Origins of Knowledge

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Experiments with young infants provide evidence for early-developing capacities to represent physical objects and to reason about object motion. Early physical reasoning accords with 2 constraints at the center of mature physical conceptions: *continuity* and *solidity*. It fails to accord with 2 constraints that may be peripheral to mature conceptions: *gravity* and *inertia*. These experiments suggest that cognition develops concurrently with perception and action and that development leads to the enrichment of conceptions around an unchanging core. The experiments challenge claims that cognition develops on a foundation of perceptual or motor experience, that initial conceptions are inappropriate to the world, and that initial conceptions are abandoned or radically changed with the growth of knowledge.

Two Views of Cognitive Development

The Peripheral-Origins Thesis

It is often proposed that human psychological functions develop from the periphery inward: Perception and action develop on the basis of sensory and motor experience, and reasoning develops on the basis of perception and action (e.g., Berkeley, 1910; Helmholtz, 1926; James, 1890; Piaget, 1952). This thesis connects to two further claims about the origins and development of knowledge. First, humans' earliest conceptions are inappropriate to the world in ways that reflect the nature and limits of early perceptual and motor experience. Second, human conceptions change fundamentally with development, as children overcome these limitations.

In recent years, research on the early development of perception and action has cast doubt on aspects of this view. Young infants appear to perceive a stable layout of objects (e.g., E. J. Gibson, 1988) and to act on that layout adaptively (e.g., Hofsten, 1989). With growth and experience, capacities to perceive and to act appear to be extended, refined, and recruited for new purposes, but not overturned (Banks & Salapatek, 1983; E. J. Gibson & Spelke, 1983; Hofsten, 1980; Thelen & Ulrich, 1991).

Changing views of perceptual and motor development have not, however, led to corresponding changes in psychologists' views of the development of thought. Following Fodor (1983), a number of psychologists have proposed that there are crucial differences between perceptual and motor processes on the one hand and central cognitive processes on the other (see Kellman, 1988; Leslie, 1988; Premack, 1990). Whereas perception and action depend on a collection of relatively autonomous mechanisms that develop rapidly under internal constraints, thinking depends on processes that operate and develop more slowly, without the internal constraints that a modular architecture would impose.

In addition, a number of psychologists have proposed to view cognitive development as a process of theory development and conceptual change (Carey, 1985, 1988; Gopnik, 1988; Wellman, 1990). From this perspective, children make sense of their experience through sets of interconnected concepts and beliefs: intuitive theories. Early-developing theories may be useful under restricted conditions, but they are inappropriate to the full range of events children confront. Cognitive development occurs when the inadequacies of an early theory lead the child to reorganize or abandon certain concepts and beliefs and to restructure his or her experience in terms of a new theory. As the child's theory changes, concepts and beliefs that were peripheral to the old theory may become central to the new theory (Carey, 1985; Kitcher, 1988). Moreover, the child may embrace concepts and beliefs that cannot even be formulated in terms of his or her former concepts (Carey, 1988; Wellman, 1990; see also Kitcher, 1983; Kuhn, 1962, 1977). Cognitive development brings radical conceptual change.

A Central-Origins Thesis

We will explore a different view of cognitive development, traceable in part from Descartes (1637/1956) and Kant (1929)[1] to Chomsky (1975). Cognition develops from its own foundations, rather than from a foundation of perception and action. Initial cognitive capacities give rise, moreover, to conceptions that are largely appropriate to the experience of children and

[1] Philosophical discussions of the origin of knowledge often arise in the context of broader epistemological questions. Research that illuminates those origins may not, however, resolve the original questions of epistemology (see Hatfield, 1990).

(nonscientist) adults. Finally, initial conceptions form the core of many later conceptions; they are enriched and refined as knowledge grows, but they are rarely overturned. Although cognitive revolutions may occur in the development of science and during formal, disciplined instruction, such revolutions are less likely to occur as children gain knowledge spontaneously.

Our view centers on two general claims about cognition in infancy: the *active representations* thesis and the *core knowledge* thesis. According to the first thesis, young infants are capable of reasoning: They can represent states of the world that they no longer perceive. By operating on these representations, infants come to know about states of the world that they never perceived. According to the second thesis, young infants' reasoning accords with principles at the center of mature, commonsense conceptions. Infants' reasoning may not accord with principles that are absent from or peripheral to mature conceptions.

The denial of the active representations thesis has been a central feature of the argument that cognitive capacities are built on sensation and action. For example, Piaget (1952, 1954) asserted that children have no representational or reasoning capacity until their earlier-developing sensorimotor activities are first coordinated and internalized; according to Piaget, this achievement occurs at about 18 months. Helmholtz (1885) asserted that knowledge of the physical world first arises as children begin to experiment on the world systematically by manipulating the things they see; such object-directed manipulations begin to appear at about 6 months. These views are extremely influential (for recent versions, see Bensen & Uzgiris, 1985; Fischer & Biddell, 1991; Mounoud, 1988). We return in the General Discussion to the question of how early in infancy representational and reasoning abilities must appear in order for their appearance to bear on these and other versions of the thesis that cognition develops from perception or action.

The denial of the core knowledge thesis has been a central feature of arguments that cognitive development brings radical conceptual change. For example, Carey (1985) and Wellman (1990) have proposed that central concepts in mature, commonsense theories of life and of mind play no role in the reasoning of young children; the emergence of those concepts brings radical change to children's thinking about biology and psychology. Even where early conceptions are retained, development has been thought to bring changes in the status of those conceptions such that conceptions that were central to the reasoning of children become peripheral to the reasoning of adults, or the reverse (Carey, 1985, 1988; Kitcher, 1988). Either type of change challenges the view that conceptions of the world are enriched, but not reorganized, over development.

Knowledge of Material Objects

We will review evidence, and present some new evidence, for these two theses as they pertain to a single domain of knowledge: knowledge of the properties and behavior of middle-sized, inanimate, material objects. In particular, we consider infants' abilities to represent and to reason about objects in accord with four constraints on object motion: *continuity* (objects move only on connected paths; they do not jump from one place and time to another), *solidity* (objects move only on unob-

structed paths; no parts of two distinct objects coincide in space and time), *gravity* (objects move downward in the absence of support), and *inertia* (objects do not change their motion abruptly and spontaneously).[2]

We focus on this domain of knowledge for three reasons. First, most studies of early cognitive development have centered on the development of knowledge of material objects, beginning with the pioneering research of Piaget (1954). Second, adults' commonsense conceptions of material objects have been studied quite extensively. Those studies provide anchor points for developmental research. Third, the development of knowledge in this domain appears to provide an excellent case for the peripheral-origins thesis and its associated claims. Research on topics as disparate as cognition in infancy and conceptual change in science suggests that early conceptions of the physical world are radically inappropriate and that physical conceptions change radically with the growth of knowledge.

In particular, the research of Piaget (1952, 1954) has been widely understood to show that young infants do not experience a world of material objects behaving in accord with physical laws, but rather a succession of ephemeral appearances produced by their own activity. The construction of a world of physical bodies whose behavior is governed by physical constraints constituted for Piaget a conceptual revolution akin to the major revolutions in science and mathematics (Piaget & Inhelder, 1969; Piaget, 1980; see also Gopnik, 1988; Harris, 1983; Helmholtz, 1885).

At the opposite pole of cognitive development, studies in the history of science suggest that conceptions of the physical world are extremely malleable. Conceptions of material objects and object motion have changed radically during the transitions between Aristotelian, medieval, classical, Einsteinian, and quantum mechanics (e.g., Crombie, 1952; Duhem, 1954; Einstein & Infeld, 1938; Kuhn, 1959). These transitions have involved every kind of conceptual change, from the development of incommensurable concepts and vocabularies (Kuhn, 1959, 1962; Kitcher, 1983) to shifts in the core conceptions that figure in scientific explanations (Kitcher, 1988). None of the above constraints has been impervious to change. The history of science suggests, therefore, that there is no unchanging core to human physical knowledge.

Between these extremes, research in developmental and educational psychology provides evidence that children are prey to a variety of misconceptions about physical objects and their behavior and that their conceptions change considerably during spontaneous and instructed learning. In particular, changes in conceptions of gravity and inertia would seem to occur whenever a student masters classical mechanics (White, 1988; but see Proffitt, Kaiser, & Whelan, 1990), and changes in conceptions

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[2] This formulation of the gravity and inertia constraints was guided by the findings of research with adolescents and adults (e.g., Halloun & Hestenes, 1985; McCloskey, 1983; White, 1988). College and high school students appreciate that unsupported objects move downward and that moving objects do not change speed or direction spontaneously and abruptly. Because the reasoning of many students does not appear to accord fully with the laws of gravitational attraction or inertia in classical mechanics, we have not investigated the development of those more general conceptions.

of continuity and solidity would seem to occur with the mastery of quantum mechanics. Human reasoning about object motion thus appears to support the peripheral-origins thesis. We will suggest, nevertheless, that these phenomena have been misconstrued.

Mature, Commonsense Knowledge of Objects

Although commonsense physical conceptions differ from the conceptions of the scientist, they reflect considerable knowledge of the behavior of middle-sized, material objects. This knowledge allows adults to act on objects effectively, to perceive or infer properties of objects from their behavior during collisions and other events, to predict objects' future behavior, and to judge the states and motions of objects in unseen or hypothetical situations.

Studies of adults' actions on objects, perceptions of objects' ongoing motions, and judgments about objects' future or hidden motions serve to shed light on the nature and organization of adults' knowledge. Extensive studies have been undertaken by cognitive and educational psychologists (for reviews, see Halloun & Hestenes, 1985; McCloskey, 1983; Proffitt & Gilden, 1989; White, 1988). Although the issues raised by this research are complex, we believe the following conclusions emerge. First, the continuity and solidity constraints are ubiquitous guides to reasoning about object motion by children and adults. To our knowledge (also McCloskey, personal communication, 1989), no subject in any study of physical reasoning has ever judged that any part of a material object would move discontinuously or would coincide in space and time with a second material object. Indeed, knowledge of the continuity and solidity constraints is so deeply ingrained that it is generally presupposed in investigations of mature physical knowledge. Discussions of this knowledge are more common in philosophy, where continuity and solidity are often considered among the foundations of our world view (e.g., Kant, 1929).

In contrast, the centrality of knowledge of gravity and knowledge of inertia is not as clear. To be sure, adults possess considerable knowledge of the effects of gravity and inertia, and their knowledge sometimes guides reasoning clearly and correctly. In particular, adults judge readily that unsupported objects will fall downward and that linearly moving objects will continue in linear motion (Kaiser, McCloskey, & Proffitt, 1985; Kaiser, Proffitt, & McCloskey, 1986). Under a variety of conditions, however, adults' judgments about the effects of gravity and inertia have been shown to be hesitant, uncertain, variable across subjects, inconsistent within a subject, or erroneous (e.g., Champagne, Klopfer, & Anderson, 1980; Clement, 1982; Halloun & Hestenes, 1985; Kaiser, Jonides, & Alexander, 1986; McCloskey, 1983; Shanon, 1976; White, 1988). Erroneous judgments abound. Some adults report that an unsupported object will fall at a constant speed (Shanon, 1976), that a horizontally moving, supported object that loses its support will fall on a straight-down path (Caramazza, McCloskey, & Green, 1981), and that an object that moves freely after moving in a circle will continue in curvilinear motion (McCloskey, Caramazza, & Green, 1980; Piaget, 1976). Inconsistent judgments also occur frequently. One person may report that a horizontally moving, carried object will fall straight down if it loses support but that

a horizontally moving, propelled object will continue moving forward (McCloskey, 1983); one person may judge that water will move on a straight path after leaving a hose whereas a ball will move on a curved path after leaving an identically shaped tube (Kaiser, Jonides, & Alexander, 1986).

One possible interpretation of these findings is that conceptions of gravity and inertia have a different status for adults than conceptions of continuity and solidity. Reasoning about object continuity and solidity may depend on general principles that apply widely, perhaps to all events involving material bodies. These principles may serve as strong guides to commonsense reasoning about object motion, yielding judgments that are clear, consistent, and confident. In contrast, reasoning about gravity and inertia may depend on a larger number of principles with relatively narrow application: principles that apply only to the behavior of particular kinds of objects undergoing particular kinds of motion. Some of these principles may guide human reasoning only weakly, yielding judgments that are uncertain and inconsistent.

The apparent limitations on knowledge of gravity and inertia are striking in view of the perceptual experience and action capacities of infants and children. Gravity and inertia have pervasive effects both on the behavior of perceptible objects and on human actions. Moreover, certain adaptations to the effects of gravity and inertia appear to be built into infants' perceptual and action systems. For example, 2- and 4-month-old infants visually track and reach for a moving object by extrapolating its trajectory, in accord with certain effects of inertia (e.g., Bower, Broughton, & Moore, 1971; Hofsten, 1980).[3] Such infants also accommodate their posture and limb displacements to effects of gravity (e.g., Hofsten, 1980; Prechtl, 1989). If cognition develops by internalizing accommodations to constraints on perception and action, then accommodations to gravity and inertia might well guide infants' early reasoning (Piaget, 1954).

For these reasons, studies of the development of knowledge of solidity, continuity, gravity, and inertia provide an interesting test of the core knowledge thesis. If infants reason about object motion in accord with the constraints that are central to the commonsense reasoning of adults, then the earliest reasoning about object motion should accord with the continuity and solidity constraints. In contrast, the earliest reasoning might not accord with the gravity and inertia constraints despite the evidence for these constraints in the infant's perceptual and motor experience.

Physical Knowledge in Infancy

We turn now to the evidence that bears on the active representations thesis and the core knowledge thesis. Because this evidence comes from studies of young infants, we must look critically not only at the findings of these studies but also at their methods. How have investigators assessed infants' representational and reasoning capacities? How should their findings be understood?

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[3] Visual tracking and object-directed reaching may not accord fully with the law of inertia in classical mechanics: Infants appear to extrapolate circular trajectories as well as linear trajectories (see Bower & Paterson, 1973; Hofsten, 1980; Mundy-Castle & Anglin, 1969).

Traditionally, investigations of infants' conceptions of material objects have focused on infants' manipulations of objects. Already evident in the observations of Helmholtz (1885), this focus reached its apogee in the research of Piaget (1952, 1954). Piaget assessed infants' developing conceptions primarily by observing patterns of search for hidden objects. He presented infants with a variety of "invisible displacement tasks" in which an attractive and desired object moved from view and then underwent some transformation. Infants' understanding of constraints on object motion were investigated by observing if and where infants searched for the object.

Piaget's observations suggested that infants' search gradually comes to accord with constraints on object motion. By 6–10 months, for example, infants begin systematically to look for laterally moving objects by extrapolating their trajectories, in accord with aspects of the continuity constraint (a moving object still exists) and the inertia constraint (a moving object remains in motion). Such infants also begin to search for falling objects by looking on the ground, in accord with aspects of the gravity constraint (a falling object falls to the floor) and the solidity constraint (a falling object does not pass through the floor). Before 18 months, however, infants' search does not accord fully with any of these constraints. For example, young infants can be induced to search for an object at a place it could not reach by any continuous motion through unobstructed space, simply by presenting an object repeatedly in such a position (Piaget, 1954). These search errors were interpreted as reflecting young infants' conceptions of physical objects as ephemeral entities whose appearances are governed by the infant's own activity and will, rather than as substantial and enduring bodies whose behavior is governed by physical laws. Young infants' limited sensitivity to physical constraints was attributed to their developing partial accommodations to constraints on their own actions, not to an independent conception of material objects.

Piaget's observations have been confirmed and extended (see Harris, 1975, 1987). Some of these extensions have led investigators to propose that young infants' physical conceptions differ from mature conceptions even more radically than Piaget had envisioned. For example, young infants have been said to conceive that one object can occupy two distinct locations at the same time (Harris, 1983) or that one object cannot appear at different locations at different times (Bower, 1982). Infants' developing search patterns can be interpreted, therefore, as evidence that early conceptions of objects fail to honor the basic physical constraints recognized by adults and that physical conceptions undergo radical change during the infancy period.

