Cognition, 51 (1994) 131–176

Early knowledge of object motion: continuity and inertia

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Received July 7, 1992, final version accepted September 2, 1993

Abstract

Experiments investigated whether infants infer that a hidden, freely moving object will move continuously and smoothly. Infants aged 6 and 10 months, like the 4-month-old infants in previous experiments, inferred that the object's path would be connected and unobstructed, in accord with the principle of continuity. In contrast, 4- and 6-month-old infants did not appear to infer that the object's path would be smooth, in accord with the principle of inertia. At 8 and 10 months, knowledge of inertia appeared to be emerging but remained weaker than knowledge of continuity. These findings are consistent with the view that common sense knowledge of physical objects develops by enrichment around constant core principles.

The core knowledge thesis

Human adults generally can predict how the things around them will behave. When a ball rolls from view on a table, for example, adults infer that it will continue to exist and to move on a connected path, that it will move smoothly in the absence of obstacles or surface irregularities, that it will rebound from or

Supported by grants from NSF (BNS-8613390) and NIH (HD-23103) and by a fellowship to E.S.S. from the John Simon Guggenheim Memorial Foundation. We thank Frank Keil for comments and Michael McCloskey for suggesting Experiment 5.

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SSDI 0010-0277(93)00582-R

displace any obstacles that it encounters, and that it will remain on the table until it reaches the edge, whereupon it will fall. Although common sense inferences are sometimes partly in error (in this example, adults may misjudge the path that a rebounding or falling ball will follow), the variety and success of most predictions suggest that adults have a rich system of knowledge of the behavior of material objects.

How does this system of knowledge develop? Here, we explore the thesis that common sense knowledge of physical objects develops around a set of principles that are constant. According to the *core knowledge thesis*, knowledge of certain constraints on objects guides the earliest physical reasoning. This knowledge remains central to common sense reasoning throughout development and constitutes the core of adults' physical conceptions. New beliefs emerge with development, amplifying and extending human reasoning and surrounding core physical conceptions with a multitude of further notions. As physical knowledge grows, however, initial conceptions are not abolished, transformed, or displaced.

The assumption of unchanging core knowledge is challenged by studies of conceptual change in science and in childhood. Studies in the history of science reveal that scientific concepts and beliefs undergo radical changes of two kinds: beliefs that were central to an earlier scientific theory become peripheral to or absent from a later theory (Kitcher, 1988), and central concepts emerge within the later theory that are not formulable in terms of the concepts of the earlier theory (Kitcher, 1988; Kuhn, 1962, 1977; Wiser & Carey, 1983). The existence of these changes suggests that no scientific beliefs are immune to change. In addition, studies of conceptual development in children provide evidence for changes in biological and physical concepts that are analogous to some of the changes that have occurred in the history of science (Carey, 1985, 1988, 1991; Smith, Carey, & Wiser, 1985).

These findings do not undermine the core knowledge thesis, however, for several reasons. First, analogies between scientific and common sense knowledge may be misleading, because everyday beliefs differ from explicit, socially constructed scientific theories (Atran, 1990; Sperber, 1991). Even scientists and science teachers appear to reason quite differently when their reasoning is based on intuition than when it is based on the rules and procedures taught in science classes (Proffitt, Kaiser, & Whelan, 1990). Second, studies of conceptual change in children have documented the emergence of new concepts and beliefs but not the overturning of initial knowledge. In particular, new conceptions of living kinds, of animals, and of matter appear to coexist with earlier conceptions of human agents and inanimate objects (Carey, 1985, 1988, 1991; Smith et al., 1985). Third, conceptual changes in science and science education may hinge not on the abandonment of initial core principles within a system of knowledge but on the use of pre-existing principles from one system of knowledge to reason about entities in the domain of a different system (Carey & Spelke, in press). These studies therefore do not resolve the question whether initial, core knowledge changes over cognitive development.

A more radical challenge to the core knowledge thesis comes from studies of action and knowledge in infancy (Bower, 1982; Fischer & Bidell, 1991; Gopnik, 1988; Harris, 1983; Moore & Meltzoff, 1978; Piaget, 1954). Numerous studies provide evidence that infants' actions are poorly accommodated to fundamental properties of objects. In particular, young infants typically fail to search for hidden objects, even when the action required to retrieve an object lies within their repertoire (e.g., Munakata, 1992). When infants begin to search for objects, they look and reach deliberately and repeatedly to places where objects could not move without violating constraints on object motion that adults recognize as fundamental (e.g., Moore, Borton, & Darby, 1978; Piaget, 1954). Infants' search patterns subsequently undergo striking qualitative changes (Harris, 1975; Piaget, 1954). It is reasonable to suppose that infants' actions on objects are guided by their conceptions of objects: for example, that infants will search for an object in the place where they believe the object to be. (Hereafter, we call this assumption the "knowledge in action thesis".) If the knowledge in action thesis is correct, then the core knowledge thesis is false: conceptions of physical objects undergo radical changes in infancy.

The present research tests the core knowledge thesis against the thesis that infants' conceptions of objects undergo the radical changes suggested by their changing actions on objects, by investigating infants' knowledge of two general principles governing the behavior of physical bodies (Fig. 1). According to the *principle of inertia*, an object moves smoothly in the absence of obstacles: freely moving objects therefore do not abruptly change speed or direction.[1] According to the *principle of continuity*, a moving object traces exactly one connected path over space and time: the path of one object therefore contains no gaps (the continuity constraint), and the paths of two objects do not intersect such that the objects occupy the same place at any point in time (the solidity constraint) (Fig. 1B).

The core knowledge thesis and the knowledge in action thesis lead to opposite predictions concerning the relative strength of infants' knowledge of these principles. Studies of mature common sense physical reasoning (reviewed below) provide evidence that the continuity principle figures in adults' core knowledge

[1] In classical mechanics, the inertia principle captures a stronger and more general constraint on object motion: an object undergoes *rectilinear* motion in the absence of *forces*. We formulate this principle in terms of the weaker constraint, because the Newtonian principle of inertia does not appear to guide the common sense reasoning of adults (e.g., Halloun & Hestenes, 1985; McCloskey, 1983). Nevertheless, the present experiments focus on infants' inferences about a pattern of motion that is consistent both with the classical inertia principle and with the weaker principle proposed here.

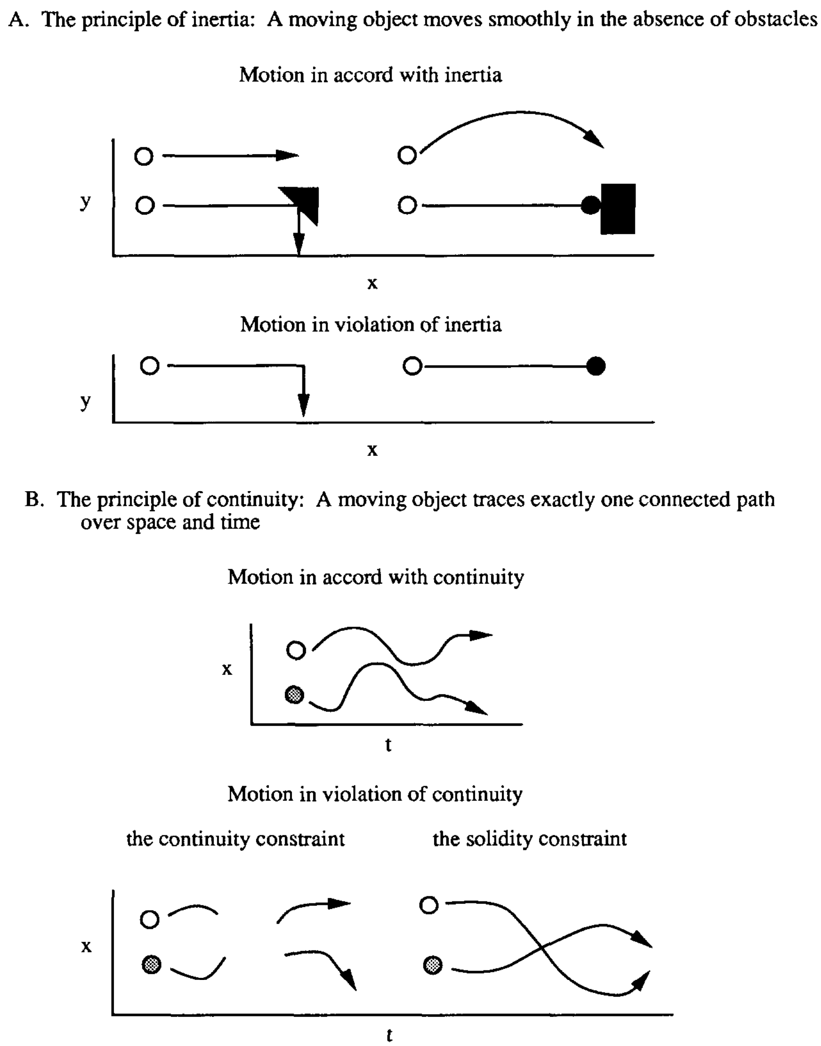


Figure 1. *The principles of inertia and continuity. In (A), each line depicts the two-dimensional path of an object (open circle) that continues in motion (arrow) or stops (filled circle). In (B), each line depicts the path of an object over one-dimensional space (vertical axis) and time (horizontal axis).*

whereas the inertia principle does not. According to the core knowledge thesis, therefore, knowledge of continuity should emerge as soon as infants begin to reason about physical objects, whereas knowledge of inertia should emerge later and should guide infants' reasoning less strongly. In contrast, studies of infants' developing actions on objects (reviewed below) provide evidence that actions are accommodated to inertia both earlier and more strongly than they are accommodated to continuity. According to the knowledge in action thesis, therefore, knowledge of inertia should emerge earlier, and guide reasoning more strongly, than knowledge of continuity.

Mature knowledge of physical objects

A variety of considerations suggest that the continuity principle is central to adults' reasoning. Within cognitive and educational psychology, evidence for knowledge of continuity is mostly indirect, because this knowledge is assumed more often than it is tested. In every situation that has been studied, nevertheless, the reasoning of adults and adolescents appears to accord with the continuity principle. For example, consider experiments in which subjects are asked to draw the path followed by an object that falls from a moving carrier or exits from a curved tube. In the many discussions and examples of correct and erroneous paths presented in the published literature, we can find no case in which a subject drew a path that was discontinuous or traversed a second object (see Halloun & Hestenes, 1985; McCloskey, 1983).

In the same experiments, in contrast, subjects have been found to reason inconsistently about inertia. In some situations, reasoning about inertia is correct: adults and school-aged children judge, for example, that a linearly moving object will continue in linear motion in the absence of obstacles (Kaiser, McCloskey, & Proffitt, 1986). In other situations, reasoning is erroneous. For example, some adults and children judge that an object dropped from a moving carrier will change direction abruptly and move straight downward, contrary to inertia (Kaiser, Proffitt, & McCloskey, 1985; Kaiser, Proffitt, Whelan, & Hecht, 1992; McCloskey, Washburn, & Felch, 1983). Reasoning about inertia also tends to vary as the objects about which people reason are changed. For example, some adults judge that water that has traveled through a curved tube will continue in linear motion, whereas a ball that has traveled through the same tube will continue in curvilinear motion (Kaiser, Jonides, & Alexander, 1986).

