, represent, and reason about the world do not appear to depend on the emergence of the sensorimotor coordinations that Piaget (1952) described, or even on earlier sensorimotor coordinations (see Spelke et al., 1990). The development of representation and reasoning

[5]The converse is not true: Physical entities can be continuous and solid but not cohesive or bounded (e.g., liquids).

appears to resemble a process of enrichment rather than a process of conceptual revolution. Finally, thought and perception are not fully interconnected: Perception itself consists of a host of distinct processes, most of which are largely separable from one another and from the processes by which humans think about the perceived world.

Nevertheless, I believe that some of the foundations of Piaget's theory deserve a central place within cognitive science. The most important of these is his conception of the goal of developmental studies of cognition. Piaget believed that an understanding of the development of knowledge in children would shed light on the most fundamental questions concerning the nature of mature human knowledge.

This belief appears to be shared by few students of cognition or development. The study of cognition in children is generally regarded as a secondary enterprise in cognitive science. The first task facing philosophers and cognitive psychologists is to elucidate the nature of human knowledge in its mature state. Insofar as this task is accomplished, investigators of cognitive development may study how human knowledge arises.

The central questions of cognitive psychology, however, are not easily answered. Mature human knowledge is difficult to characterize, because of its enormous intricacy and complexity and perhaps because of the relative inaccessibility of our most important conceptions. In view of this difficulty, it is worth considering Piaget's very different approach to the study of human knowledge. His "genetic epistemology" focuses centrally on cognitive development and conceptual change. Studies of the development of knowledge in children and in science serve to elucidate one another, and both ultimately serve to shed light on the character and the limits of human understanding. Like its rivals, this approach has perils. I believe, however, that it has led to insights, and that its most important contributions are still to come.

ACKNOWLEDGMENTS

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