Nevertheless, infants' search patterns are open to other interpretations. In particular, developmental changes in search may stem from the development of capacities for coordinated action. Piaget's own research is consistent with this possibility (Piaget, 1952). For example, his observations suggest that young infants are not capable of coordinating two actions into a means–ends relationship: a prerequisite for success on many of his tasks. In addition, more recent studies provide evidence that a number of developmental changes in search reflect the emergence of capacities to act strategically and in a coordinated manner on information in memory (Diamond, 1985; Goldman-Rakic, 1987; Wellman, Cross, & Bartsch, 1986). If limita-

tions on action capacities are an important source of search errors, then studies of search are apt to provide misleading assessments of infants' conceptions of objects.

In general, studies of early cognitive development require methods that focus on actions within the repertoire of infants of all of the ages under study. Ideally, these studies should focus on action patterns that do not change over the infancy period. Visual preference-for-novelty methods may meet this requirement.

When an infant is shown one display repeatedly, spontaneous looking time to that display typically declines. If the infant then is shown a new display, looking time typically increases. This increase has been observed as early as the first days of life (Friedman, 1972; Slater, Morison, & Rose, 1984). It occurs throughout infancy (Bornstein, 1985; Spelke, 1985) and in adults as well (see Experiment 3). It has provided students of infancy with a tool for studying such psychological functions as sensory discrimination (Banks & Salapatek, 1983), surface perception (E. J. Gibson & Spelke, 1983), categorization (Bornstein, 1981), and memory (Fagan, 1984). Recent research by Baillargeon (1987a; Baillargeon, Spelke, & Wasserman, 1985) provides evidence that preferential looking methods also can be used to study young infants' representations of hidden objects.

In Baillargeon's experiments, infants were familiarized with a screen that rotated 180° about a stationary edge that rested on a table. Then infants were tested with two events in which the screen rotated in front of an object (Figure 1). In one event, the screen rotated upward so as to occlude the object and then continued rotating until it arrived at the place the hidden object occupied. In the other event, the screen rotated upward so as to occlude the object and then continued rotating until it lay flat on the table, moving through the place that the hidden object occupied. These events presented infants with two kinds of novelty. The first event presented a novel visual motion that adults describe as natural and expected: The screen moved until it encountered the first (hidden) object in its path. The second event presented a familiar visible motion that adults describe as unnatural and surprising: The screen appeared to pass freely through the place where the hidden object had stood, revealing no object in that location. Looking times to the two test events were compared with the looking times of infants in a control condition, who viewed the same screen rotations with no hidden object in the screen's path. Relative to controls, infants in the experimental condition looked longer at the superficially familiar but inconsistent motion than at the superficially novel but consistent motion. These looking preferences, observed in infants as young as 4½ months, provide evidence that infants represented the continued existence of the hidden object.

Experiments using variations of the rotating-screen method provide evidence that 7-month-old infants represent not only the existence of a hidden object but properties of the object such as its height, rigidity, and distance from the occluder: All of these properties influenced the kinds of screen motions that evoked a novelty reaction in infants (Baillargeon, 1987b). Infants aged 4½ months also were found to represent the height of a hidden object in the presence of a visible reminder (Baillargeon, 1989).

Baillargeon's experiments suggest that preferential looking

Habituation

Test
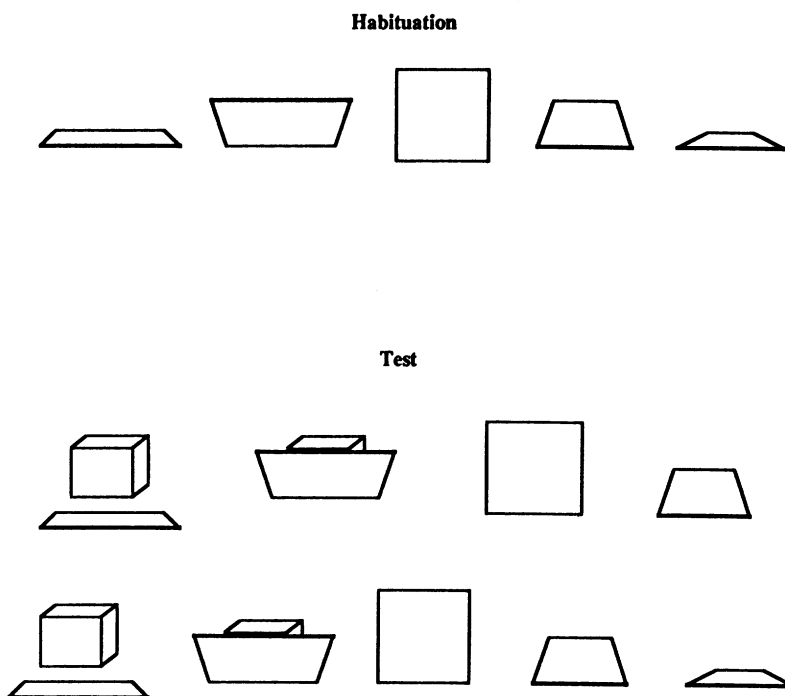
Figure 1. Schematic depiction of the events in experiments by Baillargeon (after Baillargeon, Spelke, & Wasserman, 1985).

methods can be used to assess infants' reactions to events in which objects undergo anomalous motions. When infants are presented with test events that contrast superficial novelty (a new but possible motion) with novelty of a deeper kind (a familiar but impossible motion), infants appear to respond primarily to the deeper novelty if they are able to detect it. Baillargeon's experiments also provide evidence in support of one aspect of the active representations thesis: Young infants can represent an object that they no longer perceive. Infants respond with heightened attention to an impossible visible motion even when recognition of the impossibility of the motion depends on representing the existence, location, and properties of a hidden object.

Further evidence for young infants' representational capacity comes from an experiment using a preferential looking method to assess infants' apprehension of object persistence during a simpler event (Craton & Yonas, 1990). Four-month-old infants were presented with a disk that moved repeatedly in and out of view behind a screen. The motion was such that the disk was fully visible (and fully invisible) only briefly; during most of the event, it was partly visible behind a straight vertical edge of the screen. After habituation to this event, infants were presented with two fully visible objects: a full disk and a truncated disk corresponding to the visible surface of the disk when it was half occluded. Although the half-sphere should have been more familiar to an infant who perceived only the disk's visible surfaces, infants generalized habituation to the complete disk. The experiment provides evidence that the infants perceived a persisting, complete object over this occlusion event. Evidence that young infants perceive persisting objects over occlusion also comes from other studies using preferential looking methods

(Baillargeon & Graber, 1987; Spelke & Kestenbaum, 1986; but see also Arterberry, 1989) and from studies assessing infants' reaching for objects in the dark (Clifton, Rochat, Litovsky, & Perris, 1991; Wishart, Bower, & Dunkeld, 1978).

Although these experiments provide evidence that infants represent objects that are no longer available to be perceived, they do not reveal whether infants operate on such representations so as to derive new information about the objects. Two further experiments by Baillargeon (1986; Baillargeon, Graber, DeVos, & Black, 1990) addressed the latter question. In these experiments, an object was hidden, and then further events occurred behind the screen that were either possible or impossible given certain limitations on the object's behavior. Looking time was recorded throughout these partly hidden events on the assumption that infants would look longer at the impossible events if they could reconstruct the parts of the events that were hidden.

Baillargeon (1986) presented 6- to 8-month-old infants with repeating events in which one object rolled behind a screen that hid a second, stationary object, and then the first object reappeared at the far side of the screen. In one condition, the stationary object was placed within the display such that the moving object could move freely behind the screen on the shortest-distance path. In the other condition, the stationary object was positioned within the display so as to block that path of motion: The moving object could traverse the display only by jumping discontinuously over, passing through, or turning to detour around the stationary object. Infants looked longer at the latter event. The experiment suggests that the infants made definite inferences about the path that the hidden object would follow.

Baillargeon et al. (1990) presented 5½-month-old infants with repeating events in which a stationary object was hidden behind a screen and then was retrieved by a hand that reached behind the screen. In different conditions, the retrieval appeared to be either possible or impossible given the kinds of objects involved. For example, the object might be retrieved from within a hidden, open cup (possible, on the assumption that the cup contained but was not attached to the object) or from within a hidden, transparent container (impossible, on the assumption that the container could not be opened). Infants looked longer at the hiding-and-retrieval events in which the retrieval was impossible. These findings suggest that the infants had considerable understanding of the types of manipulations that could or could not be performed on the different types of objects.

The last two experiments provide evidence that infants operate on representations of hidden objects so as to make inferences about the kinds of events in which the objects can participate. The experiments also may provide evidence concerning the constraints on object motion that infants understand. Because of the number and complexity of the constraints that could guide infants' reasoning in those experiments, however, we suggest that further research on the constraints appreciated by infants is needed. The present research was undertaken, in part, for this purpose.

Overview of the Experiments

In the experiments reported here we used a new preferential looking technique devised to capture what we believe is central to Piaget's most important object search task: the "invisible displacement" task. In the task used by Piaget to test infants' representational and reasoning capacities, an object moved out of view and then underwent some further displacement. The invisible displacement of the object was such that the object could not be found by engaging in a habitual action or by responding to a perceptually familiar position. Direct and appropriate search for the object provided evidence that the child had operated on his or her representation of the hidden array so as to infer the object's subsequent location.

Like Piaget's studies, our experiments presented infants with a situation in which an object moved out of view and then came to rest in a position that was not visible but that could be inferred from knowledge of constraints on object motion. Unlike Piaget's studies, our experiments used a habituation-of-looking-time method. Infants were presented repeatedly with an event in which an object moved behind a screen, and then the screen was raised to reveal the object at rest in a position that was consistent with all constraints on object motion. Looking time was measured only after the object appeared at its final position; the event was repeated until looking time to the event outcome declined. Then the display was modified, the object was again moved out of view, and the screen was raised to reveal the object, on alternating trials, at two different positions. One position was new but consistent with all constraints on object motion. The other position was familiar but inconsistent with one or more constraints. Looking times again were measured only after the screen was raised and the outcome displays appeared. These looking times were compared to the looking

times of infants in a control condition, who viewed the same habituation and test outcome displays as in the experimental condition. In the control condition, however, each outcome display was preceded by an event that was consistent with all constraints on object motion.

Because the infants in the experimental and control conditions viewed exactly the same displays throughout the time that their looking was recorded, any reactions to attractive or novel perceptible features of these displays should be equivalent across the two conditions. The critical measure in each experiment is the difference, between the two conditions, in looking preferences between the test outcome displays. If infants are able to represent the existence and motion of a hidden object, and if they infer that the object will move in accord with the constraints that were violated in the inconsistent event, then the infants in the experimental condition should show a greater looking preference for the inconsistent outcome display over the consistent outcome display than those in the control condition.

In the first three experiments we investigated whether 4- and 2½-month-old infants reason about hidden object displacements in accord with the constraints of continuity and solidity. After presentation of these experiments and discussion of some of the interpretive questions they raise, we present two further experiments in which we investigated whether 4- and 3-month-old infants reason about hidden object motion in accord with the constraints of gravity and inertia.

Experiment 1

In Experiment 1 we investigated whether young infants infer that an object that falls from view will continue to move on a connected, unobstructed path. The subjects in the experiment were 4 months old: just below the age at which infants begin to reach for visible objects. Infants in the experimental condition were presented with events in which an object fell behind a screen and then either appeared to land on, or appeared to pass through or jump over, the first surface in its path. If prereaching infants reason about object motion in accord with the continuity and solidity constraints, then they should regard the outcome of the latter event as novel or surprising.

Infants in the experimental condition were familiarized with an event in which a ball fell behind a screen on an empty stage (Figure 2). The screen was raised 2 s later to reveal the ball on the display floor: a position consistent with all constraints on object motion. Looking time to the display was recorded after the screen was raised, beginning with the first look at the ball and ending when the infant looked away from the display. Finally, a hand entered the display and removed the ball. This event was presented repeatedly until an infant's looking time declined to a criterion of habituation (described further on).

The test sequence followed. A second horizontal surface was introduced into the display, directly above the floor. Then the screen was lowered to cover both surfaces, and the ball was dropped as before. On alternating trials, the screen was raised to reveal the ball either on the upper surface or on the lower surface. The former position was superficially novel but consistent with the continuity and solidity constraints. The latter position was superficially familiar but violated the continuity and
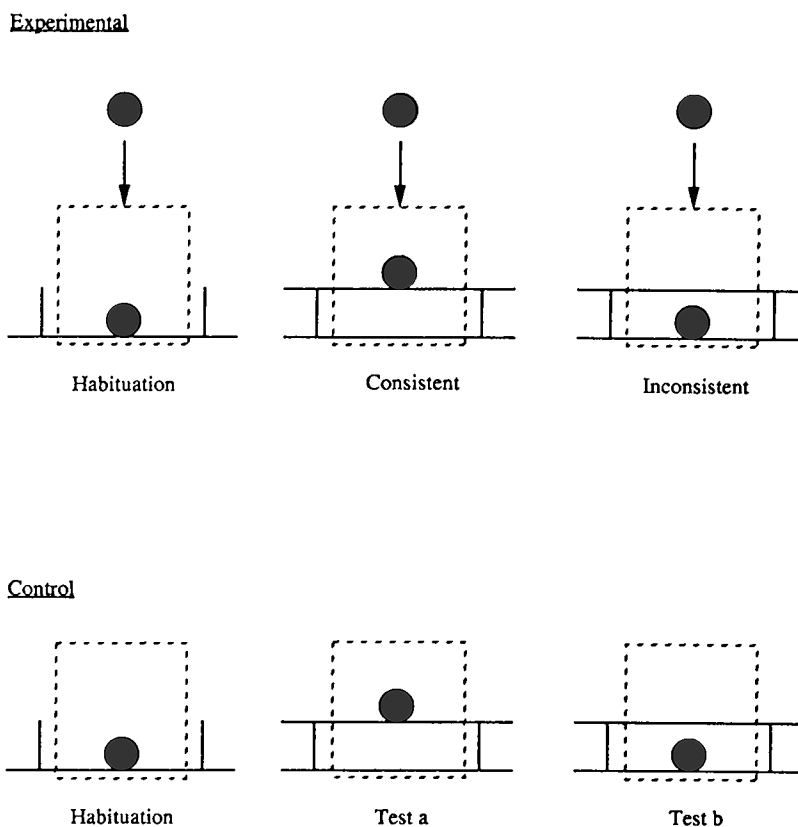
Figure 2. Schematic depiction of the events from Experiment 1. (Circles indicate the initial and final positions of the ball. Arrows depict the path of visible motion of the ball in the experimental condition events. [In the control events, the ball was moved forward in depth.] Dotted lines depict the position of the screen when it was lowered into the display.)

solidity constraints: Because the upper surface completely bisected the display, the falling ball could arrive at the display floor only if it either passed through the upper surface (in violation of the solidity constraint) or jumped discontinuously over it (in violation of the continuity constraint). Adult subjects judged that the familiarization event and the consistent test event were natural and expected but that the inconsistent test event was unnatural and unexpected (see Appendix). Looking times on each test trial were recorded after the screen was raised, beginning with the first look to either of the two object positions and ending when the infant looked away from the display.

The test trial looking times of infants in the experimental condition were compared with the looking times of infants in a control condition. In the control condition, infants were presented with familiarization and test events in which the ball was moved forward in depth to its final position, the screen was lowered for 2 s and then raised, and looking time was recorded. These events presented infants with displays that were identical to those of the experimental condition during, and for 2 s preceding, the time that the infants' looking was recorded. In all trials of the control condition, however, the final position of the ball was consistent with constraints on object motion. If infants represent hidden objects and reason about their motions in

accord with the continuity and solidity constraints, then the subjects in the experimental condition should look longer when the ball reappears on the display floor than when it reappears on the table, relative to those in the control condition. If infants do not represent and reason about hidden object motion in accord with the continuity or solidity constraints, then the infants in both conditions should show the same looking preference between the two test outcomes.