The source of these errors and inconsistencies is not clear. Adults may have no consistent understanding of inertia but only local expectations about the behavior of familiar objects in familiar situations (Cooke & Breedin, 1990). In contrast, adults may account for effects of inertia in terms of a theory of motion centering on a principle of "impetus" (McCloskey, 1983), as did many medieval physicists (Franklin, 1976). Finally, adults may have an accurate understanding of inertia, but their understanding may be too fragile to withstand the misleading situations presented in the above experiments (Kaiser et al., 1992; Proffitt & Gilden, 1989). Regardless of their source, however, subjects' errors indicate that knowledge of inertia does not guide intuitive reasoning as strongly as knowledge of continuity. The inertia principle does not appear to figure in core physical knowledge.

Infants' actions on physical objects

Observations and experiments provide evidence that many of the actions of young infants are accommodated to inertia. For example, infants as young as 2 months visually track moving objects by extrapolating paths of motion along straight lines or smooth curves, both when the objects are fully visible (Aslin, 1981; Hofsten & Rosander, 1993a) and when they are partly hidden (Bower, Broughton, & Moore, 1971; Bower & Paterson, 1973; Moore et al., 1978; Mundy-Castle & Anglin, 1969; Piaget, 1954). In addition, infants under 2 months show defensive reactions to a linearly moving object that would contact the infant if it continued on a linear path, and not to a moving object of a similar distance whose path, if linearly extrapolated, would miss the infant (Ball & Tronick, 1971; see also Bower et al., 1971; Yonas, 1981). Finally, as soon as infants begin to reach for stationary objects (at about 4 months), infants reach "predictively" for moving objects by extrapolating object motion along a straight line (Hofsten, Spelke, Vishton, & Feng, 1993) or smooth curve (Hofsten, 1980, 1983; Hofsten & Rosander, 1993b). A variety of early-developing actions therefore accord with the constraint that objects move smoothly.

In contrast, infants' visual following and object-directed reaching do not appear to accord with the principle of continuity. When a visible object moves behind an occluder, young infants typically do not look for it (Harris, 1983; Nelson, 1971; Piaget, 1954). Although infants begin to follow the object visually over repeated presentations of a partly occluded path of motion, they tend to continue to follow the same path of motion even if the object stops in full view (Bower et al., 1971; Bower & Paterson, 1973; Harris, 1975) or moves discontinuously (Moore et al., 1978). Preliminary observations suggest that young infants' object-directed reaching is perturbed by the presence of a screen that briefly occludes object's motion (Hofsten, Spelke, Feng, & Vishton, 1993). Finally, numerous studies of infants' search for hidden objects indicate that infants do not confine their search to locations that an object could reach by moving on a connected, unobstructed path (e.g., Piaget, 1954). Neither visual nor manual search for objects appears to be guided by the principle that objects exist and move continuously.

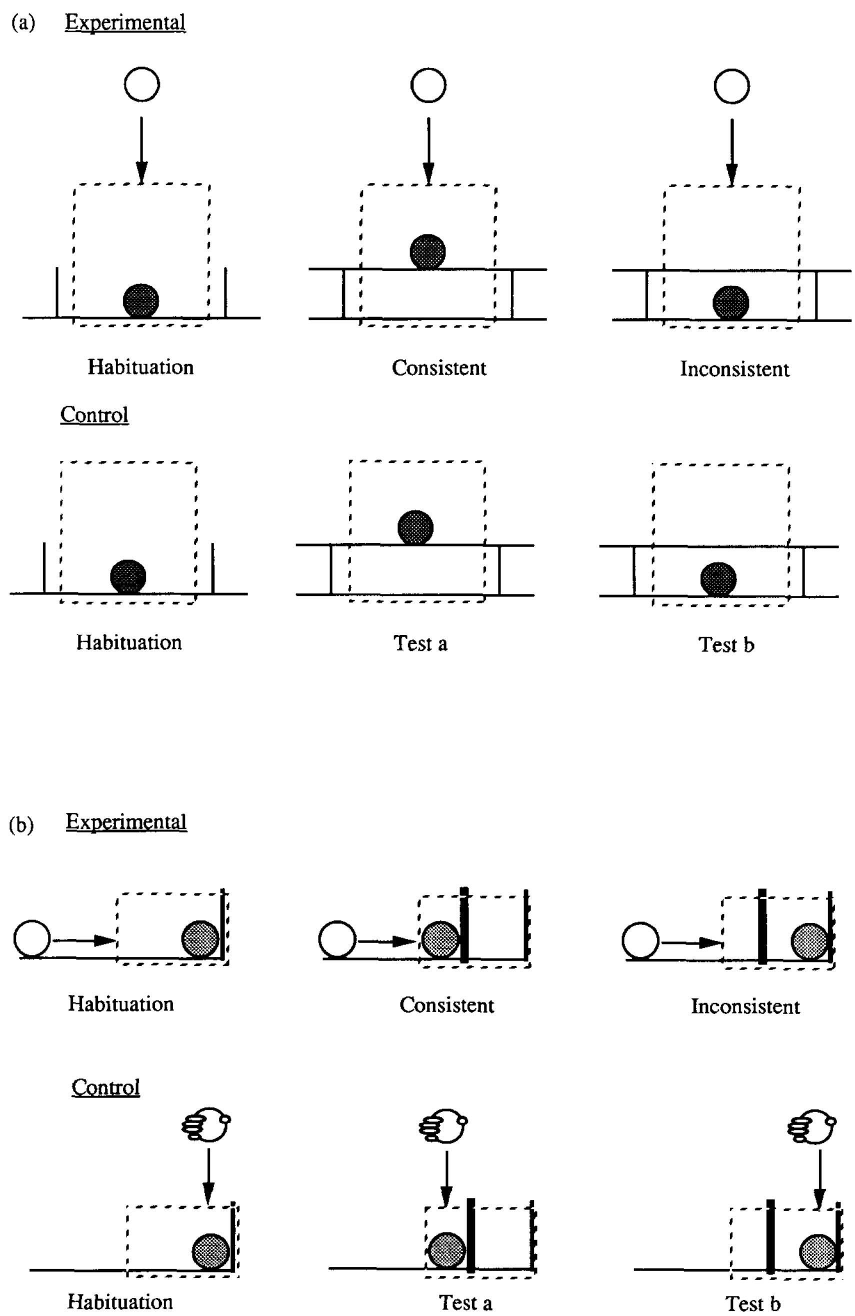
If infants' actions on objects are guided by their knowledge of object motion, these findings would suggest that infants gain knowledge of aspects of the principle of inertia before they gain any knowledge of the principle of continuity. But what is the relation between action and knowledge in infancy? To address this question, it is necessary to investigate infants' knowledge of objects by means of experimental methods that depend minimally on infants' abilities to engage in coordinated object-directed actions such as visual and manual search. Preferential looking methods meet this requirement.

Infants' reasoning about object motion

In recent years, infants' developing knowledge of object motion has been studied by means of methods that combine Piaget's (1954) invisible displacement object search task with the visual preference procedure of Fantz (1961) and others. In these studies, infants are presented with events in which objects move in and out of view under circumstances that either accord with, or violate, constraints on object motion. Infants' knowledge of a given constraint is revealed by their tendency to look preferentially at an event in which a hidden object's behavior violates the constraint, relative to events of comparable or greater superficial novelty in which the object's behavior accords with the constraint. Such research provides evidence that infants can represent hidden objects and reason about their behavior under certain conditions (e.g., Baillargeon, 1986, 1987, 1993; Baillargeon, Graber, DeVos, & Black, 1990; Ball, 1973; Carey, Klatt, & Schlaffer, 1992; Leslie, 1991; Spelke, Breinlinger, Macomber, & Jacobson, 1992; Spelke & Kestenbaum, 1986; Wynn, 1992; Xu & Carey, 1992). We focus here on experiments by Spelke et al. (1992), because they are the immediate precursors to the present studies.

Infants first were familiarized with an event in which a visible object moved out of view behind a screen and reappeared, on removal of the screen, at a position that was consistent with all constraints on object motion. The outcome display remained visible for as long as the infant looked at it, and the event was repeated until infants' looking time declined. Then the object or the display was modified, and two test events were shown in alternation. In one test event, the object moved from view and reappeared at a position that was novel but consistent with all constraints on object motion. In the other test event, the object moved from view and reappeared at a position that was familiar but inconsistent with one or more constraints. Infants' looking times to these event outcomes were compared to the looking times of infants in a control condition presenting the same outcome displays, preceded by events that were uniformly consistent with constraints on object motion. If infants were sensitive to any of the constraints that were violated by the inconsistent event, the infants in the experimental condition were expected to look longer at the inconsistent event outcome, relative to those in the control condition.

In three experiments, young infants showed a reliable preference for event outcomes in which an object appeared at a position that could not be reached by moving on any connected and unobstructed path (Spelke et al., 1992, Experiments 1–3). For example, 4-month-old infants looked longer at an event outcome in which a falling object was revealed at a familiar position below a surface in its path than at an event outcome in which the object was revealed at a novel position above that surface (Fig. 2a). In addition, 2.5-month-old infants looked