Method

Subjects. Participants were 24 infants ranging in age from 3 months, 14 days to 4 months, 19 days (M = 4 months, 0 days). An additional 6 infants were eliminated from the sample because of fussiness (4), falling asleep (1), or experimenter error (1). The 10 girls and 14 boys in the final sample were born of full-term pregnancies, had no known or suspected abnormalities, and lived in or near Ithaca, NY.

Apparatus. The events took place on an 81 × 102 × 15 cm rectangular puppet stage with white walls and a red floor. A blue surface of the same dimensions as the floor could also be positioned in the display horizontally, 15 cm above the floor. A 33 × 38 cm white screen, suspended immediately in front of the stage by monofilament lines, could be lowered to cover the lower central portion of the display. The display was illuminated by vertical fluorescent lights at its two sides, 40 cm in front of the stage and concealed from the baby by a white casing.

The events involved a yellow, foam-rubber, 10-cm-diameter ball. Curtained openings in the back wall of the stage permitted the display presenter, who stood behind the stage, to introduce the hand-held ball at positions 71 cm, 22 cm, and 7 cm above the floor of the display. A 3-cm hole at the top of the back wall of the stage permitted the presenter to observe the infant throughout the study. The infant viewed the display from a reclinable seat surrounded by curtains. Small holes in the curtains to the left and right of the display permitted two observers to view the infant's head and eyes without seeing the displays. At the infant's viewing distance (about 40 cm), the ball subtended about 1° in the infant's visual field. In the experimental condition, the ball's average velocity during the visible portion of its fall (a 33-cm distance) was 121 cm (128°)/s. All the events were silent. The events are described in detail in the *Procedure* section.

Design. Equal numbers of subjects were assigned to the experimental and control conditions so as to balance the sex ratios and the age distributions of the conditions. The two test events were presented to each subject on six alternating trials, with the order of trials counterbalanced across the subjects in each condition.

Procedure. At the start of the study, a subject was placed in the infant seat facing the empty stage. The display presenter appeared to the left of the stage, greeted the baby, and tapped on the red surface from left to right until the infant had looked at the entire display floor. Then the presenter disappeared behind the display, where she watched the baby continuously through the peephole. In the experimental condition, she lowered the screen and presented the ball in her right hand through the top opening in the display while introducing her left hand through the bottom opening behind the screen. The presenter waved the ball and called to the baby, if necessary, to elicit his or her attention. When she judged that the baby had looked at the ball steadily for approximately 1 s, she released the ball, removed her right hand as the ball fell behind the screen, caught the ball behind the screen with her unseen left hand, placed the ball in the center of the display floor, and removed her left hand. In the control condition, the screen was left in its raised position while the display presenter introduced the ball through the lowest opening in the back of the display. She waved the ball and called to the baby until the baby looked at the ball steadily for about 1 s. Then she moved the ball forward, placed it on the display floor, released it, and immediately lowered the screen.

In both conditions, the presenter raised the screen approximately 2 s after the ball disappeared behind it. When the screen was raised, she signaled the observers and the recording of looking time began. An observer began to record looking time when he or she judged that the infant first looked at the ball; thereafter, the observer recorded all looking to any part of the display within 6 cm of the path the ball followed in the experimental condition. The observers worked independently, each operating a push-button input to a microprocessor. Except for purposes of computing the interobserver reliability (see further on), the microprocessor recorded data only from the more experienced ("primary") observer. It signaled the end of the trial with a tone, after the infant had looked at the display for at least 0.5 s cumulatively and then had looked away from the display area for 2 s continuously, or after the infant had looked at the display for 120 s (whichever came first). After the tone, the presenter's right hand entered the display through the bottom window, picked up the ball and waved it, and removed the ball as the baby watched it. Then the event was repeated.

Familiarization trials continued until 14 trials were presented or until a criterial decline in looking time occurred, whichever came first. The criterion was a 50% decrease in total looking time on three consecutive trials, relative to the first three consecutive trials on which total looking time exceeded 12 s (usually the first three trials). The microprocessor calculated the criterion from the input of the primary observer, and it signaled the end of the familiarization sequence with a second tone.

After the last familiarization trial, the presenter reappeared to the left of the stage and introduced the blue surface into the display. She tapped elaborately on both surfaces until the infant had looked across each of them. Then she disappeared behind the display and presented the test sequence. In the experimental condition, she lowered the screen and placed the ball in its final position behind the screen, either on the upper surface (consistent trials) or on the lower surface (inconsistent trials). Then she presented a second, identical-looking ball above the screen, released it exactly as on the familiarization trials, and caught and removed the ball behind the screen. All of her actions occurred silently. In the control condition, the presenter either introduced the ball through the central hole and placed it on the upper surface, or she introduced the ball through the lower hole and placed it on the floor. The ball was moved exactly as on the familiarization trials; its placement was followed immediately by the lowering of the screen.

In both conditions, the presenter raised the screen approximately 2 s after the disappearance of the ball and signaled the observers to record looking time. Looking time began to be recorded when an observer judged that the infant first looked at either of the two positions that the ball could occupy. (The observers were blind to the position of the ball on any given test trial.) The test trial procedure was otherwise the same as the procedure for the familiarization trials. Interobserver agreement (the proportion of seconds, computed over all habituation and test trials, during which both observers judged that the infant was or was not looking at the display) averaged .80.

Analysis. Across the five experiments to be reported, the present method has been found to produce looking times with highly irregular distributions. Because these distributions violate the assumptions of general linear models (Darlington, 1990), nonparametric statistics were used as the principal analysis in all of the experiments. For each subject, the sum of the three looking times at the upper-surface test outcome was subtracted from the sum of the three looking times at the lower-surface test outcome. For the infants in the experimental condition, this difference score served as a measure of an infant's preferential looking to the inconsistent outcome. The experimental group's preference was compared with that of the control group by a one-tailed Wilcoxon-Mann-Whitney signed-ranks test (Siegel & Castellan, 1988). As a subsidiary analysis, looking times on the six test trials were subjected to a $2 \times 2 \times 2 \times 3$ mixed-factor analysis of variance (ANOVA) with condition (experimental vs. control) and test trial order (ball on upper surface first vs. ball on lower surface first) as the between-subjects factors and test event (ball on upper surface vs. ball on lower surface) and trial pair as the within-subjects factors. This analysis served to test for other effects and interactions beyond those on which we focus. Its results may be overly conservative, however, and should be viewed with caution.

Results

On the first three habituation trials, looking time averaged 4.7 s per trial in the experimental condition and 4.8 s per trial in the control condition. The infants in the two conditions received an average of 9 and 10 familiarization trials, respectively. Nine subjects, 3 in the experimental condition, did not meet the criterion of habituation.[4]

Figure 3 presents the mean looking times during the last six habituation trials and the six test trials. The infants in the experimental condition tended to look longer at the outcome of the

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[4] In this and in subsequent studies, the test trial looking patterns of the nonhabituators did not differ from those of the habituators. The looking patterns of all subjects were analyzed together.
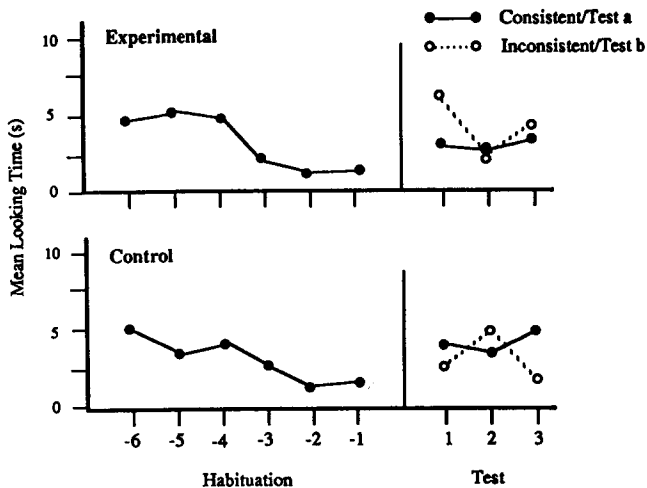
Figure 3. Mean looking times at the event outcomes during the last six habituation trials and the six test trials for the experimental and control conditions of Experiment 1.

inconsistent test event, in which the ball appeared on the lower surface. In contrast, the infants in the control condition showed no preference between the two test outcomes. This difference in preferences across the two conditions was significant by the Wilcoxon-Mann-Whitney test, $z = 1.82$, $p < .05$. In the ANOVA, this effect appeared as a significant Condition × Test Event interaction, $F(1, 20) = 5.90$, $p < .025$. The only other significant effect in the ANOVA was a triple interaction of condition, test event, and test trial order, $F(1, 20) = 12.62$, $p < .005$. Whereas infants in the experimental condition looked longer at the inconsistent event irrespective of the order of the two events, infants in the control condition tended to look longer at whichever test event was presented first.[5]

Discussion

When an object fell behind a screen, 4-month-old infants looked longer if the object reappeared on the lower of two surfaces in its path than if it reappeared on the upper surface. This looking preference was not shown by the infants in the control condition, who viewed the same outcome displays: It evidently did not stem either from an intrinsic preference for the display in which the object reappeared on the lower surface or from generalization on superficial grounds from the habituation display to the consistent test display. It appears, therefore, that infants in the experimental condition responded to the consistency or inconsistency of the falling object's final position. Because the ball could only reach the lower surface by passing through or jumping discontinuously over the upper surface, the looking preference in the experimental condition suggests that infants inferred that the ball would move on a connected, unobstructed path.

Two alternative interpretations of the present findings nevertheless may be offered. First, infants in the experimental condition might have looked longer at the display that ended the inconsistent test event because of a superficial preference for

that display induced by the prior context of observing the ball's motion. Suppose, for example, that infants tended to explore the displays by scanning between the ball's final position and its initial position. In the experimental condition, infants might have explored the inconsistent test display longer because the initial and final positions in that display were separated by a greater distance and by a novel surface. No such preference would be expected in the control condition, because the ball's initial and final positions were equally far apart during the two test events.

Second, infants in the experimental condition might have looked longer at the end of the inconsistent test event because they encountered the object in the position they *expected* it to occupy. The infants in this experiment might have expected the object to land on the lower surface because it had landed in that position in the past (see Harris, 1987; Piaget, 1954). Infants might look longer when an object reappears at an expected position, because they are led by their expectations to look in the appropriate direction (see Haith, Hazan, & Goodman, 1988) or because the confirmation of an expectation induces a more positive and attentive state.

Experiment 2

Experiment 2 was undertaken to test these alternative interpretations of Experiment 1. The events (Figure 4) involved a ball that moved behind a screen and landed on a continuous surface, below an upper surface with a gap. In the experimental condition, infants were familiarized with a ball that was slightly smaller than the gap in the upper surface: It fell behind the screen and reappeared on the floor of the display, as if it had passed through the gap. Then the infants were tested with the same event, produced with balls of two novel sizes. The consistent test event involved a smaller ball that also could fit through the gap in the upper surface, whereas the inconsistent test event involved a larger ball that could not fit through the gap. Although the familiarization and consistent test events accorded with all constraints on object motion, the inconsistent event failed to accord with the continuity and solidity constraints. If the large ball was rigid (see further on), it could only reappear on the lower surface by jumping discontinuously over, or by passing through, part of the upper surface. Adults rated the familiarization and consistent test events as natural and expected and the inconsistent test event as unnatural and unexpected, in accord with the continuity and solidity constraints (see Appendix).

Infants' looking times at the ends of the test events were compared to the looking times of infants in a control condition similar to that of Experiment 1: Each ball was introduced into the back of the display below the upper surface and was waved, moved forward in depth, and placed in its final position below the gap as the screen was lowered. When the screen was raised,

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[5] Of the 6 subjects who were eliminated from the sample, 2 subjects provided data on at least one pair of test trials. (For the remaining 4 subjects, the experiment was terminated before the test sequence began.) An analysis including the data from these 2 subjects showed the same effect of condition on looking preferences, Wilcoxon-Mann-Whitney $z = 1.90$, $p < .05$.
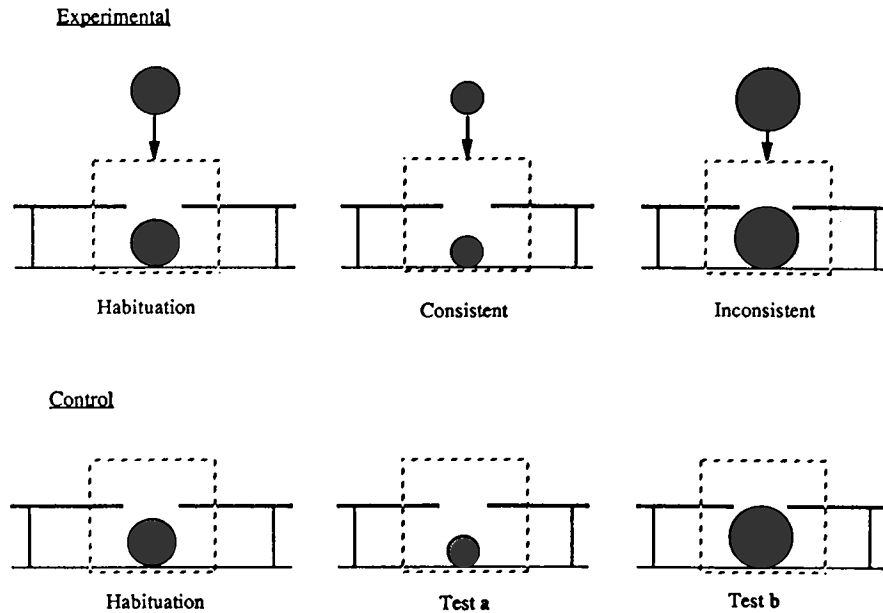
Figure 4. Schematic depiction of the events from Experiment 2.

the infants in the control condition viewed the same test displays as those in the experimental condition. Comparisons across the two conditions therefore serve to assess infants' reactions to the event outcomes independently of any differences in the intrinsic attractiveness or novelty of the two outcomes.

The events in the experimental condition of this study were designed to neutralize any context effects on infants' looking preferences. In all three events, the ball began in the same position, fell on the same path, and was revealed in the same place within the same arrangement of surfaces. Thus, every aspect of the visible and the implied motion of the ball was the same in the two test events, with one exception: The larger ball's motion violated the solidity and continuity constraints because the ball was too large to pass through the hidden gap in its path.

The events of Experiment 2 also were designed to distinguish between preference-for-novelty and preference-for-expectedness interpretations of infants' looking time. If infants fail to infer that the test objects will move in accord with the solidity and continuity constraints, then both test events should be equally expected (because both test objects reappear in the familiar position) or unexpected (because both test objects are new). In either case, the infants in the experimental and control conditions should show the same looking preference between the two test events. In contrast, if infants infer that the larger test object will not pass through or jump discontinuously over the surfaces in its path, then the direction of preference between the two test events will depend on whether infants tend to look longer at events whose outcomes are consistent or inconsistent with their inferences. If infants tend to look longer at consistent outcomes, then the infants in the experimental condition should look longer at the end of the event involving the small ball, relative to the infants in the control condition. If infants tend to look longer at inconsistent outcomes, then the

infants in the experimental condition should look longer at the end of the event involving the large ball, relative to controls.

Method

The method was the same as that of Experiment 1, except as follows.

Subjects. Participants were 24 infants (15 boys and 9 girls) ranging in age from 3 months, 16 days to 4 months, 12 days (M = 4 months, 0 days). Four additional subjects were eliminated from the sample because of fussiness (2), vision problems (1), or experimenter error (1).

Apparatus. The display was similar to that of Experiment 1, except for the upper surface and the objects. The blue upper surface was 4 cm thick, had an 11-cm gap in its center, and remained in the display throughout the study. The object used in the familiarization event was a green ball 10 cm (1 1°) in diameter. The smaller test object was a bright yellow ball 6 cm (7°) in diameter. The larger test object was a dull blue ball 17 cm (19°) in diameter.[6] All of the balls were made of foam rubber and moved silently.

Procedure. At the start of the study, the presenter tapped across the display floor and across each side of the upper surface, and she moved her hand through the gap in the upper surface, until the infant had looked at all of these parts of the display. These actions were repeated before the start of the test sequence. Each event in the experimental condition followed the procedure for the inconsistent test event of the experimental condition of Experiment 1. Each event in the control condition followed the procedure of the lower-surface test event in the

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[6] Pilot experiments with objects of these colors had suggested that a bright yellow ball was more attractive to infants than a dull blue ball. These colors were chosen in the hope that the more attractive color of the yellow ball would compensate for its smaller size and neutralize baseline preferences between the objects. In fact, the looking preferences exhibited in the control condition suggest an overcompensation: a marginally significant preference for the event outcome with the small yellow ball, $p < .10$ (binomial test).

control condition of Experiment 1. Interobserver agreement averaged .84.

Because preference-for-inconsistency and preference-for-consistency interpretations yield opposing predictions about the direction of looking preferences in this study, a two-tailed Wilcoxon-Mann-Whitney test was performed.

Results

On the first three habituation trials, looking time per trial averaged 6.0 s in the experimental condition and 7.7 s in the control condition. The number of familiarization trials averaged 10 in each condition. Four subjects in each condition failed to meet the habituation criterion and were tested after 14 familiarization trials.

Figure 5 depicts the principal findings. During the test, the infants in the experimental condition looked longer at the end of the event with the large ball; the infants in the control condition showed the reverse preference. The difference in looking preferences between the two conditions was significant by the Wilcoxon-Mann-Whitney test, $z = 3.03$, $p < .005$. It produced the only significant effect in the ANOVA: a Condition $\times$ Test Event interaction, $F(1, 20) = 6.14$, $p < .025$.[7]

Discussion

When a ball fell behind a screen toward a surface with a gap and then was revealed on the far side of the gap, infants looked longer at the final display if the ball was larger than the gap than if it was smaller than the gap. This looking preference differed from the preference shown by infants in the control condition, who were familiarized and tested with the same outcome displays. Thus, it did not reflect any intrinsic preference for the larger ball or any perception of greater similarity between the small ball and the ball presented for familiarization.

The experimental group's longer looking at the outcome of the inconsistent test event did not reflect any contextually induced, superficial preference for that outcome, because the initial positions, visible motions, and final positions of the balls in the two test events were the same. Furthermore, the experimental group's looking preference did not reflect an expectation that objects will appear in places that they have occupied in the past. If infants had such an expectation, then the outcomes of the two test events should have been equally expected, because the final object position in the two test events was the same. Finally, the looking preference in the experimental condition did not reflect any tendency for infants to look longer at consistent or expected events. If infants had such a tendency, they should have shown either the opposite preference (if infants infer that hidden objects will move on connected, unobstructed paths) or no preference (if infants do not make this inference).

Experiment 2 thus provides evidence that the infants inferred that only the smaller test object would appear below the gap, in accord with the solidity and continuity constraints. They looked longer at the test event involving the large ball, because that event failed to accord with their inferences about object motion. This conclusion, in turn, supports the present interpretation of looking patterns in experiments using the invisible
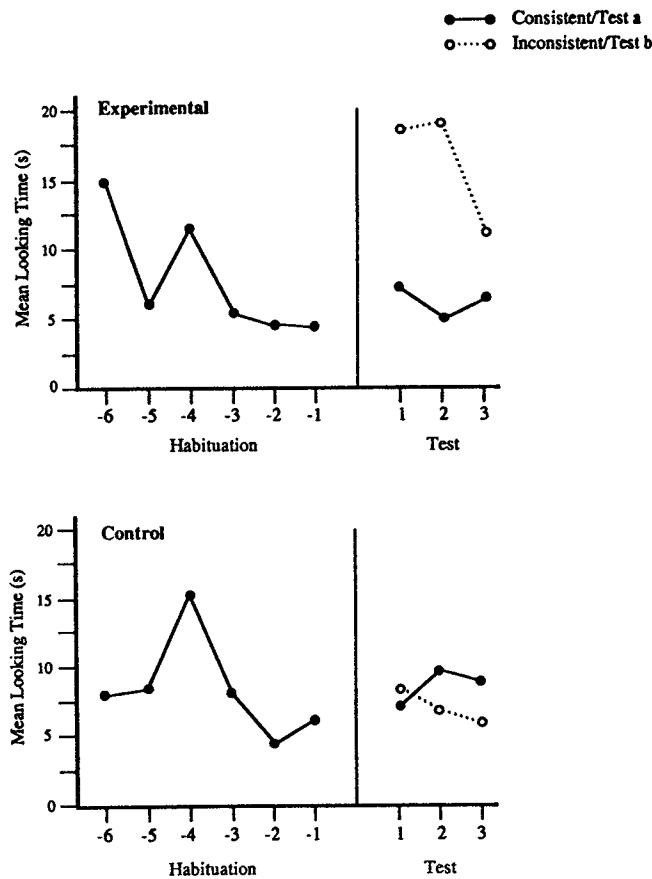

Figure 5. Mean looking times at the event outcomes during the last six habituation trials and the six test trials for the experimental and control conditions of Experiment 2.

displacement, preferential looking method. Visual preferences serve to assess infants' inferences about a hidden object's motion in the present situation, just as they serve to assess infants' representations of hidden objects in Baillargeon's experiments.

Experiment 2 provides further evidence concerning 4-month-old infants' cognitive abilities. First, infants evidently represent not only the existence of hidden objects and surfaces but metric properties of objects and surfaces. In Experiment 2, inferences about the occluded object's motion depended on infants' representation of the size of the object relative to the size of the gap in the surface in its path: Only the relative sizes of the objects distinguished the consistent and inconsistent test events. Second, infants evidently infer that *no part of* an object will pass through or jump discontinuously over a surface. In the inconsistent event, only the sides of the object were blocked by the hidden surface. Third, infants evidently infer that a hidden object will maintain a constant size and shape as it moves. If the

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[7] Three of the 4 subjects eliminated from the sample provided data in at least one pair of trials. An analysis including their data showed the same effect of condition on looking preferences, Wilcoxon-Mann-Whitney $z = 2.69$, $p < .005$.

objects in this experiment could have shrunk or deformed spontaneously, then the large object could have reduced its width and moved through the gap on a connected, unobstructed path. The thesis that infants represent the size of hidden objects and infer that hidden objects will move rigidly, maintaining a constant size and shape, is supported by the findings of experiments by Baillargeon (1987b, 1989; Baillargeon & Graber, 1987). In the absence of information to the contrary, the 4- to 7-month-old infants in Baillargeon's experiments inferred that a stationary or moving object would maintain a constant height while it was hidden and that a stationary, rigid object would not deform when a second object contacted it.

An alternative interpretation of the findings of Experiments 1 and 2 nevertheless remains. In the control conditions of these experiments, infants observed the object as it was placed in its final position, just before the screen was lowered and raised and the trial began. Although the screen began to be lowered as the ball was placed in that position, infants saw the ball in its final position for nearly 1 s prior to each test trial. The outcome displays presented to the two groups of infants, therefore, were not equally familiar to them. Whereas the infants in the experimental condition viewed each display for the first time when the first test trial began, those in the control condition had viewed each display previously for up to 1 s, immediately prior to the test trial.

How might this additional familiarization time have affected infants' looking times? One plausible assumption is that for the infants in the control condition, the actual looking times to the test displays were 1 s lower than they would have been if the infants had not already viewed the test displays for that amount of time. If this assumption is correct, then a better measure of looking time to the test displays, for infants in the control condition, would increment their looking times on each test trial by 1 s. This new measure does not change the principal analysis of each experiment, which is based on the difference in looking times to the two outcome displays. The new measure does affect the subsidiary ANOVA, which is based on the actual test trial looking times. Accordingly, new ANOVAs were performed for Experiments 1 and 2, based on the original looking time data from infants in the experimental condition and the new, 1-s incremented looking time data from the infants in the control condition. The results of the new analyses were the same as the results of the original analysis. In particular, the Condition × Test Display interaction was significant both for Experiment 1, $F(1, 20) = 5.90$, $p < .025$, and for Experiment 2, $F(1, 20) = 6.15$, $p < .025$.

One could argue, however, that the 1-s pretrial exposure to the objects' final position had a disproportionate effect on the novelty preferences of infants in the control condition, introducing artifactual differences in preference between the two conditions. This possibility is best addressed by further research, in which infants in the experimental and control conditions view the test displays for the first time when the screen is raised. In the next experiment we used this procedure.

Experiment 3

In Experiment 3 we investigated the earlier development of knowledge of the continuity and solidity constraints. Younger infants were studied in order to shed light on the question of how infants develop knowledge of these constraints. The findings of Experiments 1 and 2 cast doubt on the thesis that physical knowledge develops from object manipulation, because 4-month-old infants cannot reach for objects effectively or manipulate them systematically. Nevertheless, 4-month-old infants engage in one exploratory activity that might serve as a basis for the development of physical knowledge. At about 3 months of age, infants begin to look systematically at their own hands (see Piaget, 1952). It is possible that humans learn about object motion by moving a hand as they watch it, observing properties of its visible and felt motion. Infants might learn in this manner that a hand's path of motion is continuous and that a hand never moves through a solid object. To address this possibility, we conducted Experiment 3 with infants just under 3 months of age.

The events of Experiment 3 were modified to accommodate younger infants' more limited ability to follow moving objects (Figure 6). Infants were presented with a ball that rolled slowly on a horizontal surface. In the experimental condition, a screen was lowered over the right side of the display, the ball appeared on the left and moved rightward behind the screen, and the screen was raised to reveal the ball at rest at the display's right wall. For the test, an obstacle was introduced so as to block any possible path of the ball's hidden motion, the ball rolled behind the screen as before, and the screen was raised to reveal the ball either at a new position against the obstacle (consistent) or at its old position against the wall (inconsistent). Adults judged that the familiarization and consistent test events were natural and expected and that the inconsistent test event was unnatural and unexpected (see Appendix).

Looking times were recorded as in the previous experiments. The test trial looking times in the experimental condition were compared with the test trial looking times of infants in a control condition, who viewed the same outcome displays as in the experimental condition. In the control condition, these outcome displays followed events in which the hand-held ball was lowered vertically and disappeared behind the top of the screen directly above its final position. Thus the infants in each condition viewed the test displays for the first time when the screen was raised. If young infants infer the final position of a hidden, moving object in accord with the continuity and solidity constraints, then infants in the experimental condition should look longer at the end of the test event in which the ball appears against the far wall, relative to infants in the control condition.

A further purpose of Experiment 3 was to compare the reactions of infants with the reactions of adults. Accordingly, the experimental condition of Experiment 3 was also conducted with a group of adult subjects.

Method

The method was the same as that in Experiment 1, except as follows.

Subjects. Participants were 18 female and 14 male infants ranging in age from 2 months, 9 days to 2 months, 28 days ($M = 2$ months, 19 days). Eight additional infants were eliminated from the experiment because of fussiness (5) or experimenter error (3). For the study with adults, participants were 12 college students or staff members, aged 16–52 years. One additional subject was eliminated from the adult sample because of experimenter error.
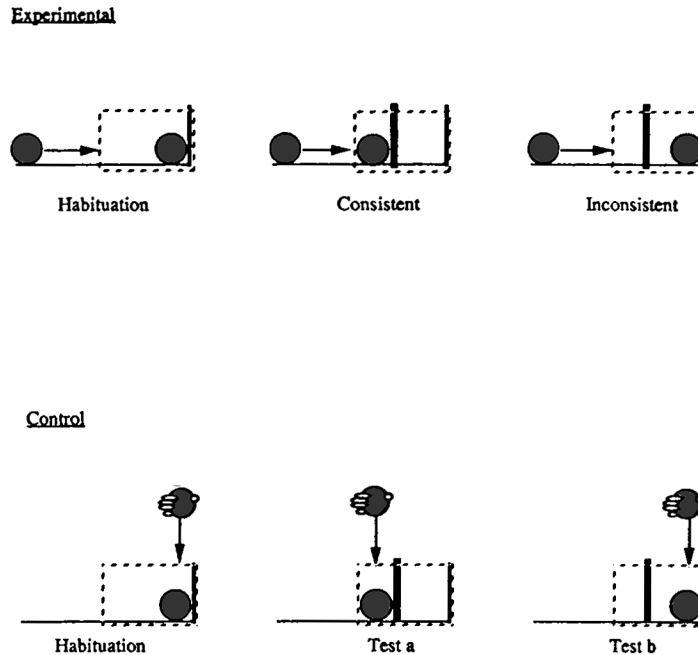
Experimental

Habituation   Consistent   Inconsistent

Control

Habituation   Test a   Test b

Figure 6. Schematic depiction of the events from Experiment 3.

Apparatus. The display consisted of an 82 × 37 × 24 cm red horizontal platform. Two glass rods running the length of the top of the platform served as a track that guided the motion of the ball. At the right side of the platform was an 18 × 3 × 24 cm bright blue wall. A 31 × 4 × 24 cm blue box (the "obstacle") could be placed on the platform, 20 cm to the left of the wall. A white, 56-cm-high screen could be lowered over the right side of the display, covering the right half of the platform and all but the top 12 cm of the obstacle. The screen was 40 cm wide for the familiarization trials and 50 cm wide for the test trials.

The moving object was the ball from Experiment 1, covered with a symmetrical pattern of red, blue, and green polka dots. In the experimental condition, the ball was tapped by a hand so that it rolled on the platform from left to right. Its speed was somewhat variable but averaged 27 cm (30°)/s. In the control condition, the ball moved vertically: It was held by a hand and lowered onto the surface at about the same rate as in the experimental condition. The ball was introduced and moved through 11 × 32 cm curtained openings in the back of the display, to the left of the wall and the obstacle.

Infants were tested in the same position as in the previous studies, in a seat fitted with a three-sided pillow to support their heads and center their bodies in front of the display. The infant seat was removed for the adult subjects, who observed the display from a crouched position on the table at the infants' station point.

Design. A pilot experiment suggested that looking times were more variable at 2½ months of age. Accordingly, 16 infants were observed in each condition of the experiment, experimental and control. Twelve adults participated in the experimental condition only. The order of test trials was counterbalanced across the subjects in each condition.

Procedure. At the start of the experiment with infants, the display presenter appeared to the left of the display, spoke to the infant, and tapped his hand across the floor of the platform and the left side of the wall until the infant had looked across the display. Then he disappeared behind the stage and lowered the screen. In the experimental condition, he introduced the ball, held by his right hand, through the curtain at the left side of the stage, while placing his left hand through the rightmost opening in the stage behind the screen. He waved the

ball and called to the baby, as necessary, until he judged that the baby had looked at the ball steadily for 1 s. Then he placed the ball on the glass track, struck it gently with his hand, and removed that hand while the ball rolled on the track behind the screen. The presenter caught the ball with his left hand, positioned it on the track next to the wall, and removed that hand. In the control condition, the presenter introduced the ball above the screen through the top of the rightmost opening in the display. He waved the ball and called to the baby until the baby looked at the ball for 1 s, and then he lowered the ball behind the screen by moving his hand down the rectangular opening, placed the ball at the end of the track next to the wall, and removed his hand. The events were silent in both conditions, and the ball was hidden for approximately 2 s. Next, the presenter raised the screen and the observers began to record looking time. At the end of the trial, the presenter's hand entered the display through the opening behind the ball, waved the ball until the infant looked at it, and removed the ball.