(a) Experimental
Habituation
Consistent
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Test a
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(b) Experimental
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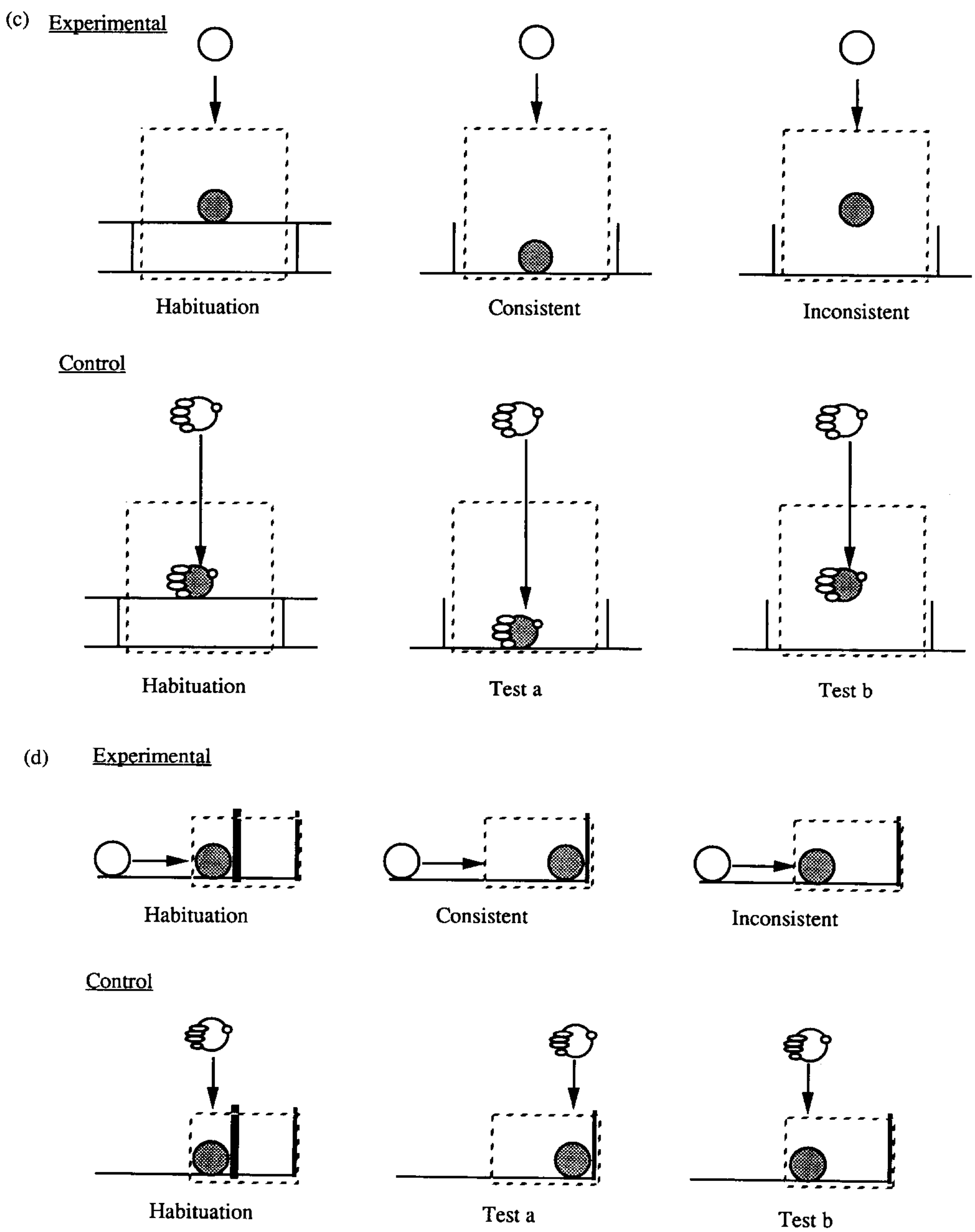

Figure 2. *Schematic depiction of the displays from two studies of infants' knowledge of continuity and two studies of infants' knowledge of inertia. Arrows indicate the path of visible object motion. (In the control condition of (a), the object moved forward in depth.) Dotted lines indicate the position of the occluder. An open circle indicates the object's position at the start of an event. When the occluder was removed, the object appeared at the position of the shaded circle. (After Spelke et al., 1992, Experiments 1, 3 and 4, and Spelke, Simmons, Breinlinger, Jacobson, & Macomber, submitted, Experiment 2).*

longer at an event outcome in which a rolling object appeared at a familiar position on the far side of the barrier that at an outcome in which it appeared at a novel position on the near side of the barrier (Fig. 2b). Control conditions within these experiments investigated a number of potential artifactual explanations for these preferences. Their findings provided evidence that infants' preferences for the inconsistent event outcomes were not attributable to the superficial novelty or intrinsic attractiveness of the inconsistent outcome displays, to a contextually induced preference for superficial features of those outcomes, or to learning about the events during the familiarization period. The design of the experiments also served to test – and the results validated – the principal assumption behind the invisible-displacement preferential looking method: infants looked longer at event outcomes that were inconsistent with their inferences about object motion (see Spelke et al., 1992). The experiments therefore provided evidence that 2.5- and 4-month-old infants infer that a hidden object will move in accord with the principle of continuity.

In contrast, two experiments provided no evidence that young infants infer that a hidden object will move in accord with the principle of inertia. In one study (Spelke et al., 1992, Experiment 4), 4-month-old infants looked no longer at an event outcome in which a falling object was revealed at a familiar position in midair, contrary to inertia (and gravity), than at an event outcome in which the object was revealed at a novel but consistent position on a surface (Fig. 2c). In the other study (Spelke, Simmons, Breinlinger, Jacobson, & Macomber, submitted, Experiment 2), 6-month-old infants looked no longer at an event outcome in which a rolling object was revealed at a familiar position next to its point of disappearance, contrary to inertia, that an event outcome in which the object was revealed at a novel but consistent position against an obstacle (Fig. 2d).

The above findings suggest that infants' knowledge of the continuity principle is stronger than their knowledge of the inertia principle, in accord with the core knowledge thesis and contrary to the knowledge-in-action thesis. This suggestion may be questioned, however, because no study presented infants with a compelling violation of the inertia principle. In the inconsistent events of Figs. 2c and 2d, a subject might reason that the hidden ball moved in accord with inertia, but that it slowed down rapidly owing to friction or rebounded off an obstacle. In addition, the above studies tested whether infants' reasoning about object motion accords with the constraint that a moving object does not abruptly stop moving in the absence of obstacles, but they did not test whether infants' reasoning accords with the constraint that a moving object does not abruptly change direction. It is the latter aspect of inertia that is most relevant to the knowledge-in-action thesis, because infants' patterns of looking and reaching appear to depend on smooth extrapolations of the path of object motion.

Experiments by Baillargeon (1986; Baillargeon & De Vos, 1991) suggest that 4- and 6-month-old infants are sensitive to this aspect of inertia. Infants were familiarized with a wagon that moved behind a screen on a straight line and reappeared at the far side of the screen on the same line. Then infants were tested with the same event, with a hidden barrier placed behind the screen in different positions. Infants looked longer at the event when the barrier was placed on the line connecting the wagon's visible motions than when it was placed in front of or behind that line. This looking pattern suggests that the infants inferred that the hidden wagon continued to move on a straight line. Baillargeon notes, however, that the infants may have extrapolated this path of motion because the wagon traveled on a brightly colored, linear track. Existing research therefore does not reveal whether young infants' reasoning about object motion is guided by knowledge that freely moving objects move smoothly.

Overview of the experiments

The present studies investigated whether young infants infer that a linearly moving object will continue on a path that is linear and continuous. The studies used the invisible displacement, preferential looking method of Spelke et al. (1992). Experiments 1, 2, 3, and 5 investigated infants' knowledge of the inertia principle at ages ranging from 4 to 12 months. Experiment 4 tested infants' knowledge of the continuity principle at 6 and 10 months. Because the method and displays of Experiment 4 were similar to those of Experiments 1–3, a comparison of the findings of these experiments serves to assess the relative strength of knowledge of inertia and continuity.

EXPERIMENT 1

This experiment investigated whether 4.5-month-old infants infer that a linearly moving object will continue in a linear motion after it moves from view. Infants were presented with a billiard-style table whose right side was continuously visible and whose left side was alternately covered and uncovered by a screen. They were familiarized with an event in which the screen covered the left side of the table, a ball was introduced in one of the visible right corners, the ball rolled on the table's diagonal and disappeared behind the screen, and the screen was raised to reveal the ball at rest at the opposite left corner, on a line with its former motion (see Fig. 3). Looking time was recorded after the raising of the screen, beginning with the first look at the ball and ending when the infant looked away from the table. This event occurred repeatedly until looking time declined to a criterion of habituation.

The test sequence followed. The ball was presented in the other visible right corner, and it rolled behind the screen on the opposite diagonal. When the screen was raised, the ball either appeared at a new position on a line with its former

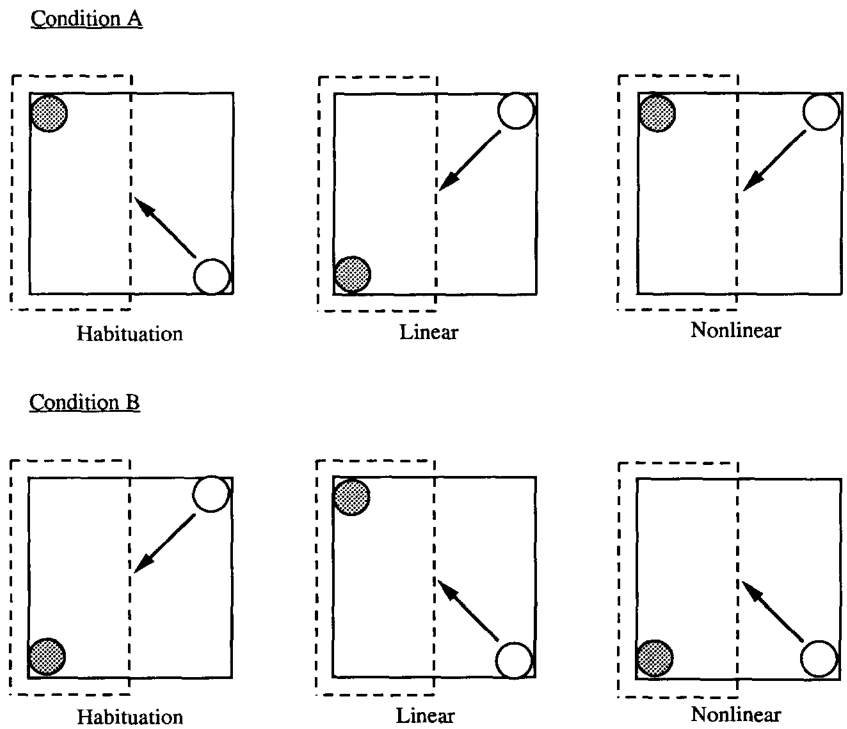

Figure 3. *Schematic depiction of the events for Experiment 1, viewed from above. The events are not drawn to scale (see Fig. 4 and text).*

motion (consistent with inertia) or at its familiar position: a position it could only reach by making a 90° turn behind the screen (inconsistent with inertia). Looking times to the two event outcomes were recorded. If infants infer that a linearly moving object will continue in linear motion, they were expected to look longer at the outcome of the inconsistent event, despite its superficial familiarity. If infants fail to make this inference, they might show the opposite looking preference: longer looking at the superficially more novel, consistent event outcome.

Method

Subjects

Participants were 16 infants ranging in age from 4 months, 11 days to 4 months, 28 days (mean age = 4 months, 19 days). One additional infant failed to complete the study because of fussiness and was replaced.[2] The 10 male and 6 female infants in the final sample were born of full-term pregnancies, had no known or suspected abnormalities, and lived in or near Ithaca, New York.

Apparatus and events

The events were presented on a white, horizontal, 80 × 80 cm surface surrounded by 12 cm high walls and containing a white, solid, 12 cm high insert in the shape of a box with a central indentation (see Fig. 4).[3] The right side of the display was continuously visible to the infant, who looked downward from a position 28 cm in front of and 50 cm above the surface. The left side of the surface was hidden at the beginning of each event by a horizontal 36 × 76 cm white screen that stood 13 cm above the surface (Fig. 4a). This screen was raised to a vertical position at the left side of the display at the end of each event (Fig. 4b). The back and sides of the display were surrounded with beige curtains that blocked the infant's view of any other objects or people in the room. Small holes in the curtains enabled observers and experimenters to watch the infant throughout the study.