After the last familiarization trial, the presenter reappeared to the left of the display and positioned the obstacle on the display floor. He tapped on the platform, the left side of the obstacle, and the left side of the wall until the infant had looked across each surface. Then he disappeared behind the display, lowered the screen, and presented the test sequence. In the experimental condition, he placed the ball in its final position behind the screen, either next to the obstacle (consistent event) or next to the wall (inconsistent event). Then he introduced a second ball, of identical appearance, on the left as before, placed his other hand through the bottom of the central opening, out of sight behind the screen, set the ball in motion so that it rolled behind the screen, and then caught the ball and removed it. In the control condition, the presenter introduced the ball above the screen through the top of either the central opening or the rightmost opening and lowered the ball as before. The events taking place behind the screen were silent in both conditions. The presenter raised the screen approximately 2 s after the disappearance of the ball, and the observers began to record looking time. Interobserver agreement averaged .87.

Before the experiment with adults, subjects were read the following instructions: "The purpose of this study is to see how adults react to

some of the displays we present to infants. We will be showing you a few displays, and we want you just to look at them. When we are done, we will ask you some questions." During the study, the procedure was the same as for infants, except for the intonation of the display presenter, which was less inflected than his speech to infants. No explanations were given for the presence of the observers (whose eyes were visible through the peepholes) or other factors. If a subject asked any questions during the study, he or she was told that questions would be answered after all the events were presented. Interobserver agreement averaged .79.

Analyses. The 2½-month-old infants in this experiment showed longer looking times than their older counterparts in Experiments 1 and 2, and their looking times were positively skewed. In addition, significant numbers of infants became fussy before the end of the test sequence. To avoid replacing large numbers of subjects, we included any subject who received at least four test trials, eliminating Trial 5 if Trial 6 was not given. The differences in total looking times to the outcomes of the two test events over the four- or six-trial sequence were analyzed nonparametrically as in Experiment 1. Log-transformed total looking times also were submitted to a 2 (condition) × 2 (test order) × 2 (test event) ANOVA. A final nonparametric analysis compared the looking preferences of adults and infants in the experimental condition.

Results

On the first three habituation trials, looking time averaged 41.1 s in the experimental condition with infants, 29.4 s in the control condition with infants,[8] and 21.4 s in the experimental condition with adults. The mean numbers of familiarization trials were 9 (experimental condition, infants), 10 (control condition, infants), and 10 (experimental condition, adults). Four infants in the experimental condition, 5 infants in the control condition, and 4 adults failed to meet the criterion of habituation and were tested after 14 familiarization trials.

Figure 7 presents the findings of the experiment with infants. During the test, the infants in the experimental condition looked longer at the event outcome in which the ball appeared against the wall: the inconsistent event. The infants in the control condition did not show this preference. The difference in total looking times differed significantly across these two conditions, Wilcoxon-Mann-Whitney $z = 2.32$, $p < .02$. The ANOVA revealed both a main effect of test event, $F(1, 30) = 6.18$, $p < .02$, and an interaction of test event with condition, $F(1, 30) = 6.47$, $p < .02$. Infants looked longer in general when the ball appeared against the wall, but they did so significantly more when that position was inconsistent with the solidity and continuity constraints.[9]

Figure 8 presents the mean looking times on the last six habituation trials and the six test trials for the adults. The looking patterns are similar to those of the infants in the experimental condition: Adults looked longer at the inconsistent test outcome. The Wilcoxon-Mann-Whitney test revealed no age difference in the preference for the inconsistent event, $z < 1$.

Discussion

After observing a ball that rolled behind a screen toward a hidden obstacle, 2½-month-old infants looked longer at a display in which the ball appeared on the far side of the obstacle than at a display in which the ball appeared on the near side of
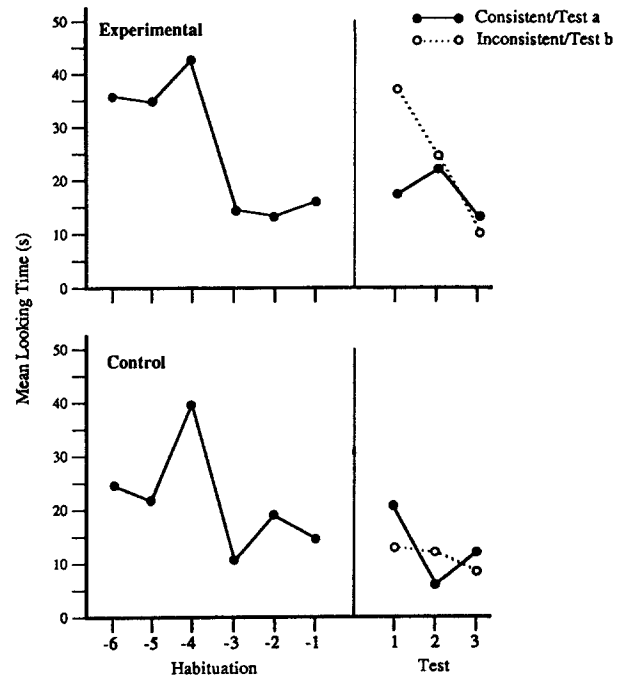

Figure 7. Mean looking times at the event outcomes during the last six habituation trials and the six test trials for infants in the experimental and control conditions of Experiment 3.

the obstacle. The findings of the control condition indicated that this preference did not stem from an intrinsic preference for the former display or from any superficial similarity of the inconsistent outcome display to the display presented for familiarization. The difference in preferences between the two groups also did not stem from differences in the familiarity of the two outcomes for the infants in the two conditions. The experiment provides evidence that the infants in the experimental condition inferred that the hidden ball would come to rest in front of the obstacle in its path: It would not pass through the obstacle or jump discontinuously from one side of the obstacle to the other. At 2½ to 3 months of age, reasoning about object motion appears to accord with the solidity and continuity constraints.

The experiment with adults suggests that looking patterns to the present event outcomes, assessed by the present methods, differ little between these two ages. Adults, like infants, appear to infer that an object will move on a connected, unobstructed path; they look longer when an object appears at a position that is inconsistent with this inference. Spontaneous comments by

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[8] What appears to be a large discrepancy between the two conditions was attributable to a small number of subjects: Four infants, 3 in the experimental condition, gave maximum looks of 120 s on at least one of the first 3 trials. Median looking times in the two conditions were 38.9 s (experimental) and 35.5 s (control).

[9] Four of the 8 subjects eliminated from the sample provided data on at least one pair of trials. An analysis including their data showed the same effect of condition on looking preferences, Wilcoxon-Mann-Whitney $z = 2.03$, $p < .025$.
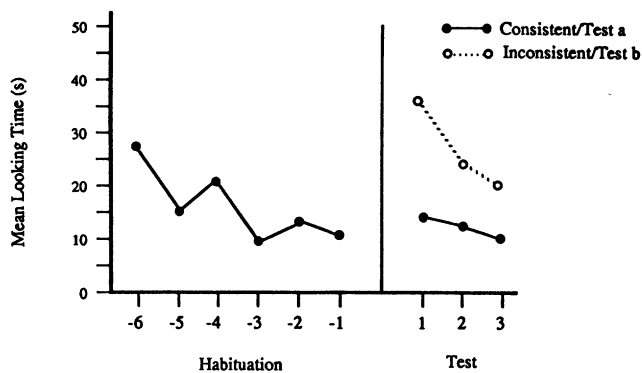
Figure 8. Adults' mean looking times at the event outcomes during the last six habituation trials and the six test trials of Experiment 3.

the adult subjects are consistent with this interpretation. It suggests that the "invisible displacement" preferential looking method can be used to investigate inferences about objects at a number of ages.[10]

The findings of Experiment 3 extend the findings of Experiments 1 and 2 in three respects. First, they provide evidence that the solidity and continuity constraints guide infants' inferences about the motions of objects in a variety of events. These constraints apply to objects that move slowly as well as rapidly, horizontally as well as vertically, on a surface as well as through the air, and toward a delimited object as well as toward an extended surface. Second, they provide evidence that these constraints guide inferences for adults as well as infants. Third, they provide evidence that sensitivity to object solidity and continuity develops at an early age. Before the end of the 3rd month, infants evidently infer that an object exists when it is out of view and that it moves only on a connected, unobstructed path.

Discussion of Experiments 1–3

In Experiments 1–3, young infants appeared to represent an object that moved from view and to infer that it would continue to move in accord with the continuity and solidity constraints. Evidence for this inference came from a comparison of infants' looking preferences between two test displays, across conditions in which only the events preceding those displays were varied. In each experiment, the infants in an experimental condition viewed event outcomes that were either consistent or inconsistent with the continuity and solidity constraints. The infants in a control condition viewed the same two outcome displays, both preceded by consistent events. In all three experiments, the infants in the experimental condition showed a preference for the inconsistent event outcome, relative to controls.

A number of alternative interpretations of this difference in looking preferences have been tested by one or more of these experiments. In none of the experiments can infants' preference for an inconsistent test outcome be attributed to novel or attractive perceptible features of the outcome displays. Because the perceptible features of the displays were the same in the experimental and control conditions, the difference in preferences must depend on events that occurred before each test

display was presented. In Experiment 2, the experimental group's preference for the inconsistent test outcome over the consistent test outcome cannot be attributed to properties of the events such as the moving objects' initial positions, points of disappearance, or points of reappearance, because the consistent and inconsistent events involved the same path of motion. In Experiment 3, the preference for the inconsistent outcome cannot be attributed to the differential novelty of the outcome displays for infants in the experimental and control conditions. No finite series of experiments ever can rule out all alternative interpretations of any observed behavior. Nevertheless, Experiments 1–3 give plausibility and support to the present interpretation of their findings: Infants looked longer at the inconsistent event outcomes because they inferred that the hidden objects would move on connected, unobstructed paths.

Before turning to the next experiments, it is worth considering two further questions of interpretation that are raised by the present studies. One question concerns the effect of the familiarization trials on infants' test trial performance: Over the familiarization period, did infants learn that the object that moved from view would move on a connected, unobstructed path? The second question concerns the infants' cognitive state during the test events: Did infants expect the hidden object to reappear at a certain location, were they surprised when it appeared elsewhere, and did they regard that reappearance as impossible?

Learning During the Experiments

Contrary to the proposal that infants have a preexisting conception of continuity and solidity, one might argue that infants acquired aspects of this conception during an experiment. On every familiarization trial of Experiment 1, for example, infants viewed an object that fell behind a screen and then was revealed at rest on the first surface in its path. Perhaps infants learned, over the course of the familiarization trials, that the object would appear in that position.

This hypothesis gains plausibility from informal observations of changes in infants' looking patterns during the familiarization period. At the start of an experimental session, most infants failed to follow an object's motion or to attend to the display after the object's disappearance. With repeated trials, most infants began to follow the moving object, and they continued to attend to the display after the object disappeared. Thus, infants may have learned, during the familiarization period, when and where to look for the moving object (see Haith et al., 1988). Did they also learn where the object would reappear?

Such learning would be possible only if infants were predisposed to attend to the right aspects of these events. In Experiment 1, for example, infants were familiarized with a ball that fell from view and then was revealed (a) on a red surface, (b) at a

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[10] We have encountered difficulty, however, in using this method with young preschool children. Beyond 12 months of age, a number of children have reacted to inconsistent event outcomes by turning away from the display to look at a parent or experimenter. Others have moved to the side of the display and attempted to look behind it. Neither of these reactions is captured by the preferential looking method.

position 61 cm below its starting point, (c) in a direction 20°
below eye level, and (d) on the first surface that stood in its path.
During the test, infants inferred that the object's behavior
would conform to (d) and *not* to (a), (b), or (c). If infants learned
to make this inference during the familiarization period, they
must have been predisposed to focus on properties of object
motion captured by (d). One might formulate this predisposi-
tion as follows:

> 1. Attend to the visible or implied motion of an object in rela-
> tion to the first surface in its path. If the object appears to land on
> that surface, infer that the object will land, in the future, on the
> first surface in its path.

This predisposition cannot account, however, for infants' per-
formance in Experiment 2. Each of the test events in Experi-
ment 2 involved an object that moved through the same surface
array and landed on the same lower surface. In addition, the
test events presented two new objects that differed from the
familiar object in size and color. If learning is to account for the
findings of Experiment 2, therefore, a different predisposition
must be specified. The least general predisposition appears to
be the following:

> 2. Attend to the visible or implied motion of an object in rela-
> tion to all surrounding surfaces. If the object appears to move to a
> place that it could reach by following a connected and fully unob-
> structed path, then infer that the object, and other objects that
> may differ from it in size and color, will move in the future to a
> place that can be reached by following a connected and fully un-
> obstructed path.[11]

We are skeptical of a learning account that centers on Predis-
position 2, for two reasons. First, an account that endows in-
fants with this predisposition seems no more parsimonious
than an account that endows infants with sensitivity to the solid-
ity and continuity constraints directly.[12] Second, infants en-
dowed with Predisposition 2 probably would have learned, be-
fore participating in the present experiments, that the solidity
and continuity constraints govern the motions of many kinds of
objects. For example, infants would learn that all spherical ob-
jects conform to the continuity and solidity constraints the first
time that they saw a moving ball. Even 2-month-old infants are
likely to have seen such an event.

We suggest, therefore, that the familiarization events in our
experiments did not lead infants to learn that the test objects'
motion would conform to the solidity and continuity con-
straints. It remains possible that infants learn about these con-
straints prior to 2½ months of age. We return to this possibility
in the General Discussion.

Predictions, Expectations, and Recognition of Natural Laws

One might ask whether the infants in the present experi-
ments generated predictions about the motions and resting po-
sitions of the objects that left their view, whether they were
surprised when an object reappeared at an unexpected posi-
tion, and whether they viewed such a reappearance as impossi-
ble. None of these questions are addressed, however, by the
present experiments. The experiments do not bear on these
questions because of three limitations of the present method.

First, the preferential looking method does not assess the
time course of infants' inferences about object motion. It is
possible that infants represented an object's hidden motion only
retrospectively, after the object was revealed at its final position.
If that is the case, then infants' performance still would depend
on representations and reasoning, because the motion of the
ball was never visible. Their reasoning would not, however,
result in any prediction about the ball's behavior. Second, the
method does not assess infants' affective state. It is possible, for
example, that infants' heightened looking at inconsistent event
outcomes reflected a state of interest, not surprise. In that case,
infants' reasoning could not be said to engender any expecta-
tions about an object's position. Third, the method does not
assess the nature or degree of infants' commitment to the princi-
ples governing their inferences. It is possible that infants re-
garded the inconsistent event outcomes as novel but not as un-
natural or impossible. In that case, infants' reasoning could not
be said to reflect their recognition of natural laws.

The present experiments provide evidence that young infants
represent hidden objects and reason about their motions. The
experiments can be used, moreover, to investigate the princi-
ples that govern infants' reasoning in this domain. Neverthe-
less, limitations of the present method may preclude its use in
investigations of the time course or affective consequences of
infants' reasoning, or of the status, for infants, of the principles
that guide their reasoning.

Conclusions

Experiments 1–3 provide evidence in support of the two
theses stemming from the central-origins view of cognitive de-
velopment. Concerning the active representations thesis, the
experiments provide evidence that infants aged 4 months and
2½ months represent objects and surfaces that they no longer
perceive: the upper surface in Experiment 1, the upper surfaces
and the gap in Experiment 2, the obstacle in Experiment 3, and
the moving object in each of those studies. These findings ac-
cord with the findings of studies by Baillargeon (1987a, 1987b,
1989; Baillargeon et al., 1985) and others (e.g., Clifton et al.,
1991; Craton & Yonas, 1990), and they extend those findings to
younger infants.

In addition, the experiments provide evidence that 4-month-
old and 2½-month-old infants operate on their representations
so as to derive information about an event they have never per-
ceived: the motion of the ball behind the screen. Like Piaget's

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[11] For simplicity, we ignore the further assumption that hidden, mov-
ing objects maintain a constant size and shape. If that assumption were
learned during the familiarization period as well, then Predisposition
2 would need to be strengthened.

[12] If the amount of motion the infant must see to satisfy the condition
of Predisposition 2 is small, then the consequences of the two accounts
are nearly the same. An infant sensitive to the continuity and solidity
constraints would infer that an object will move in accord with these
constraints as soon as he or she saw the object; an infant endowed with
Predisposition 2 would make this inference as soon as he or she saw the
object begin to move. Although the two infants might respond differ-
ently to events involving illusory objects, they would differ little in
their reactions to ordinary physical events.