The events involved a yellow sponge-foam ball, 6.2 cm in diameter, covered with red, blue, and green dots. Two events involving linear motion and two events involving non-linear motion could be presented within this display. In one linear event, the screen was lowered and the hand-held ball was placed in the back right corner of the display through a hole in the side wall. The hand struck the ball and withdrew from the display, and the ball rolled leftward on a straight line toward the center of the surface, where it disappeared behind the screen. The screen was raised 2 s later to reveal the ball at rest in the front left corner of the display, on a line with its previous motion. In the other linear event, the ball was placed initially in the front right corner, it rolled leftward to the center, and it reappeared at the back left corner. The two non-linear events were the same as the linear events, except for the final position of the ball. In the event in which the ball rolled from the back right corner to the center, the ball reappeared at the back left corner; in the event in which the ball rolled from the front right corner,

[2]Although attrition rates in the present studies were not high, the data from rejected subjects were analyzed whenever possible (i.e., whenever such a subject contributed data to at least one pair of test trials) in order to assess whether effects were sufficiently robust as to survive the inclusion of subjects tested under less than optimal conditions. Because the single subject eliminated from Experiment 1 received no test trials, no such analyses were possible for this experiment.

[3]The dimensions and shape of the insert were chosen so as to assure that the ball was fully visible at each of its two final positions from the infant's station point, and that the two final positions were equidistant from the ball's point of disappearance.

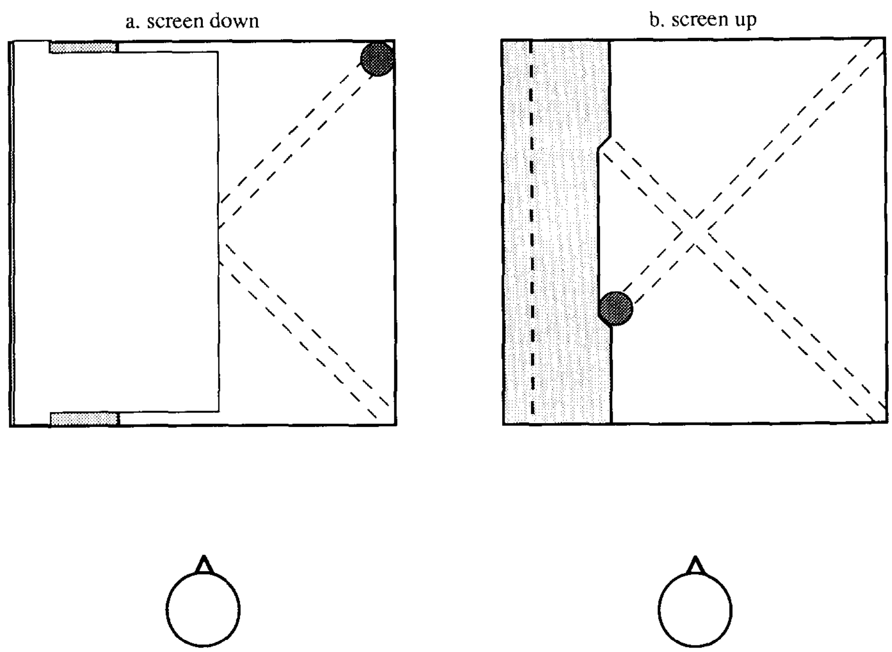

Figure 4. *Overhead view, drawn to scale, of the display used in the present experiments and of the position of the baby in relation to the display. (a) The display at the start of an event, with the ball (filled circle) at its starting position. Thin dotted lines indicate the position of the glass rods, thick solid lines indicate the walls of the display, and thin solid lines indicate the position of the (horizontal) screen. (b) The display at the end of an event, with the ball at its final position. The large shaded figure indicates the solid insert against which the ball rested, and the thick dotted line indicates the position of the (vertical) screen.*

it reappeared at the front left corner. Both non-linear events therefore presented the ball at an outcome position that was 90° displaced from the line of the ball's previous, visible motion. After the raising of the screen, an outcome display remained visible for as long as the infant looked at it (see below), and then a hand entered the display from a hole in the left wall and grasped and removed the ball. The procedure used to produce the four events is described below.

The motion of the ball in these events was guided by parallel, colorless glass rods at the positions indicated in Fig. 4, sitting on the table and spaced such that the ball rolled on the table without wobbling or deviating from a linear path. These rods were visible (to adults) but inconspicuous. The ball moved silently at approximately 15 cm/s. At the infant's point of observation, the ball subtended 5.1° and 3.1° at its most extreme front and back positions, and it moved at approximately 10°/s.

A group of 12 adult subjects were shown the two linear and two non-linear events while standing with their eyes at the infant's point of observation. Subjects were shown each event three times and were asked to rate the naturalness and expectedness of the event on a scale from +3 (very natural and expected) to −3 (very unnatural and unexpected), following the method of Spelke et al. (1992). Adults judged that the two linear events were highly natural (each mean rating was 2.83, each $t\ (11) = 24.2$, $p < .001$) and that the two non-linear events were highly unnatural (for the nonlinear outcome with the object in the left back position, the mean rating was −2.50, $t\ (11) = -10.3$, $p < .001$; for the non-linear outcome with the object in the left front position, the mean rating was −2.42, $t\ (11) = -10.0$, $p < .001$).

Design

Equal numbers of infants were tested in each of two conditions (see Fig. 3). The infants in condition A were habituated to the linear event that began in the front right corner and then were tested with the linear and non-linear events that began in the back right corner. The infants in condition B were habituated to the linear event that began in the back right corner and were tested with the linear and non-linear events that began in the front right corner. Because the outcome display for the linear event of condition A was identical to the outcome display for the nonlinear event of condition B, the experimental design controls for any intrinsic preferences between the two outcome displays. Infants were presented with the linear and nonlinear test events on six alternating trials. Within each of the two conditions, half the infants were shown the linear test event first.

Procedure

The infant was placed in a booster seat and was held around the waist by a parent, who stood behind him. The first experimenter asked the parent not to interact with the infant during any trial and not to look at the display during the test sequence, and then he moved behind a curtain adjacent to the infant and parent and monitored the parent, the infant, and the events throughout the study. Parental compliance with these instructions was high.

At the start of the study, the screen was placed in its raised position. The second experimenter appeared from behind the back curtain of the display, greeted the baby, and tapped in turn at the center and the four corners of the display until the infant looked at each position. Then the experimenter disappeared behind the curtain and lowered the screen for the first habituation trial. A third experimenter, seated to the right of the display and watching the baby through a peephole, introduced a ball in one of the two visible corners of the display, tapped the ball on the horizontal surface, and called to the baby, if necessary, until the baby looked at the ball for 1 s. Then the third experimenter struck the ball lightly so that it rolled on the surface along the diagonal rods and disappeared under the screen at the display's center. The second experimenter caught the ball, placed it in the appropriate left corner, and raised the screen approximately 2 s after the ball's disappearance. The second experimenter's actions were silent and hidden from the infant's view.

Two observers recorded the infant's looking time after the raising of the screen. The primary observer was seated beside the second experimenter, positioned such that she could see the infant but not the display. The third experimenter served as the secondary observer; from his viewing position, he could see the baby and the right side of the display but not the display's left side. Each observer recorded looking time by depressing a push-button input to a computer. Looking time began to be recorded when the primary observer judged that the infant first looked at the corner that contained the ball. (Observers were told the position of the ball during the habituation sequence.) The observers then recorded all looks at any location on the horizontal surface. The trial ended with a tone signal from the computer when the primary observer recorded no looking at the surface for 2 s continuously, or when the baby had looked at the display for 120 s. Then the second experimenter's hand entered the display from the opening on the left, grasped the ball, waved it and called to the baby as necessary until the baby looked at it, and removed the ball from the display.

Habituation trials were presented until a maximum of 14 trials were given or until the computer determined, from the primary observer's record, that the infant had met the criterion of habituation. The criterion was a 50% decrease in looking time on three consecutive trials, from the infant's looking time on the first three consecutive trials whose looking time exceeded 12 s. The end of the habituation sequence was signaled by a second tone from the computer.

Before the test sequence, the second experimenter again appeared from behind the display, greeted the baby, and called the baby's attention to the four corners and center of the table. Then the experimenter withdrew behind the curtain, the screen was lowered, and the test sequence began. On each test trial, the screen was lowered and the third experimenter introduced the ball into the other visible corner of the display. As before, the ball was waved and tapped, and it disappeared at the center of the table. The second experimenter caught the ball and placed it in one of the two left corners. (Over the six test trials, the ball was placed alternately at the front and back left corners.) Then he withdrew his hand and raised the screen. The second experimenter's actions again were hidden, were silent, and lasted 2 s.

Looking time began to be recorded when the primary observer judged that the infant first looked at either left corner of the table. (Observers were not told, and could not see, the position of the ball on any given test trial.) Thereafter, looking time was recorded following the same procedure as for the habituation trials.

Interobserver agreement (i.e., the proportion of seconds during which both observers recorded that the infant was or was not looking at the display) averaged .90.

Analyses

In research using this method, looking time distributions are highly irregular and fail to meet the assumptions of general linear models even after a variety of metric transformation (Darlington, 1990; Darlington & Van de Walle, in preparation). Non-parametric statistics were used, therefore, for all the analyses. Looking times to the three consistent outcomes and to the three inconsistent outcomes were summed, and then the proportion of test trial looking at the inconsistent outcome was calculated for each infant. This proportion served as the measure of the infant's preference for the inconsistent outcome. A Wilcoxon test compared these proportions to the chance value of .5; a Wilcoxon–Mann–Whitney test (Siegel and Castellan, 1988) compared the looking preferences of infants in different conditions. Except where noted, one-tailed tests were performed.

Finally, the test trial data were analyzed by a 2 (condition: A vs. B) × 2 (test trial order: linear first vs. non-linear first) × 3 (trial pair) × 2 (test event: linear vs. non-linear) analysis of variance, with the last two factors within subjects. This analysis served to assess other main effects and interactions beyond those on which we focus. This test appears to be conservative, because of the outlier problem (Darlington & Van de Walle, in preparation).

Results

Looking time averaged 16.4 s per trial on the first three habituation trials. Infants received an average of eight familiarization trials; one infant failed to meet the habituation criterion and was tested after 14 familiarization trials.

Figure 5 presents the mean looking times on the last six habituation trials and on the six test trials. After habituation, infants tended to look longer at the superficially novel, *linear* outcome, Wilcoxon $z = 1.71$, $p < .10$, two-tailed ($N = 16$). The preference for the outcome that was consistent with inertia did not differ across the two conditions of the experiment, Wilcoxon–Mann–Whitney $z < 1$ (each $n = 8$; $N = 16$). The results of the analysis of variance accorded with these findings. The only significant effect was a main effect of test event, $F\ (1, 12) = 5.15$, $p < .05$: infants looked longer at the linear event outcome.

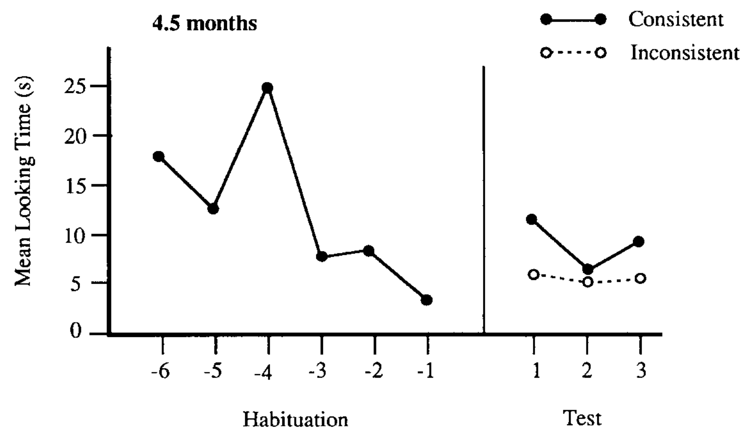

Figure 5. *Mean duration of looking by the 4.5-month-old infants in Experiment 1.*

Discussion

At 4.5 months of age, infants tended to look longer when an object was revealed at a novel position on a line with its former visible motion than when it was revealed at a familar position on a line orthogonal to its former visible motion. This preference is opposite in direction to the preference expected if infants inferred that the hidden object would continue in linear motion; it suggests that infants responded only to the superficial novelty or familiarity of the object's final position. Experiment 1 therefore provides no evidence that young infants' inferences are guided by knowledge of inertia. Accordingly, the next experiment investigated developmental changes in reactions to the present events, by presenting the method of Experiment 1 to infants at two older ages: 6 and 8 months.

EXPERIMENT 2

Method

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

Subjects

Sixteen infants participated in the study. The younger participants were 4 male and 4 female infants ranging in age from 5 months, 26 days to 6 months, 14 days (mean = 6 months, 5 days). Two additional infants were eliminated from the sample because of fussiness (1) or experimenter error (1). The older participants were 3 male and 5 female infants ranging in age from 7 months, 18 days to 8 months, 15 days (mean = 8 months, 2 days). No further subjects were eliminated from the sample.

Design, procedures, and analyses

Within each age group, equal numbers of subjects were tested in condition A and condition B. The order of test trials was counterbalanced across the infants at each age and in each condition. Interobserver agreement during the test trials averaged .94 for the 6-month-old infants and .93 for the 8-month-old infants. The non-parametric analyses were the same as in Experiment 1. Further non-parametric analyses tested for changes with age in preferences between the events. Finally, the test trial data were subjected to a 2 (age: 6 months vs. 8 months) × 2 (condition: A vs. B) × 2 (test trial order: linear first vs. non-linear first) × 3 (trial pair) × 2 (test event: linear vs. non-linear) analysis of variance, with the last two factors within subjects.

Results

Mean looking time per trial on the first three habituation trials was 10.5 s for the 6-month-old infants and 8.2 s for the 8-month-old infants. Infants received an average of seven familiarization trials at 6 months and eight familiarization trials at 8 months. One infant at 6 months and 2 infants at 8 months failed to meet the habituation criterion and were tested after 14 trials.

Figure 6 presents the mean habituation and test trial looking times at each age. During the test, infants looked longer at the superficially novel, linear test outcome, Wilcoxon $z = 2.12$, $p < .05$, two-tailed ($N = 16$).[4] The preference for this outcome did not differ across the two ages or conditions, both Wilcoxon–Mann–Whitney zs < 1 (each $n = 8$; each $N = 16$).

In the analysis of variance, the preference for the linear outcome display was marginally significant, $F\ (1, 8) = 3.51$, $p < .10$. The only significant effects in the analysis were the main effects of condition, $F\ (1, 8) = 7.98$, $p < .05$, and trial pair, $F\ (2, 16) = 5.42$, $p < .02$. Looking times during the test sequence were higher overall for infants in condition B, and looking times declined over successive pairs of test trials.

A final analysis compared the looking times of the infants in Experiment 2 to those of the infants in Experiment 1. Although the preference for the linear

[4]With the test trial data from rejected subjects included, $z = 1.54$, $p < .10$.

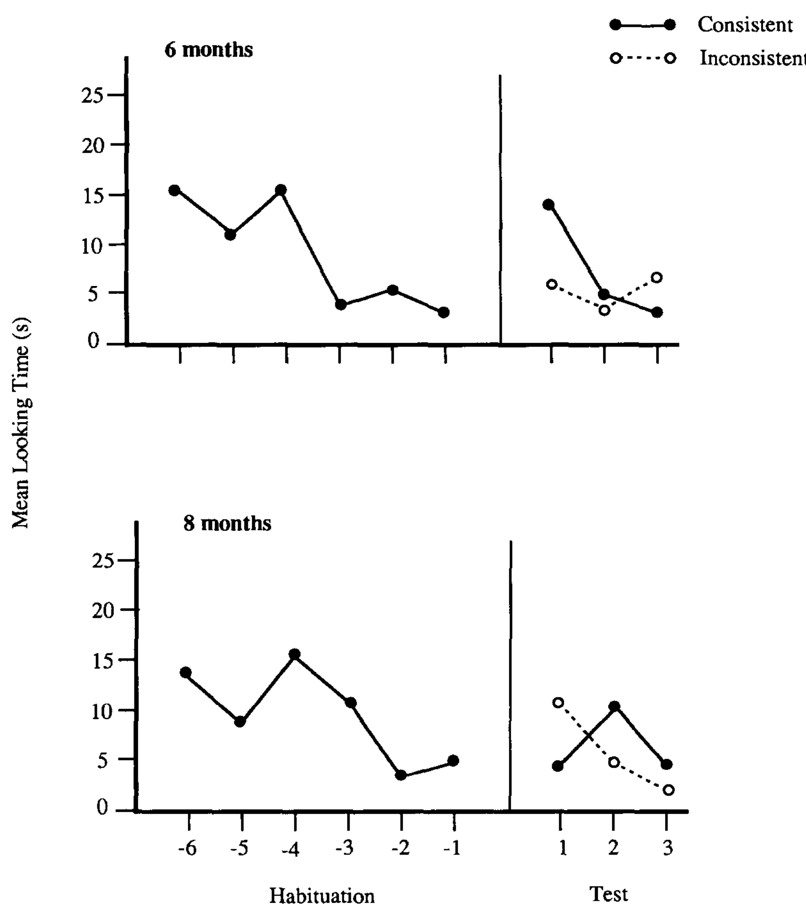

Figure 6. *Mean duration of looking by the 6- and 8-month-old infants in Experiment 2.*

outcome display appeared to decrease with age, this decrease was not significant. There was no difference in looking preferences for the linear outcome display across the two experiments, Wilcoxon–Mann–Whitney $z = 1.09$, $p > .20$ (each $n = 16$; $N = 32$).

Discussion

The findings of Experiment 2 were similar to those of Experiment 1: infants tended to look longer at an event outcome that was novel but consistent with inertia than at an event outcome that was superficially familiar but inconsistent with inertia. The experiment therefore provides no evidence that 6- or 8-month-old infants infer that an object in linear motion will continue in linear motion.

Accordingly, the next experiment focused on 10- and 12-month-old infants' reactions to the same event outcomes.

EXPERIMENT 3

Method

The method was the same as in Experiment 2, except as follows.

Subjects

Sixteen infants participated in the experiment: Four male and 4 female infants ranging in age from 9 months, 17 days to 10 months, 9 days (mean = 10 months, 0 days), and 4 male and 4 female infants ranging in age from 11 months, 17 days to 12 months, 13 days (mean = 12 months, 2 days). One additional 10-month-old infant was eliminated from the sample because of an experimenter error, and 2 additional 12-month-old infants were eliminated from the sample because of fussiness.

Procedure

Interobserver agreement averaged .83 (10 months) and .87 (12 months).

Results

On the first three trials, looking time per trial averaged 8.5 s at 10 months and 7.6 s at 12 months. The mean number of familiarization trials was ten (10 months) and nine (12 months). One infant at each age failed to meet the habituation criterion and was tested after 14 trials.

Figure 7 presents the mean looking times on the familiarization and test trials at each age. During the test, the infants at both ages looked about equally at the linear and non-linear event outcomes, Wilcoxon $z < 1$ ($N = 16$).[5] There was no change in preferences from 10 to 12 months and no difference between preferences in the two conditions, both Wilcoxon–Mann–Whitney zs < 1 (each $n = 8$; each $N = 16$).

In the 2 (age: 10 months vs. 12 months) × 2 (condition: A vs. B) × 2 (test trial

[5] With the data from rejected subjects included, $z < 1$.

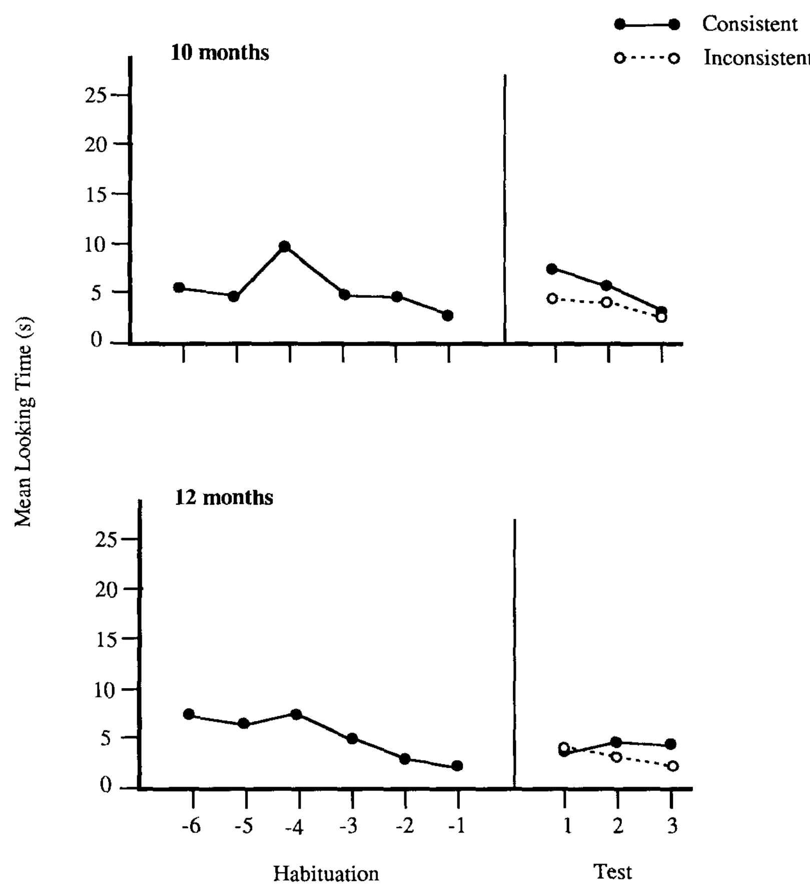

Figure 7. *Mean duration of looking by the 10- and 12-month-old infants in Experiment 3.*

order: linear first vs. non-linear first) × 3 (trial pair) × 2 (test event: linear vs. non-linear) analysis of variance, the only significant effects were an interaction of age, condition, and trial pair, $F\ (2, 16) = 4.24$, $p < .05$, and an interaction of test trial order, trial pair, and test event, $F\ (2, 16) = 6.66$, $p < .01$. The first interaction is not interpretable; the second interaction appears to reflect a decline in looking time over trials: infants looked longer at whichever test event was presented first, and this difference declined over successive pairs of trials.