18-month-old children, the infants in these experiments inferred that a hidden object would come to rest in a new position consistent with physical constraints on object motion. These findings accord with the findings of Baillargeon's studies with infants aged 5½ months to 8 months (Baillargeon, 1986, Baillargeon et al., 1990).

Concerning the core knowledge thesis, the experiments provide evidence that infants inferred that the hidden object would move on a connected, unobstructed path. Infants appear to reason about object motion in accord with two constraints—continuity and solidity—that are central to the physical conceptions of adults.

In the next experiments we probed the core knowledge thesis further by investigating infants' sensitivity to certain effects of gravity and inertia on object motion. The experiments focus on effects of gravity and inertia that are appreciated by older children (see Kaiser et al., 1985; Kaiser, Proffitt, & McCloskey, 1986) and adults (see Appendix). We investigated whether young infants appreciate that a freely falling object will continue falling to a supporting surface (Experiment 4) and that a stationary, supported object will begin to fall if its support is removed (Experiment 5).

Experiment 4

The 4-month-old infants in Experiment 4 were presented with falling-object events similar to those of Experiment 1. In the habituation event, a ball fell behind a screen and was revealed on the first of two surfaces in its path (Figure 9). After habituation, the upper surface was removed and the ball fell as

before, reappearing either in a new position on the lower surface (consistent outcome) or in its former position, now in midair (inconsistent outcome). Adults judged that the consistent event outcome was natural and expected, whereas the inconsistent event outcome was unnatural and unexpected (see Appendix). The unnaturalness of the latter outcome follows both from knowledge of gravity (because the ball appeared to be unsupported at its final position) and from knowledge of inertia (because the ball appeared to have stopped moving abruptly in the absence of obstacles).

Looking times to the two test outcomes were compared with the looking times of infants in a control condition, who viewed a hand-held ball that was lowered slowly to its final position, stopped gradually at that position, and remained supported by the hand. Thus, the infants in the control condition viewed displays that were similar (although not identical) to those in the experimental condition during the time that looking was recorded and that were equally consistent with constraints on object motion. If 4-month-old infants are sensitive either to gravity or to inertia, then the infants in the experimental condition should look longer at the outcome in which the ball stands in midair, relative to controls.

In accord with the core knowledge thesis, the principal prediction for this experiment was negative: Infants were not expected to take account of effects of gravity or inertia in reasoning about the falling object's motion. This prediction is problematic, however, for two reasons. First, the experiment might fail to provide evidence for knowledge of gravity and inertia because of flaws in the method used to assess infants' knowledge: The task might be too difficult; the events might be con-
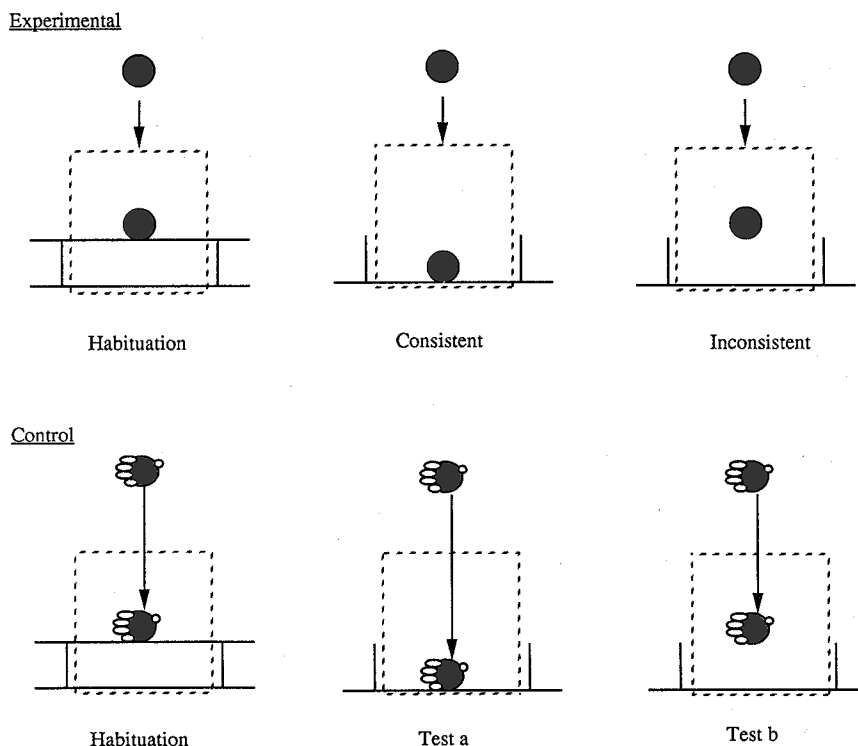

Figure 9. Schematic depiction of the events from Experiment 4.

fusing. Second, infants who lacked knowledge of gravity or inertia would not be expected to respond differentially to event outcomes that were consistent versus inconsistent with those constraints. No conclusions can be drawn, however, from an absence of differential responses.

In Experiment 4 we addressed these problems by using the same method, and nearly the same displays and events, as in Experiment 1, in which 4-month-old infants responded reliably to the inconsistent event outcomes. Preferential looking at the inconsistent outcome in Experiment 4 was compared with preferential looking at the inconsistent outcome in Experiment 1. If infants fail to respond to object positions that are inconsistent with gravity or inertia, then the subjects in Experiment 4 should look reliably less at the inconsistent outcome than their counterparts in Experiment 1. This prediction does not depend on accepting the null hypothesis. Because Experiment 4 used nearly the same displays and method as Experiment 1, moreover, the predicted difference in responding to the inconsistent outcome cannot plausibly be attributed to the difficulty or inappropriateness of the tasks used to assess infants' knowledge.

Method

The method was the same as that of Experiment 1, except as follows.

Subjects. Participants were 14 boys and 10 girls ranging in age from 3 months, 13 days to 4 months, 14 days ($M = 4$ months, 1 day). Six additional subjects were eliminated because of fussiness (5) or experimenter error (1).

Apparatus. In addition to the objects and displays from Experiment 1, a ball with a permanently attached wooden rod was used for the test events. This ball was visually indistinguishable from the other ball. In its final position, it was supported from behind by the rod (not visible from the infant's observation point).

Procedure. In both the experimental and the control conditions, the procedure closely resembled that in Experiments 1–3. Before the start of the study the experimenter greeted the baby and tapped on both surfaces. After habituation, the experimenter disappeared and removed the upper surface. She tapped all across the floor of the display and elaborately waved her hand, wiggling her fingers, through the space where the upper surface had been. These gestures were comparable in length and style to those of Experiment 1.

In the experimental condition, the familiarization event was identical to the consistent test event from Experiment 1. Both test events were similar to the familiarization event from Experiment 1: One ball fell behind the screen on the open stage, and then the ball with the concealed rod was revealed either on the floor of the display (consistent) or in its former position, now in midair (inconsistent). The events for the control condition used the same displays, objects, and positions as the corresponding events in the experimental condition. In each event of the control condition, the presenter introduced a hand-held ball at the top of the display and lowered the ball steadily to its final position at the approximate rate of 45 cm (52°)/s. When the ball reached its final position, the screen was lowered for 2 s and then was raised to reveal the hand-held ball in the same position. Interobserver agreement averaged .83.

Results

On the first three habituation trials, looking time per trial averaged 6.6 s in the experimental condition and 10.1 s in the control condition.[13] The infants in each condition received an average of 11 familiarization trials; 11 subjects, 7 in the experi-

mental condition, failed to meet the habituation criterion and were tested after 14 familiarization trials.

Figure 10 presents the principal findings. In the experimental condition, infants tended to look longer at the consistent test event. In the control condition, infants looked longer at the inconsistent event. The difference in looking preferences between the two conditions was marginally significant by the Wilcoxon-Mann-Whitney test, $z = -1.70$, $p < .10$ (two-tailed). The ANOVA revealed a significant Condition × Pair × Test Event interaction, $F(2, 40) = 3.36$, $p < .05$: On the first two trial pairs, infants in the experimental condition looked longer at the consistent test event, whereas those in the control condition looked longer at the inconsistent event. No other effects were significant.[14]

Further analyses compared the looking preferences of the infants in Experiment 4 with those of the infants in Experiment 1. First, the looking preferences of infants in the two control conditions of the experiments were compared by the Wilcoxon-Mann-Whitney test. This comparison revealed no differences in baseline looking preferences between the two event outcomes, $z < 1$. Next, the looking preferences of infants in the two experimental conditions were compared by means of the same test. This analysis revealed that the preference for the inconsistent event outcome was reliably greater in Experiment 1 than in Experiment 4, $z = 2.68$, $p < .005$ (one-tailed).[15]

Discussion

The 4-month-old infants in the experimental condition tended to look longer at the outcome of the consistent test event, in which a falling object was revealed at a superficially novel position, than at the outcome of the inconsistent test event, in which a falling object was revealed at a position where it appeared to have halted abruptly and spontaneously without support. Because this preference did not differ reliably from that observed in the control condition, it is not clear whether the infants in the experimental condition inferred that the ball would land where it landed before (looking longer at the event outcome that did not accord with their inference) or whether they made no inference about the ball's position during the test. In either case, Experiment 4 provides no evidence that 4-month-old infants infer that a falling object will continue falling to a supporting surface, in accord with the gravity and inertia constraints.

The present findings differed reliably from the findings of Experiment 1. Because the two experiments used the same method and nearly the same displays, it is unlikely that the negative findings of Experiment 4 stem from inadequacies of the method or from general limits on infants' perceptual or representational capacities. A more plausible interpretation of

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[13] This difference was produced by 1 outlying subject in the control condition, who gave a maximum, 120-s look. Median looking times were 3.5 s (experimental) and 3.8 s (control).

[14] Three of the 6 subjects eliminated from the sample provided data on at least one pair of test trials. In an analysis including their data, the effect of condition on test preferences was not significant, Wilcoxon-Mann-Whitney $z = -1.38$.

[15] With the data from the rejected subjects in Experiments 1 and 4 included, the Wilcoxon-Mann-Whitney z was 2.79, $p < .005$.
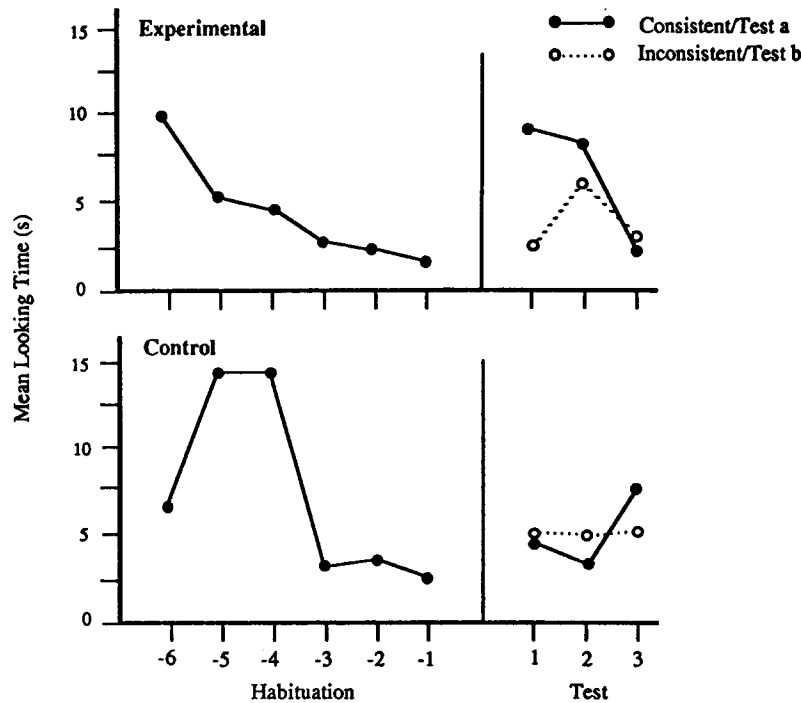
Figure 10. Mean looking times at the event outcomes during the last six habituation trials and the six test trials for the experimental and control conditions of Experiment 4.

Experiment 4 is that the infants failed to infer that the object would land on the lower, supporting surface. When 4-month-old infants are presented with an object that falls from view, they infer that the object will move on a connected, unobstructed path, but they do not appear to infer that it will fall to the first obstacle (inertia) or supporting surface (gravity) in its path.

In one respect, the method of Experiment 4 differed from that of Experiments 1–3: The control condition outcome displays presented the ball held by a hand. The use of a hand may be problematic for two reasons. First, the infants in the experimental and control conditions of Experiment 4 did not see exactly the same displays during the time that their looking was recorded. It is possible that the presence of a hand in the control condition somehow influenced infants' baseline preferences between the two object positions in the test displays. Second, successful performance in Experiment 4 may require that infants appreciate not only that falling balls are subject to gravity or inertia but also that hand-held balls are not. Infants may have failed to look longer at the inconsistent events not because they lacked sensitivity to the gravity and inertia constraints but because they applied those constraints in both conditions of the experiment.[16] In Experiment 5 we addressed these problems. We tested infants' sensitivity to gravity by means of events whose outcomes (a) were identical in the experimental and control conditions and (b) presented freely standing objects.

Experiment 5

In this experiment we investigated whether 3-month-old infants infer that a supported object will begin to fall if its support

is removed. The infants in the experimental condition were presented with events similar to those of Experiment 2 (Figure 11). In the habituation event, a ball was introduced on the left side of a horizontal surface, it was tapped and rolled across the surface and behind a screen, and then the screen was raised to reveal the ball against the right wall of the display. After habituation, a gap wider than the ball was introduced into this surface at approximately the same position as the barrier in Experiment 2. In the inconsistent event, the ball rolled on the surface behind the screen as before, and it reappeared in its familiar position on the far side of the gap. If young infants appreciate that the ball will not continue to move horizontally without support, then the infants in the experimental condition should react to the inconsistent outcome as novel or surprising.

An experiment that exactly paralleled Experiment 2 would have presented a consistent event in which the ball rolled on the same path and was revealed at rest before the gap in the surface. Unfortunately, that event outcome is inconsistent with inertia and was described by adults in a preliminary experiment as unnatural. Accordingly, the consistent test event was a hybrid between the consistent events of Experiments 1, 2, and 3. Throughout the study, a second horizontal surface stood below the surface on which the ball rolled during the habituation trials, in the same position as the lower surface in Experiments 1, 2, and 4. For the consistent test event, the ball was rolled

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[16] Research by Baillargeon (1990), Leslie (1984), and Needham (1990) casts doubt on this possibility. The methods and events used in those studies differed, however, from those of the present studies.
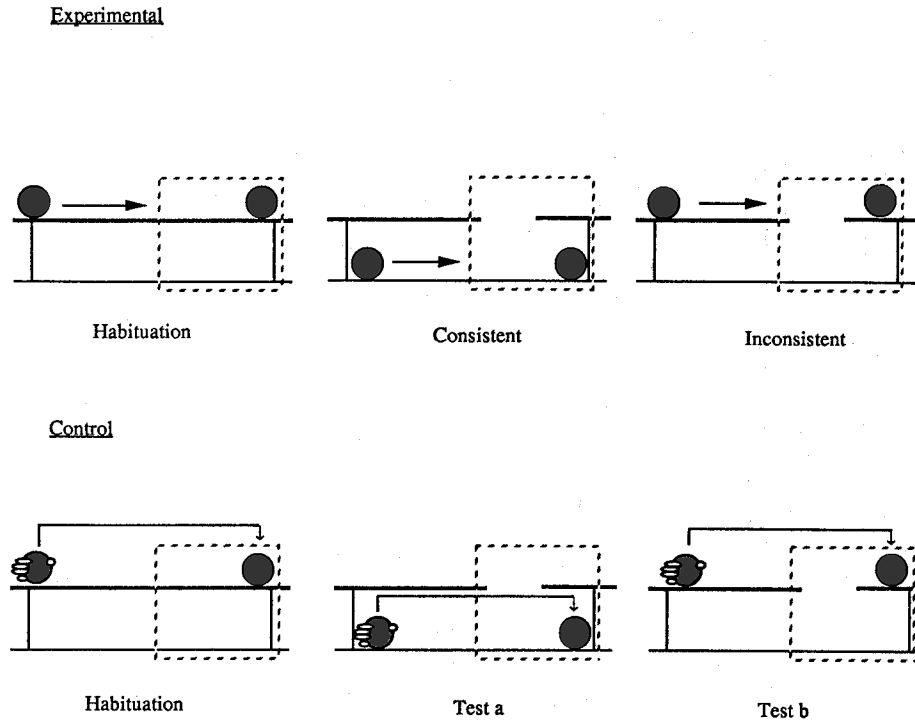
Experimental

Control

Figure 11. Schematic depiction of the events from Experiment 5.

behind the screen on this lower surface and was revealed at rest against the right wall. This outcome position was superficially novel but consistent with gravity, because the ball appeared to be supported by the surface throughout its motion.