Further analyses compared the looking preferences of the infants in Experiment 3 to those of the infants in Experiments 1 and 2. Although the preference for the linear outcome appeared to be lower in Experiment 3 than in the previous studies, this difference was not significant. There were no reliable differences between the preferences of infants at 10/12 months and those at 6/8 months or at 4.5 months, both Wilcoxon–Mann–Whitney $zs < 1$ (each $n = 16$; each $N = 32$).

Discussion

The 10- and 12-month-old infants in Experiment 3 showed no preference between a superficially novel outcome that was consistent with inertia and a superficially familiar outcome that was inconsistent with inertia. The experiment therefore provides no evidence that 10- and 12-month-old infants infer that a hidden object will continue to move on a line with its former visible motion.

DISCUSSION OF EXPERIMENTS 1–3

Table 1 summarizes the principal findings of these experiments. At no age, from 4.5 months to 12 months, did infants exhibit any preference for an event outcome in which an object appeared at a position 90° displaced from the line of its previous motion. Experiments 1–3 therefore provide no evidence that infants aged 4–12 months infer that a linearly moving object will continue in linear motion. The findings of these experiments accord with and extend the findings of previous studies using this method to investigate infants' reactions to events in which an object appears to stop moving abruptly and spontaneously (Spelke et al., 1992; Spelke, Simmons, Breinlinger, Jacobson, & Macomber, submitted). None of these experiments suggest that infants expect smoothly moving objects to continue in smooth motion.

As Table 1 indicates, the younger infants in these studies tended to look longer at the outcome of the event that was consistent with inertia, in which the object appeared at a superficially novel position. In contrast, no preference for the consistent event outcome was evident at the oldest ages. Although no age differences in looking preferences were statistically reliable, the apparent decline with age in infants' preference for the superficially more novel, consistent event outcome raises the possibility that some knowledge of inertia is emerging over this age period. We return to this possibility in Experiment 5.

The findings of Experiments 1–3 contrast with the findings of studies of infants' knowledge of the continuity principle (Spelke et al., 1992). This contrast suggests

Table 1. *Proportion of looking at outcomes inconsistent with inertia (Experiments 1–3)*

Age (months)	Median	Mean
4.5	.399	.425
6	.426	.429
8	.447	.470
10	.449	.451
12	.493	.474

that knowledge of continuity is a stronger guide to infants' reasoning than knowledge of inertia, as predicted by the core knowledge thesis. Nevertheless, a comparison of the findings of these two sets of experiments is complicated by a number of extraneous differences between their methods. In particular, the studies of infants' knowledge of continuity were conducted with younger infants than Experiments 1–3, and they used different displays and events. It is possible that the invisible displacement preferential looking method is less effective at older ages, or that the present events were more difficult to follow than the events in previous studies.

Accordingly, Experiment 4 was conducted to investigate directly the relative strength of infants' knowledge of continuity and inertia. Six- and 10-month-old infants were shown displays and events very similar to those of Experiments 1–3, but in which the object's final position was either consistent or inconsistent with the continuity principle. Looking times to the consistent and inconsistent event outcomes were compared to the looking times of the subset of infants in Experiments 2 and 3 who were tested at the same ages and with comparable events that were consistent or inconsistent with the inertia principle (see below). If the negative findings of Experiments 1–3 stem from limitations of the method, displays, or events, then the findings of Experiment 4 should be equally weak or negative. If the findings of Experiments 1–3 reflect the weakness of infants' knowledge of inertia, relative to their knowledge of continuity, then the infants in Experiment 4 should show stronger looking preferences for the inconsistent test outcomes than their counterparts in Experiments 2 and 3.

EXPERIMENT 4

Infants were familiarized with the event from the previous studies in which the ball moved linearly to the table's front left corner. Then a barrier was placed in the display in front of that corner (Fig. 8). On alternating test trials, the ball moved behind the screen and either reappeared at a new corner outside the barrier (novel but consistent with the continuity principle) or at its former position (familiar but inconsistent with the continuity principle). Looking times to the two test outcomes were compared to each other and to the looking preferences of infants in Experiments 2 and 3. If infants' inferences about object motion are guided more strongly by the continuity principle than by the inertia principle, then the infants in Experiment 4 should look longer at the familiar but inconsistent outcome, and this preference should exceed the corresponding preference for the inconsistent outcome shown by the infants in Experiments 2 and 3.

As Fig. 8 indicates, there was a confounding factor in the design of this experiment: because the outcome of the inconsistent event always presented the

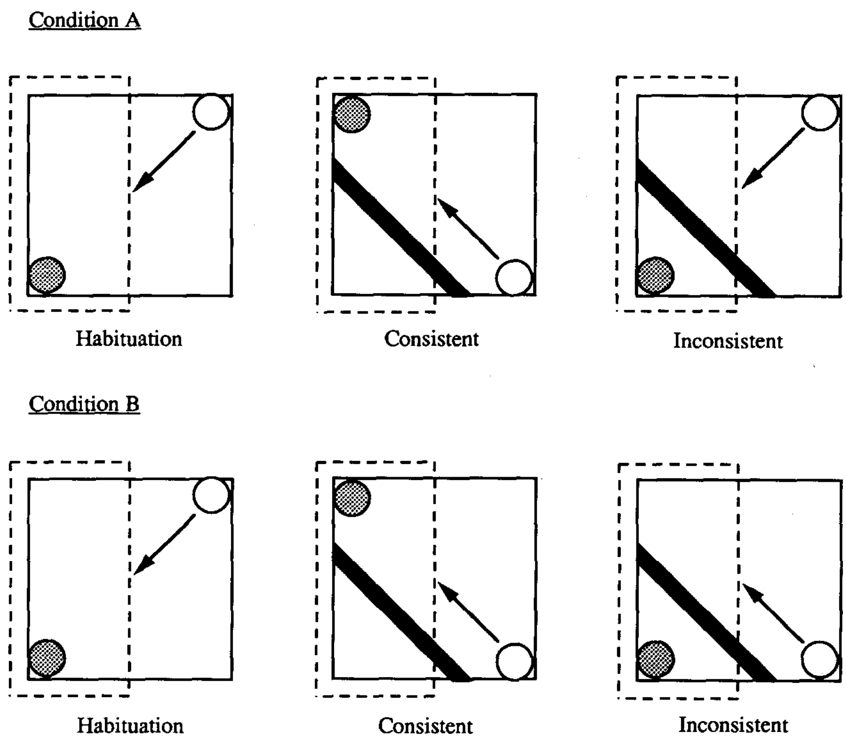

Figure 8. *Schematic depiction of the events for Experiment 4, viewed from above. The events are not drawn to scale (see Fig. 4 and text).*

ball in the front position, the predicted preference for the inconsistent outcome could be produced by an intrinsic preference for that position.[6] Although no such preference emerged from the analyses of Experiments 1–3, we controlled for this preference in the analyses comparing the findings of Experiment 4 to those of Experiments 2 and 3. The looking preferences of the infants in Experiment 4 were compared to the looking preferences of only half the 6- and 10-month-old infants in Experiments 2 and 3 – those who had viewed the ball in the front position on the inconsistent test trials. Any difference in looking preferences across these experiments therefore cannot be attributed to a preference for a given position of

[6]The confound was unavoidable, because any barrier that blocked the path of a ball that rolled to the left back corner would also occlude the ball when it stood in that corner. A second possible confound in this experiment concerns the position of the ball relative to the barrier: infants may look longer at the inconsistent outcome display because of an intrinsic preference for a display in which a ball stands near a barrier, relative to a display in which the ball is further from the barrier. Previous control studies using the present method cast doubt on this possibility: infants aged 4, 6, and 9 months have shown no preferences between an outcome display in which a ball stands next to a barrier over a display in which the ball is further away (Spelke et al., 1992; Spelke, Jacobson, Keller, & Sebba, submitted; Spelke, Simmons, Breinlinger, Jacobson, & Macomber, submitted).

the ball, because the position of the ball on the inconsistent events was the same across the studies.

For all the infants in Experiment 4, the consistent test outcome was consistent with both the continuity and the inertia principles: the ball appeared to move on a linear and unobstructed path. For half the infants (condition A), the inconsistent test event was inconsistent with the continuity principle but consistent with inertia: the ball appeared to move on a linear path through a hidden obstacle. This condition is similar to previous studies of infants' knowledge of the continuity principle (Spelke et al., 1992). For the remaining infants (condition B), the inconsistent test event was inconsistent with both the continuity principle and the inertia principle: the ball appeared to move on a non-linear path through the hidden obstacle. A comparison of conditions A and B permits a further test of infants' knowledge of inertia: if infants infer that a linearly moving object will continue in linear motion, then reactions to the inconsistent event outcome should be stronger in condition B than in condition A.

Method

Subjects

Participants were 16 infants at 6 months of age and 16 infants at 10 months of age. The younger age group consisted of 7 males and 9 females ranging from 5 months, 15 days to 6 months, 15 days (mean = 5 months, 27 days). One additional infant was eliminated because of errors in stimulus presentation. The older age group consisted of 9 males and 7 females ranging in age from 9 months, 17 days to 10 months, 15 days (mean = 9 months, 28 days). Two additional infants were eliminated because of fussiness (1) or experimenter error (1).

Displays

The habituation event was the same as in condition B of Experiments 1–3: the ball began at the back right corner, moved forward on the table's diagonal, and reappeared at the front left corner. For the test events, a bright orange barrier, rectangular in shape and measuring 53 × 8 × 4 cm, was placed in front of the front left corner of the display. When the screen was lowered, it covered all but the right end of the barrier. For the consistent test event, the ball was rolled from the front right corner and reappeared in the back left corner. For the inconsistent test events, the ball either rolled from the back right corner and reappeared at the front left corner (condition A) or it rolled from the front right corner and reappeared in the front left corner (condition B).

Design

Half the infants at each age were tested in each condition. The order of test trials was counterbalanced within each age and condition.

Procedure

The procedure for the familiarization trials was the same as in Experiments 1–3. Before the test sequence, the second experimenter appeared behind the display with the screen raised and positioned the barrier in the display. In addition to tapping the four corners and the center of the table, he tapped along the sides of the barrier, calling to the infant until the infant looked along the barrier's full length. Then the second experimenter withdrew, the screen was lowered, and the third experimenter introduced and rolled the ball as before. The second experimenter caught and positioned the ball as in Experiments 1–3. Interobserver agreement averaged .85 (6 months) and .88 (10 months).

Analyses

Test trial looking times were analyzed as in Experiments 1–3. In addition, a non-parametric analysis compared the looking preferences of the infants in Experiment 4 to those of the 6-month-old infants from condition B of Experiment 2 and the 10-month-old infants from condition B of Experiment 3. Finally, non-parametric analyses focused separately on the looking preferences of the infants in each condition of Experiment 4 and on the difference in looking preferences across the two conditions.

Results

Figure 9 presents the mean looking times on the last six familiarization trials and the six test trials. On the first three familiarization trials, looking time per trial averaged 11.4 s at 6 months and 6.7 s at 10 months. At each age, infants received an average of ten familiarization trials. Two 6-month-old infants and 4 10-month-old infants failed to meet the habituation criterion and were tested after 14 trials.

During the test, infants of both ages tended to look longer at the outcome of the event that was inconsistent with the continuity principle. This preference was significant both at 6 months, Wilcoxon $z = 1.94$, $p < .05$ ($N = 16$), and at 10

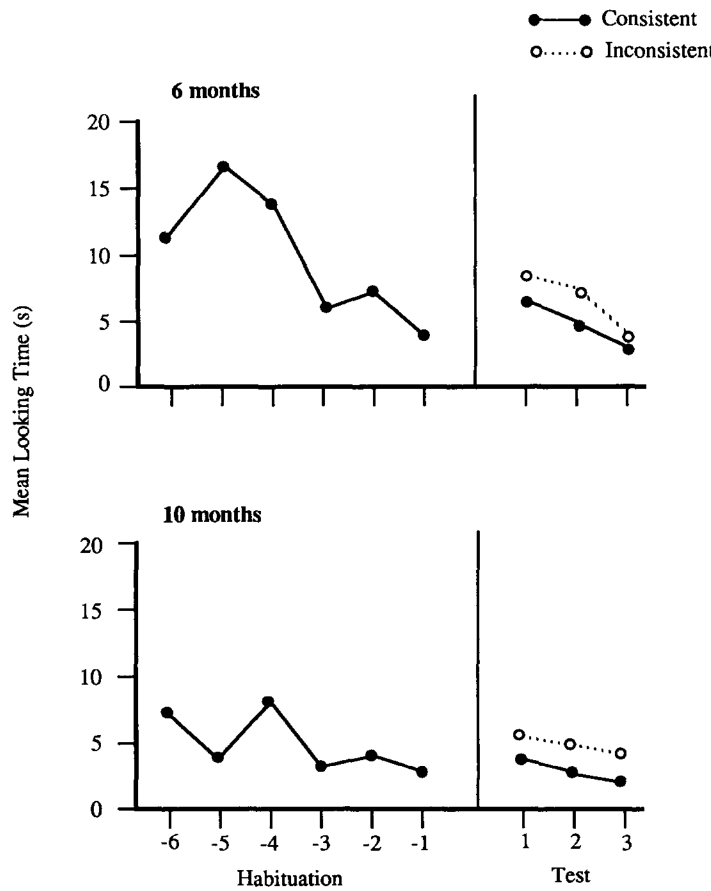

Figure 9. *Mean duration of looking by the 6- and 10-month-old infants in Experiment 4.*

months, Wilcoxon $z = 2.36$, $p < .01$ ($N = 16$).[7] Preferences did not differ across the two ages, Wilcoxon–Mann–Whitney $z < 1$ (each $n = 16$; $N = 32$).

The 2 (age: 6 months vs. 10 months) × 2 (condition: A vs. B) × 2 (test event order: consistent first vs. inconsistent first) × 3 (test trial pair) × 2 (test event: consistent vs. inconsistent) analysis of variance gave concordant findings. The only significant effects in this analysis were the expected main effect of test event, $F\,(1, 24) = 7.53$, $p < .02$, and a main effect of trial pair, $F\,(2, 48) = 4.34$, $p < .02$: infants looked longer at the event outcome that was inconsistent with the continuity principle, and they looked longer on the earlier test trials.

The central question concerned the relative strength of infants' preference for an event outcome that was inconsistent with continuity and an event outcome that

[7]With the data from the rejected subjects included, $z = 1.94$, $p < .05$ (6 months) and $z = 1.75$, $p < .05$ (10 months).

Table 2. *Proportion of looking at outcomes inconsistent with continuity (Experiment 4)*

Age and condition	Median	Mean
(a) Experiment 4		
6 months	.573	.565
10 months	.595	.593
(b) Experiments 2b and 3b		
6 months	.473	.473
10 months	.445	.452

Table 3. *Proportion of looking at outcomes inconsistent with continuity and consistent or inconsistent with inertia (Experiment 4)*

Condition	Median	Mean
(a) Condition A (consistent with inertia)	.593	.594
(b) Condition B (inconsistent with inertia)	.560	.564

was inconsistent with inertia. The analysis comparing the present data to the data from the subset of 6- and 10-month-old infants tested in condition B of the earlier experiments revealed that reactions to the inconsistent event outcome were significantly greater in the present study (see Table 2), Wilcoxon–Mann–Whitney $z = 2.11$, $p < .02$ (respective ns = 32 and 8; $N = 40$).

The final analyses assessed infants' sensitivity to violations of inertia within Experiment 4. First, separate analyses of the looking time data from each condition revealed that infants showed a reliable preference for the event outcome that was inconsistent with continuity, both when the outcome was consistent with inertia, Wilcoxon $z = 3.13$, $p < .001$ ($N = 16$) and when it was not, Wilcoxon $z = 1.76$, $p < .05$ (see Table 3). Preferences for the event outcome that was inconsistent with continuity did not differ across these two conditions, Wilcoxon–Mann–Whitney $z < 1$ (each $n = 16$; $N = 32$), suggesting no effect of inertia on infants' looking preferences.

Discussion

At 6 and 10 months, infants showed a reliable preference for an event outcome in which an object moved from view and reappeared on the far side of an obstacle, contrary to the continuity principle. Infants' preference for this event outcome was reliably greater than the preference of infants in previous experiments for an event outcome that was inconsistent with inertia. This difference in preferences was observed, despite the fact that all the infants were tested by means of the same method and closely similar displays. It provides evidence that the infants' knowledge of continuity is stronger than their knowledge of inertia, in accord with the core knowledge thesis.

Experiment 4 extends the findings of the previous studies of infants' knowledge of the continuity principle (Spelke et al., 1992). First, it provides evidence that the continuity principle guides inferences about object motion in infants beyond 4 months of age, with no apparent developmental change in infants' inferences between 6 and 10 months. Further analyses of the data from this experiment, reported in the Appendix, provide additional evidence that knowledge of continuity is not undergoing developmental changes at these ages. Second, it provides evidence that the continuity principle guides infants' inferences when objects move in depth as well as when they move vertically or horizontally (Spelke et al., 1992). Infants appear to infer continuous motion in a variety of events.

Experiment 4 sheds light on the proper interpretation of Experiments 1–3. Its findings indicate that the invisible displacement method is appropriate for research with infants as old as 10 months, and that the present displays and events were not too difficult for infants to follow: infants showed no across-the-board preference for novel positions over familiar ones, and they were able to attend to and extrapolate the object's hidden motion. A comparison of Experiment 4 with Experiments 1–3 suggests that success or failure in these experiments depended on the principles that were available to guide inferences about object motion. When inferences about object motion depended on the continuity principle, infants looked longer at a superficially familiar object position that failed to correspond to the object's inferred motion. When inferences about object motion depended on the inertia principle, in contrast, infants showed no preference for the inconsistent event outcome. In Experiments 1–3, infants tended to look longer at the event outcome presenting the object at a superficially novel position. In Experiment 4, infants' preferences for an event outcome that was inconsistent with continuity were equally strong, regardless of whether the outcome was consistent or inconsistent with inertia. Four experiments therefore provide no evidence that infants infer that a smoothly moving object will continue to move smoothly, in accord with the inertia principle.

One aspect of the findings of Experiments 1–3 suggests, nevertheless, that this negative portrait of infants' reasoning about inertia is too strong. Across the three experiments, the proportion of looking at the event outcome that was consistent with inertia progressively increased with age, from a minimum at 4.5 months to a maximum at 12 months (see Table 1). Although this increase was not statistically reliable, it suggests that knowledge of inertia may begin to develop over the first year of life.[8] When this knowledge first emerges, it may be fragile: in contrast to

[8]Although it would be desirable to pursue this development by testing older infants with the present method and displays, pilot research suggested that the present events would not capture or maintain the attention of infants older than 1 year.

knowledge of continuity, knowledge of inertia may be too fragile to overcome a tendency to look longer at superficially novel event outcomes. Thus, 10- and 12-month-old infants' equal looking at the consistent and inconsistent outcomes might derive from opposing tendencies to look longer at superficially novel outcomes and to look longer at outcomes inconsistent with inertia. The latter tendency might be revealed if infants were tested with event outcomes that were equally novel on superficial grounds.

These considerations motivated a final experiment. In Experiment 5, infants at four ages were presented with test events in which an object appeared at either of two novel positions: a position on a line with its former motion and a position orthogonal to that motion. If such infants (weakly) infer that an object in linear motion should continue in linear motion, they should look longer at the non-linear outcome.

EXPERIMENT 5

Separate groups of infants aged 4.5, 6, 8, and 10 months were familiarized with an event in which a ball rolled diagonally across a table and behind a screen. When the screen was raised, the ball was seen at rest next to a barrier at the table's center (Fig. 10). For the subsequent test, the barrier was removed, the ball was rolled from view on the same diagonal path, and the screen was raised to reveal the ball in one of the two corners of the display, equidistant both from its point of disappearance and from its final position during the familiarization sequence. If infants infer that an object in linear motion will continue in linear motion in the absence of obstacles, then the infants were expected to look longer at the event outcome in which the ball reappeared at a position 90° displaced from the line of its visible motion. If infants do not make this inference, then the infants were expected to look equally at the two event outcomes.

Method

The method is the same as Experiments 1–4, except as follows.

Subjects

Sixty-one infants participated in the experiment. At 4.5 months, the 7 male and 6 female subjects ranged in age from 4 months, 0 days to 5 months, 0 days

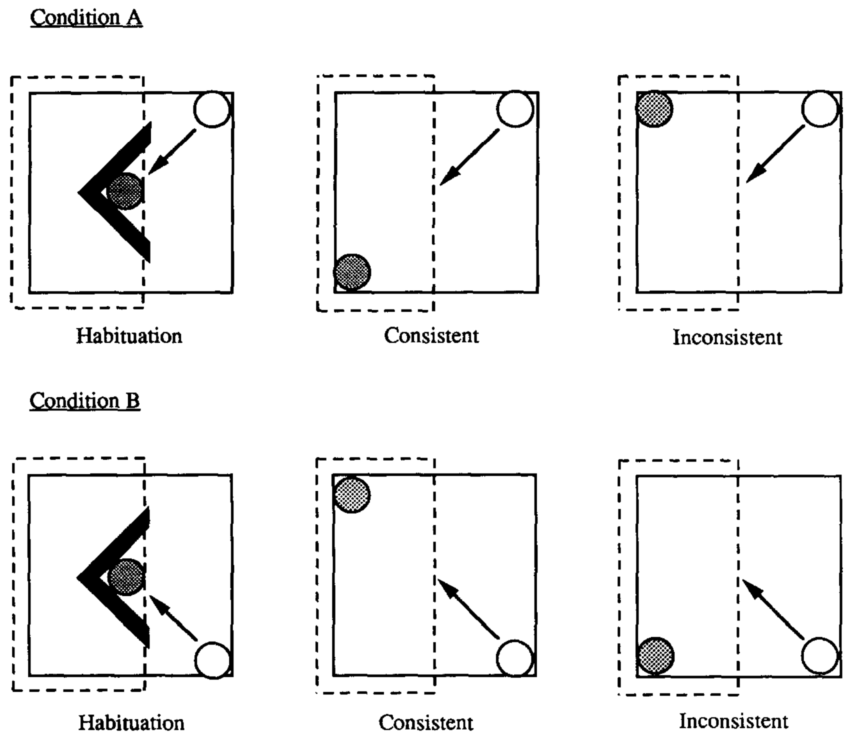

Figure 10. *Schematic depiction of the events for Experiment 5, viewed from above. The events are not drawn to scale (see Fig. 4 and text).*

(mean = 4 months, 15 days). No subjects were eliminated from the sample.[9] At 6 months, the 8 male and 8 female subjects ranged in age from 5 months, 18 days to 6 months, 16 days (mean = 6 months, 3 days). One additional subject was rejected from the sample because of experimenter error. At 8 months, the 10 male and 6 female subjects ranged in age from 7 months, 16 days to 8 months, 13 days (mean = 7 months, 30 days). One additional subject failed to complete the experiment because of fussiness. At 10 months, the 9 male and 7 female subjects ranged in age from 9 months, 15 days to 10 months, 15 days (mean = 10 months, 0 days). One additional infant was eliminated from the sample because of experimenter error.