Looking times to the two test outcomes were compared with the looking times of infants in a control condition, who viewed a hand-held ball that was introduced in its initial position, raised and carried through the air to its final position, and then released at that position immediately before the screen was lowered and raised. The events viewed by infants in the control condition thus were identical to those viewed by infants in the experimental condition, beginning when the screen was lowered and continuing throughout the time that looking was recorded. If 3-month-old infants appreciate that a horizontally moving, supported object will begin to fall when its support is removed, then the infants in the experimental condition should look longer at the event outcome in which the ball appears at the familiar but inconsistent position on the upper surface. This preference should exceed the analogous preference of infants in the control condition.

As in Experiment 4, the principal prediction for this experiment was negative. Accordingly, the looking preferences of the infants in Experiment 5 were compared with those of the infants in Experiments 1, 2, and 3. Comparisons with each of these experiments were undertaken, because Experiments 1–3 used the same invisible displacement method at ages bracketing those of the infants in Experiment 5 and because features of the events for Experiments 1–3 were combined to create the events for Experiment 5. If infants fail to respond to the effect of gravity on object motion, then the subjects in Experiment 5

should look reliably less at the inconsistent outcome than did their counterparts in Experiments 1, 2, and 3.

Method

Subjects. Participants were 14 boys and 18 girls ranging in age from 2 months, 29 days to 3 months, 14 days (M = 3 months, 7 days). Three additional subjects were eliminated because of fussiness.

Displays. The display consisted of two 3.5 × 81 × 20 cm horizontal surfaces, bounded on the right by a 90-cm-high white wall. As in Experiment 1, the lower surface was painted red and constituted the floor of the display. The upper surface was painted blue and positioned 18.5 cm above the red surface. During the habituation sequence, the upper surface was continuous. For the test sequence, it was replaced by two blue surfaces measuring 3.5 × 40 × 20 cm (left) and 3.5 × 9 × 20 cm (right), separated by a 31.5-cm gap. A 40.5 × 50 cm white screen could be lowered to cover the right ends of both surfaces, including the entire gap between upper test surfaces.

The events involved a yellow ball 8 cm in diameter. Curtained openings that ran across the stage above each surface permitted the display presenter to introduce and move the ball at any location above the surfaces. In the experimental condition, the screen was lowered, the ball was introduced on the left side of the upper surface (habituation and inconsistent test events) or the lower surface (consistent test event), and it was tapped by a hand so that it rolled rightward behind the screen, as in Experiment 3. In the control condition, the ball was introduced at the same positions on the upper or lower surface, it was lifted 2 cm off that surface, it was carried rightward by the hand to the rightmost wall, and then it was placed on the surface and released as the screen was lowered. In both conditions, the screen was raised to reveal the ball at its final position on the upper or lower surface.

Design, procedure, and analyses. These were the same as in Experi-

ment 3, except as follows. Before the first habituation trial in each condition, the display presenter tapped on both the upper and the lower surfaces. Before the first test trial, she tapped on both surfaces and waved her hand through the gap in the upper surface. The elaborateness of her hand motions through the gap were designed to be equivalent to those of the presenter's motions in Experiment 2. In the experimental condition, the presenter manipulated the ball as in Experiment 3. In the control condition, she lifted and carried the ball with her right hand, and then she released the ball and lowered the screen as in Experiments 1 and 2. Interobserver agreement averaged .79.

Results

On the first three habituation trials, looking time averaged 6.1 s in the experimental condition and 16.8 s in the control condition.[17] The mean number of familiarization trials was 10 in each condition. Eleven infants, 6 in the experimental condition, failed to meet the habituation criterion and were tested after 14 familiarization trials.

Figure 12 presents the principal findings. During the test, infants in the experimental condition looked longer at the superficially more novel, consistent outcome. Although the preference for this outcome appeared to exceed the corresponding preference in the control condition, the difference in looking times across the two conditions was not significant, Wilcoxon-Mann-Whitney $z = 1.57$, $p < .12$ (two tailed). No significant effects emerged from the ANOVA.[18]

Further analyses compared the looking preferences of the infants in Experiment 5 with those of the infants in Experiments 1, 2, and 3. The first analyses focused on the looking preferences of the infants in the control conditions of the different experiments. There were no significant differences between the looking preferences in the control condition of Experiment 5 and those in Experiment 1 (Wilcoxon-Mann-Whitney $z < 1$), Experiment 2 ($z = 1.14$), or Experiment 3 ($z < 1$). The next analyses focused on the looking preferences of the infants in the experimental conditions. The preference for the inconsistent event outcome was significantly lower in Experiment 5 than in Experiment 1 ($z = 2.26$, $p < .02$), Experiment 2 ($z = 3.88$, $p < .001$), or Experiment 3 ($z = 3.00$, $p < .005$).[19]

Discussion

The findings of Experiment 5 are very similar to those of Experiment 4. The 3-month-old infants looked nonsignificantly longer at the outcome of the consistent event, in which the rolling ball appeared in a new position, than at the outcome of the inconsistent event, in which the ball appeared at a familiar position on the far side of a gap. This preference is opposite in direction to the preference one would expect if infants are sensitive to the effect of gravity on object motion. Experiment 5 provides no evidence that young infants infer that a supported object will begin to fall when its support is removed, in accord with gravity.

The method of Experiment 5 was the same as that of Experiments 1, 2, and 3. Its events were very similar to those of Experiment 3, and its displays were similar to those of Experiments 1 and 2. The ages of the infants were intermediate between those
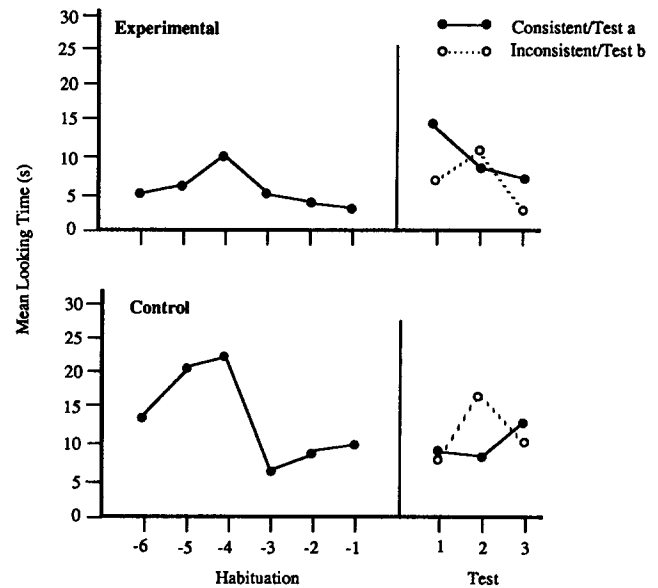

Figure 12. Mean looking times at the event outcomes during the last six habituation trials and the six test trials for the experimental and control conditions of Experiment 5.

of the infants in Experiments 1 and 2 and those of the infants in Experiment 3. The event outcomes were identical in the experimental and control conditions and involved no hand-held object. The findings of Experiment 5 nevertheless differed from those of each of the first three studies. The most likely interpretation of this difference centers on the different constraints that govern object motion in these experiments.

Discussion of Experiments 4 and 5

Young Infants' Sensitivity to Gravity

The findings of Experiment 4 provide no evidence that 4-month-old infants infer that an object that falls from view will continue moving downward to a supporting surface. The findings of Experiment 5 provide no evidence that 3-month-old infants infer that an object that rolls from view on a surface will begin to move downward when it loses the support of the surface. These inferences follow from the constraint that objects move downward in the absence of support: Object motion is subject to gravity. Experiments 4 and 5 provide no evidence that

[17] This discrepancy was attributable primarily to 1 subject in the control condition who gave maximum looks of 120 s on all three trials. Median looking times in the two conditions were 6.3 s (experimental) and 7.8 s (control).

[18] Two of the 3 subjects eliminated from the sample provided data on at least one pair of test trials. In an analysis including their data, the effect of condition on test preferences showed the same nonsignificant trend, $t = 1.57$, $p < .12$.

[19] With the data from the rejected subjects included, these findings are not changed: each $z \leq 2.42$, $p < .01$.

young infants reason about the behavior of hidden, falling objects in accord with this constraint.

Young infants responded reliably less to violations of gravity than to violations of continuity and solidity. When 2½-month-old and 4-month-old infants were presented with objects that fell or rolled from view toward a barrier, the infants evidently inferred that the objects would move on connected, unobstructed paths. Young infants thus appear to be more apt to reason in accord with the constraints of continuity and solidity than to reason in accord with the constraint of gravity.

Further research from our laboratory provides evidence that sensitivity to effects of gravity begins to develop later in the 1st year. Reactions to the falling-object events of Experiment 4 change reliably between 4 and 6 months; reactions to the rolling-object events of Experiment 5 change reliably between 3 and 6 months (Spelke, Simmons, Breinlinger, Jacobson, Keller, & Macomber, 1992). Analyses of the looking patterns of 6-month-old infants suggest, nevertheless, that sensitivity to gravity is still fragile at that age: Six-month-old infants do not show robust preferences for event outcomes that are inconsistent with gravity (Spelke et al., 1992). Sensitivity to gravity also appears to be quite limited at 6 months: Six-month-old infants fail to make appropriate inferences about the effect of gravity on the behavior of a stationary object (Spelke et al., 1992; Spelke & Jacobson, 1992) or on the path of motion of a moving object (Kim & Spelke, 1991). Knowledge of gravity thus may develop rather slowly and in a piecemeal fashion.

One can never conclude, from the findings of any experiments, that young infants have *no* sensitivity to a constraint on object motion; one can conclude only that such knowledge is not manifest in a particular set of situations. Contrary to the more extreme conclusion, recent research by Baillargeon (1990) and by Needham (1990) provides evidence that infants as young as 3½ months are sensitive to effects of gravity that are manifest when fully visible objects lose their support. In Needham's study, a subset of 3.5-month-old infants (those whose looking time to an initial display declined over trials) looked longer at an event in which an object was pushed wholly off a supporting surface and rested in midair than at an event in which the object underwent a similar motion but remained on the surface. In experiments by Baillargeon (1990), 6-month-old infants looked longer when an object was pushed more than halfway off a supporting surface than when it was pushed less than halfway off the surface (see also Baillargeon & Hanko-Summers, 1990). These findings raise the possibility that infants are more sensitive to object support relations in fully visible events than in events involving hidden objects. Because the displays and procedures of the Baillargeon and Needham experiments differ from our own, this possibility needs to be tested directly.

Although young infants appear to have some sensitivity to the effects of gravity, we are struck by the limits of their sensitivity. The infants in Experiments 4 and 5 showed no novelty reaction to events in which a falling object was revealed at rest wholly in midair, or in which a rolling object was revealed to have moved horizontally, without support, over a gap. These findings suggest that 3- and 4-month-old infants have not developed any unified conception that unsupported objects move downward.

Young Infants' Sensitivity to Inertia

Experiment 4 also investigated infants' sensitivity to inertia. In the test events of that study, a rapidly moving object that disappeared from view was revealed either at a novel position against an obstacle or at a familiar position in midair. The latter position is inconsistent with inertia: The object appeared to have stopped moving abruptly and spontaneously. Because 4-month-old infants showed no looking preference for this inconsistent event, Experiment 4 provides no evidence that young infants are sensitive to inertia.

The negative findings of Experiment 4 accord with the findings of experiments by Katz, Spelke, and Purcell (1990), who focused on a different aspect of the inertia constraint. These experimenters used the present method to investigate whether infants infer that an object in linear motion will continue in linear motion in the absence of obstacles. Infants viewed a ball that rolled on a straight line on a horizontal surface and disappeared at the center of the surface behind a horizontal screen. During the critical test sequence, the screen was raised to reveal the ball at one of two positions equidistant from its point of disappearance: a position on a line with its former motion and a position 90° displaced from its former motion. In one experiment, both positions were novel. Six-month-old infants looked equally at the two outcomes, whereas 8- and 10-month-old infants tended to look longer at the nonlinear outcome. In a second experiment, the nonlinear position was superficially familiar. Infants aged 6 months and 8 months looked longer at the consistent, linear outcome, whereas infants aged 10 months and 12 months showed no reliable preferences between the two outcomes. These preferences differed reliably from the preferences shown in parallel experiments in which 6- and 10-month-old infants viewed events whose outcomes were either consistent or inconsistent with the continuity and solidity constraints. The experiments provide evidence that knowledge of inertia begins to develop between 6 and 8 months and is still fragile at 1 year of age. As always, however, it remains possible that sensitivity to inertia will be manifest at younger ages if it is tested by different methods or with different events.

The present findings complement the findings of studies of children's and adults' intuitive reasoning about object motion. As we noted in the introduction, adults have been found to reason inconsistently about the effects of gravity and inertia on object motion, making correct inferences about object motion under certain conditions but not under other conditions that are formally identical (e.g., Kaiser, Jonides, & Alexander, 1986; McCloskey, 1983). Children also show certain inconsistencies in their judgments (Kaiser et al., 1985; Kim & Spelke, 1991). Mature knowledge of gravity and inertia may reflect a lifetime of learning about how particular kinds of objects move under particular kinds of circumstances, rather than the discovery of general constraints on object motion.

General Discussion

The Origins of Knowledge

The present experiments support the active representations thesis: They provide evidence that capacities to represent and

reason about the physical world develop at an early age, in parallel with capacities to perceive and to act. At 3 and 4 months of age, infants are not able to talk about objects, produce and understand object-directed gestures, locomote around objects, reach for and manipulate objects, or even see objects with high resolution. Nevertheless, such infants can represent an object that has left their view and make inferences about its occluded motion. In particular, infants represent objects and reason about object motions in accord with two constraints on the behavior of material bodies: continuity and solidity.

These findings, like research by Baillargeon (in press), Mandler (1988), and others, provide evidence against Piaget's thesis that physical knowledge depends on internalized sensorimotor structures that arise gradually as perceptions and actions become intercoordinated (Piaget, 1952; see also Forman, 1982). The findings also provide evidence against a variety of empiricist theories that root knowledge of physical objects in activities of manipulating objects (e.g., Helmholtz, 1885; see also Bushnell, 1981), locomoting around objects (e.g., Berkeley, 1910; see also Campos & Bertenthal, 1987), or communicating about objects through language or gesture (e.g., Quine, 1960; see also Gopnik, 1988). Although perceptual-motor coordination, object manipulation, locomotion, and communication may contribute to the later development of physical knowledge, knowledge does not appear to originate in any of these activities.

In its general form, however, the peripheral-origins thesis is not tied to any particular claim about the time of emergence of knowledge or about the nature of the perceptual or motor experience that gives rise to knowledge. Faced with the present findings, one might suggest that knowledge of physical objects develops from perceptual or motor experiences that occur before the 3rd month of life. For example, knowledge of the continuity and solidity constraints might arise through visual learning that takes place in the first 2 months. If future studies were to provide evidence for such knowledge in newborn infants, that finding could be explained by sensorimotor learning that occurs prior to birth.[20] For example, humans might learn about object continuity and solidity by experiencing, as fetuses, the movements of their own body parts.

These considerations bring to the foreground an ambiguity in the active representations thesis. The thesis states that representational and reasoning abilities arise early in development. Support for these claims can always be countered, however, by the argument that such abilities have not been demonstrated early enough. Such counterarguments can be taken seriously only if they are specific. A proponent of a peripheral-origins thesis must explain how early conceptions arise from still earlier-developing perceptions and actions. To our knowledge, no existing perception-based or action-based account of cognitive development encompasses the present findings (cf. Fischer & Biddell, 1991; Gopnik, 1988; Mounoud, 1988). We now attempt to evaluate the prospects for such an account by considering, in turn, the character of young infants' perceptions of objects and actions upon them.

If physical knowledge develops on the basis of perception, then infants should first understand those aspects of object motion that are most frequent and prominent in their percep-

tual experience. Studies of visual perception[21] suggest that young infants perceive a layout of surfaces and their motions (Banks & Salapatek, 1983; E. J. Gibson & Spelke, 1983), as do adults (J. J. Gibson, 1950; Marr, 1982). Thus, infants might be predisposed to learn about how objects move in relation to surfaces.

Such a predisposition cannot easily account for the findings of the present experiments. Consider an infant who must predict the resting positions of falling objects. Three of the many possible inductions consistent with the behavior of a falling object, and stated in terms of the relation of the object to surrounding surfaces, are these:

1. A falling object will land on some surface.
2. A falling object will land on the first surface in its path.
3. A falling object will land in a place it can reach by moving continuously such that no part of it passes through any surface in its path.

Informally, the simplest of these inductions appears to be Induction 1. The findings of Experiment 4 suggest, however, that young infants do *not* make this induction: Four-month-old infants do not appear to infer that a falling object will land on a surface rather than in midair. If objects and surfaces provide the primitives on which infants' knowledge about object motion is built, then the simplest induction that accounts for infants' patterns of success and failure in the present experiments appears to be Induction 3. Why do infants respond to the regularity captured by Induction 3 rather than that captured by Induction 1?

A proponent of the thesis that physical knowledge results from relatively neutral inductions over perceptual experience might propose that the perceptual experience of infants under 3 months favors Induction 3 over Induction 1. This could occur either because perceptual mechanisms are biased to perceive motions that accord with Induction 3, relative to any bias to perceive motions that accord with Induction 1, or because motions that accord with Induction 3 are observed more frequently

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[20] It may not be possible to investigate knowledge of physical objects in newborn infants. Research by Slater et al. (1990) provides evidence that newborn infants fail to perceive objects under conditions that are effective for infants at 3 or 4 months. This difference may stem from developmental changes in attention, depth perception, motion perception, or object perception itself (see Spelke & Van de Walle, in press). Such changes may prevent newborn infants from using whatever knowledge of objects they possess.

[21] One might question the present focus on visual perception, because two other perceptual modes are relatively well developed at birth: the auditory and oral/gustatory modes. Neither mode, however, appears to provide a better basis for inducing the continuity and solidity constraints. Audition provides little information about the properties and motions of objects unless it is combined with vision (Clifton et al., 1991). Whereas oral perception might provide considerable information about objects to young infants (e.g., Rochat, 1983), that information is likely to be misleading in the present case. Many of the objects introduced into infants' mouths are edible. They do not, therefore, appear to persist over time or to resist penetration. Information gained from oral perception thus might work against the development of conceptions of object continuity and solidity.

(either absolutely or relative to motions that violate Induction 3) than are motions that accord with Induction 1. Research with human adults casts doubt on the first explanation. Humans appear to perceive surface motions that violate the continuity and solidity constraints quite readily even in situations where perceptual interpretations consistent with those constraints exist (e.g., Ames, 1951; Wertheimer, 1912; see Leslie, 1988, for further evidence and discussion). Thus, the visual system does not appear to be predisposed to represent motion as continuous and unobstructed. On the surface, the second explanation is more plausible. Whereas some objects (birds, helium balloons, mobiles) are not supported from below, and others (animals, people, rocking boats, and falling leaves) appear to change their motion abruptly and spontaneously, all material objects move on connected, unobstructed paths. The explanation encounters difficulties, however, on closer examination.

Consider first the perceptual evidence for object continuity. As Piaget and many others have observed, objects are *not* continuously visible: They enter and leave the field of view with nearly every movement of the eyes. Indeed, young infants' visual experience of objects appears to be especially discontinuous, because of infants' limited abilities to follow moving objects (Aslin, 1988). Perceptual experiences of objects appear to be even more discontinuous in the auditory and haptic modes (see J. J. Gibson, 1962, Piaget, 1954, and Footnote 21). Thus, young infants are seldom in a position to determine, by direct sensory experience, whether a perceptible object endures through time and whether its motion is continuous or discontinuous (Harris, 1983).

Consider next the perceptual evidence for object solidity. The solidity constraint is violated by light, shadows, reflections, and projected images. Moreover, it appears to be violated by nonsolid substances and nonrigid objects. If infants experienced only solid, rigid, material bodies, then infants might be able to induce the solidity constraint from their limited visual encounters with objects. In a world in which objects cast shadows that pass through one another, and in which objects appear to penetrate deformable objects, liquids, and powders, the solidity constraint is more difficult to discern.

In light of these observations, it is not surprising that psychologists who have proposed that conceptions of object continuity and solidity develop from perceptual experience have also proposed that those conceptions develop relatively late in infancy, after humans have begun to manipulate objects and locomote around them (e.g., Harris, 1983). Research with infants now casts doubt on these proposals.

We turn to the thesis that physical knowledge is founded in action. This thesis appears more plausible, because actions begin to be observed early in fetal development. For example, fetuses in the second trimester move their limbs frequently and systematically (Prechtl, 1989). Infants might experience the continuity of each limb movement and its interruption on contact with an external surface or body part. Could these experiences lead infants to learn that their own motions (and, by extension, the motions of other objects) are governed by the continuity and solidity constraints?

There are two reasons to doubt this possibility. First, infants' actions, like their perceptions, are directed to nonrigid objects, soluble objects, penetrable objects, and nonsolid substances as well as to objects that are rigid, insoluble, and impenetrable. Thus, the objections to a perception-based developmental account apply to an action-based account. Second, limb motions are constrained not only by continuity and solidity but also by gravity and inertia. Infants must exert more force to raise a limb than to lower it; they must exert more force at the beginning than in the middle of a limb movement; they must adjust to the effects of gravity and inertia continuously to maintain posture and balance.[22] If infants learn about object motion by moving their limbs (or raising their heads, or engaging in virtually any other action), one would expect infants to master the gravity and inertia constraints at least as early as they master the solidity and continuity constraints.

These observations do not prove that conceptions of object motion are founded in initial cognitive capacities. They suggest, however, that explicit versions of the peripheral-origins thesis consistent with the findings of research on infants will not be easy to devise. It is time to consider an alternative thesis: Cognitive capacities may be as much a part of human endowment as are capacities to perceive and to act. The development of initial cognitive capacities may be triggered, but not shaped, by perceptual or motor experience.

The Development of Knowledge

The present experiments, and those of others (e.g., Baillargeon, 1990; Kim & Spelke, 1992; Spelke et al, 1992), suggest that infants do not reason correctly about object motion under all of the circumstances in which adults and older children do. In particular, the infants in the present studies did not appear to infer that a moving object would move downward in the absence of support and forward in the absence of obstacles. Both inferences are made by adults (see Appendix) and by 6-year-old children (Kaiser et al., 1985; Kaiser, Proffitt, & McCloskey, 1986).

Despite these differences between infants and adults, the experiments provide tentative support, we believe, for the core knowledge thesis. The two principles that have been found to guide young infants' inferences about object motion also appear to be central to mature, commonsense conceptions of the physical world. The apparent centrality, to mature thought, of the principles of continuity and solidity suggests that development leads to the enrichment of physical knowledge around a constant core. It does not result either in the reorganization of knowledge, such that core conceptions become peripheral or vice versa, or in conceptual change, such that initial conceptions are abandoned and new, incommensurable conceptions are embraced.

Studies in the history of science do not support the view that physical knowledge has a constant core. In particular, the emergence of quantum mechanics demonstrates that the continuity and solidity constraints are not preserved over the development of scientific understanding. Scientists, at least, can develop sys-

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[22] The effects of gravity and inertia change when an infant moves from its prenatal to its postnatal environment. By 2 months, however, infants evidently have adjusted to such changes: Their actions are appropriately adapted both to gravity and to inertia (Hofsten, 1989; Prechtl, 1989).

tems for understanding physical phenomena that do not center on these constraints. Their knowledge systems may deny to the elementary constituents of matter two properties that were taken, throughout most of the history of science, to be essential: continuous motion and impenetrable extension (Dijksterhuis, 1961; but see Sorabji, 1988, for exceptions from ancient science). The existence of this conceptual change in science, overturning both common sense and longstanding scientific theory, poses a challenge to adherents of the core knowledge thesis: The spontaneous development of commonsense knowledge must be distinguished in some way from the development of scientific knowledge. The difficulty of drawing this distinction as well as the drive for unity and simplicity in theories of knowledge development appears to detract from the core knowledge thesis (see Carey, 1985, 1988; Kitcher, 1988; Kuhn, 1977; Piaget, 1980; Smith, Carey, & Wiser, 1985).

There are reasons, nevertheless, to question the analogy between spontaneous cognitive development in children and conceptual change in science. Studies in the history of science suggest that mathematical abstraction plays a central role in the development of physical theory: a role it does not appear to play in commonsense physical reasoning (Duhem, 1954). When humans reason intuitively, mathematical abstraction may be impossible in many cases, even for those with extensive training in physics (Proffitt & Gilden, 1989; Proffitt et al., 1990). In addition, studies in the history of science suggest that revolutionary changes in scientific theories occur infrequently, that many scientists who have labored under one theory never embrace its newer rival, and that other scientists embrace a new theory only after a period of considerable difficulty (Kuhn, 1962). In contrast, commonsense physical knowledge appears to develop spontaneously and with ease. Some of this knowledge develops during the infancy period itself, before children can benefit from instruction or, it seems, from disciplined reflection and formal mathematics. The ubiquity, spontaneity, and speed of development of commonsense physical knowledge all suggest that this process of development differs from the processes by which scientists extend, revise, and overturn theories.

If there is a connection between commonsense physical reasoning and scientific reasoning, it may be reflected best in the difficulty that ordinary adults, and at least some scientists, experience in conceiving of physical phenomena to which the continuity and solidity constraints do not apply. Although systematic evidence is lacking, it would seem to be more difficult to develop clear and consistent intuitions about a world lacking continuously persisting, impenetrable bodies than to develop intuitions about a world lacking gravity or inertia. Continuity and solidity appear to be deeply embedded in human conceptions of the physical world and human ways of tracing physical bodies through time.

Nativism and Explanation in Psychology

A cognitive-origins thesis may appear empty and unmotivated. It rejects several classes of explanation for the foundations of cognition, but it offers no explanation in their place. The apparent emptiness and arbitrariness of nativist proposals in psychology are characteristic, and they lead characteristically to discontent. If cognition is built on other psychological processes such as perceiving and acting, then the task of explaining the origins of thought falls naturally to the psychologist, among other scientists. If cognition is part of humans' psychological beginnings, however, psychologists cannot contribute to the explanation of its origins. That explanatory task falls entirely to other disciplines.

A central-origins thesis can contribute, nevertheless, to psychological explanations of three kinds: explanations of early behavioral capacities, explanations of the course of cognitive development, and explanations of the content of mature knowledge. Concerning early behavior, one of us has proposed that initial conceptions of object continuity and solidity underlie not only infants' reasoning about object motion but also infants' apprehension of object boundaries in perceived surface layouts (Spelke, 1990) and infants' apprehension of object identity through time (Spelke & Kestenbaum, 1986). The same initial conceptions thus may figure in accounts of a variety of early abilities.

Concerning cognitive development, a close linkage between object perception and physical reasoning could explain both why conceptions of material objects are not overturned during spontaneous development and how they can be overturned during science education. These conceptions will be perpetuated over spontaneous development, because they serve to single out the objects about which humans gain knowledge (Spelke, 1991). They can be overturned by instruction or disciplined reflection if the student or scientist can use conceptions in a different domain of knowledge, such as mathematics, in order to single out a new set of entities in the physical world (Carey & Spelke, in press). Studies in psychology (Proffitt et al., 1990) and in the history of science (Duhem, 1954) suggest that it is difficult to translate commonsense physical notions into the language of another domain. That difficulty may explain why conceptions of continuity and solidity are central aspects of mature commonsense knowledge. In any knowledge domain in which initial conceptions specify the objects about which one learns, and in which translation into the language of a different cognitive domain poses difficulties, studies of initial conceptions may shed light on the deepest principles guiding mature thought.

The central-origins thesis developed here has implications concerning the place of developmental research within the study of human cognition. In any domain in which humans are endowed with conceptions of the world, and in which further conceptions develop through a process of enrichment, studies of infants may shed light on the conceptions of adults. Such studies may elucidate conceptions whose nature and importance are not readily apparent in an adult's immediate experience, because they are rarely subjected to scrutiny and because they are overlaid by a wealth of specific, later-developing notions. Both the nature and the limits of human commonsense understanding may be revealed, in part, through studies of the ways in which physical knowledge develops and of the principles with which it begins.

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Appendix

In an experiment using a verbal rating method we investigated adults' reactions to all of the test events presented to infants in the experimental conditions of Experiments 1–5. Participants were 36 subjects, aged 18–54, who were college students or staff members. The subjects were recruited through signs posted near the laboratory where the experiments with infants were conducted.

Twelve subjects were presented with the events from Experiments 1 and 4, 12 subjects were presented with the events from Experiments 2 and 3, and 12 subjects were presented with the events from Experiment 5. In all cases, the events were presented in a Latinized order and were preceded or followed by three events from experiments not reported here.

Subjects were tested in the laboratory room used for infants, arranged as for the infant experiments except that the infant seat was removed. The subject sat in a chair, such that his or her head was approximately 1.7 m from a display, at about the same eye height as that of the infants. To the side of the display was a 7-point scale numbered from −3 to +3 with the labels *very unnatural* and *very natural* at the negative and positive extremes.

Subjects were told that the purpose of the study was to see how adults would react to some of the displays shown to infants. They would see several events involving objects, and they would be asked to rate how natural or unnatural the behavior of each object appeared. Subjects were asked to give their immediate reaction to each event without scrutinizing the displays or analyzing the objects and events in detail. They were shown each event twice, and then they rated its naturalness by choosing a number from the scale.

Table A1 presents the mean judgments of naturalness for each of the events. *T* tests revealed that each habituation and consistent test event was rated as more natural, and each inconsistent test event was rated as less natural, than the neutral point of 0 (see Table A1). Further analyses comparing the judgments for the consistent versus inconsistent events within a single experiment revealed significant differences for every pair of events, all *t*s (11) > 4, *p* < .01.

Table A1
*Adults' Mean Ratings of Naturalness of the Events
From Experiments 1–5*

Experiment	Event	Mean naturalness rating	*t*
Solidity/continuity experiments			
1	Habituation	2.67	18.76***
	Consistent	2.13	6.09***
	Inconsistent	−2.58	−13.38***
2	Habituation	1.17	2.18*
	Consistent	1.25	2.32*
	Inconsistent	−2.00	−3.55**
3	Habituation	2.92	35.00***
	Consistent	2.75	11.00***
	Inconsistent	−2.83	−17.00***
Gravity/inertia experiments			
4	Habituation	2.13	6.09***
	Consistent	2.67	18.76***
	Inconsistent	−2.92	−35.00***
5	Habituation	2.92	35.00***
	Consistent	2.92	35.00***
	Inconsistent	−2.50	−9.57***

* *p* < .05.   ** *p* < .01.   *** *p* < .001.