Apparatus and events

During the habituation sequence, a bright orange, L-shaped barrier stood on the table, positioned such that it stopped the motion of the ball along either

[9]Because of an oversight, three fewer subjects were observed at this age than in the earlier experiments or at the older ages.

diagonal at the table's center. Each side of the barrier measured 31.5 × 3.5 × 4.5 cm. When the screen was lowered, the ends of the barrier were visible but its center was hidden. For the habituation event, the screen was lowered, the ball was introduced in the front or back right corner of the table, it rolled toward the barrier along the table's diagonal, and it disappeared behind the screen. Then the screen was raised to reveal the ball at the table's center, adjacent to the barrier. For the test, the barrier was removed and the test events from Experiments 1–3 were presented.

Design

Half the infants at each age (6 infants at 4.5 months) were habituated to and tested with events in which the ball began in the back right corner and moved forward (condition A); the remaining infants were habituated to and tested with events in which the ball began in the front right corner and moved backward (condition B). The design was otherwise the same as in Experiments 1–3.

Procedure

At the start of the study, the second experimenter appeared behind the display with the screen raised. In addition to tapping at the four corners and center of the table, he tapped along the sides of the barrier, as in Experiment 4. Then the experimenter withdrew, the screen was lowered, and the ball was introduced and rolled as in previous experiments. The second experimenter caught the ball silently and out of view beneath the screen, and he positioned it against the barrier. The screen was raised 2 s later to reveal the ball, and looking time was recorded as in the previous experiments.

After the last habituation trial, the second experimenter reappeared behind the display and removed the barrier. In addition to tapping the four corners and center of the table, he waved his hand over the table where the barrier had stood. Then the test trials were given, following the same test procedure as in the previous studies. During the test, the ball underwent the same visible motion as during habituation, and it reappeared alternately at the front left and back left corners of the table.

Analyses were the same as in Experiments 1–3. Because the design was unbalanced at 4 months, the analysis of variance was performed only on the data from the older three ages. Interobserver agreement averaged .88 (4 months), .83 (6 months), .90 (8 months), and .88 (10 months).

Results

On the first three familiarization trials, mean looking times per trial at 4, 6, 8, and 10 months respectively were 17.5 s, 10. s, 8.5 s, and 8.4 s. The mean number of familiarization trials respectively was 10, 9, 8, and 9. Three infants at 4 months, two infants each at 6 and at 10 months, and one infant at 8 months failed to meet the habituation criterion and were tested after 14 familiarization trials.

Figure 11 presents the mean looking times on the last six familiarization trials and on the six test trials, and Table 4 presents the mean and the median preferences for the inconsistent test event. There was no reliable preference for either event at 4 months, Wilcoxon $z < 1$ ($N = 13$) or at 6 months, $z < 1$ ($N = 16$). At 8 months, infants looked longer at the inconsistent test outcome, $z = 2.15$, $p < .02$ ($N = 16$). The same preference was observed at 10 months but was not significant, $z = 1.14$ ($N = 16$).[10]

Further analyses tested whether infants' looking preferences changed between successive ages. Although no change in preferences occurred between 4 and 6 months (Wilcoxon–Mann–Whitney $z < 1$; respective ns $= 13$ and 16; $N = 29$) or between 8 and 10 months ($z < 1$; each $n = 16$; $N = 32$), a marginally significant increase in preference for the inconsistent event outcome occurred between 6 and 8 months, $z = 1.62$, $p < .06$ (each $n = 16$; $N = 32$). Additional analyses probed this change by combining together the 4- and 6-month age groups and the 8- and 10-month age groups. In these analyses, the 4- and 6-month-old infants continued to show no preference between the two event outcomes, Wilcoxon $z < 1$ ($N = 29$). In contrast, the 8- and 10-month-old infants showed a reliable preference for the inconsistent outcome, Wilcoxon $z = 2.31$, $p < .01$ ($N = 32$). Nevertheless, the preference for the inconsistent outcome was only marginally greater at 8 and 10 months than at 4 and 6 months, Wilcoxon–Mann–Whitney $z = 1.36$, $p < .10$ (respective ns $= 29$ and 32; $N = 61$).

The findings of the analysis of variance accord with those of the non-parametric analyses. The 3 (age: 6 vs. 8 vs. 10 months) × 3 (trial pair) × 2 (test event: linear vs. non-linear) analysis revealed a marginally significant interaction of age by test event, $F\,(2, 45) = 2.69$, $p < .10$. The only significant effect in the analysis was the main effect of trial pair, $F\,(2, 90) = 8.17$, $p < .001$.

Discussion

The findings of this experiment provide no evidence that 4- or 6-month-old infants infer that an object in linear motion will continue in linear motion. No

[10]The rejected 8-month-old subject received no test trials. With the data from the rejected subjects at 6 and 10 months included, $z = 1.35$ and $z = 1.11$, respectively.

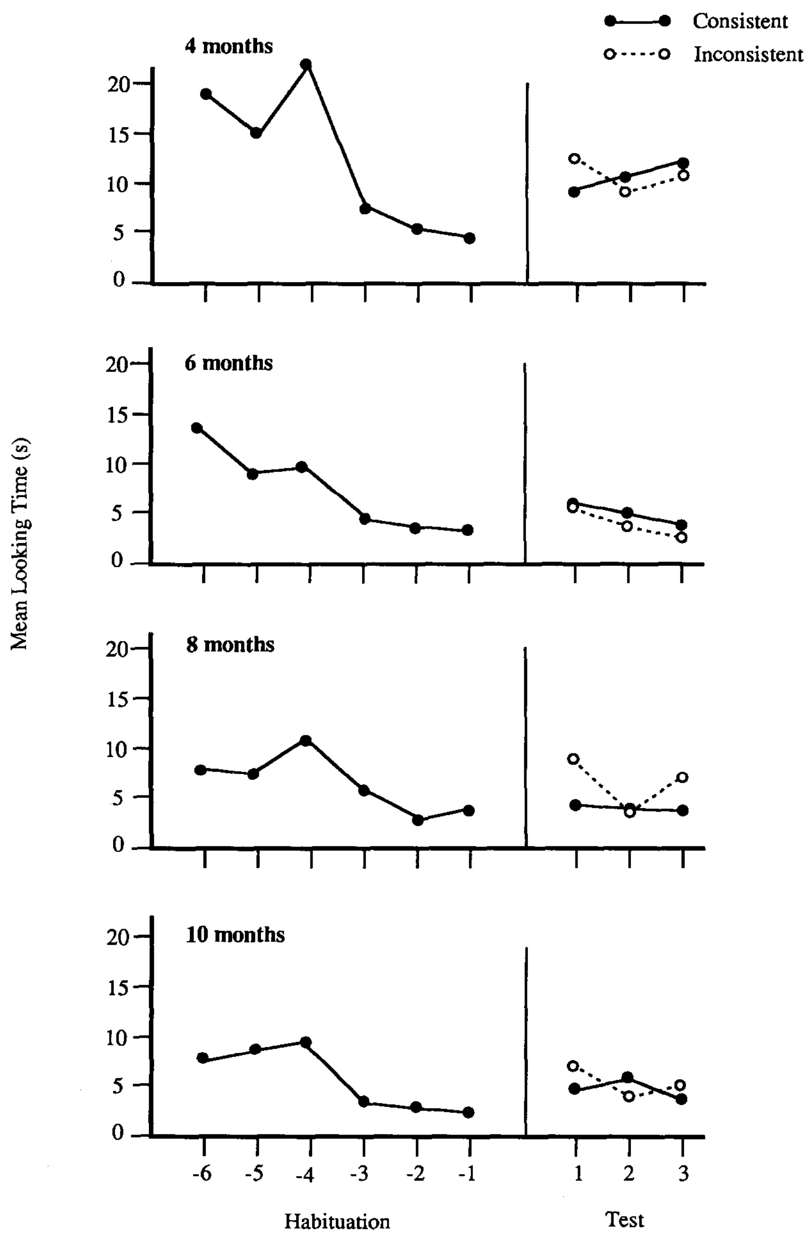

Figure 11. *Mean duration of looking by the 4-, 6-, 8-, and 10-month-old infants in Experiment 5.*

preference for the non-linear event outcome was observed either in separate analyses at 4 and at 6 months or in an analysis of the two ages combined, even though the linear and non-linear outcomes presented the object at positions that were equally novel. In contrast, the experiment provides evidence that older

Table 4. *Proportion of looking at outcomes inconsistent with inertia (Experiment 5)*

Age (months)	Median	Mean
4.5	.480	.528
6	.491	.494
8	.582	.580
10	.570	.539

infants make this inference. At 8 months, infants looked longer at the outcome of an event that was inconsistent with inertia, relative to an event outcome that was consistent with inertia, when both outcomes presented an object at a novel position. Several aspects of the data suggest that this preference was maintained at 10 months: the preferences of 8- and 10-month-old infants did not differ from one another, and the infants at 8 and 10 months showed a highly significant preference for the non-linear event outcome when the data from those two ages were combined.

Although these findings suggest that knowledge of inertia is developing over this age range, other aspects of the data weaken that conclusion. First, the preference for the non-linear event outcome was not significant at 10 months when the data at that age were analyzed separately. Second, the increase in preference for the non-linear outcome between 6 and 8 months was only marginally significant. These findings suggest considerable variability in older infants' reactions to event outcomes that are inconsistent with inertia.

One possibility, consistent with the findings both of Experiment 5 and of Experiments 1–3, is that sensitivity to inertia develops over an extended period of time. The slow development of this knowledge would explain why comparisons of reactions at different ages yielded equivocal results in all these experiments. It would explain, as well, why older infants exhibit sensitivity to inertia in the present study but not in Experiment 2, 3, or 4: their fragile, still-developing knowledge is overpowered by the differences in the superficial familiarity or novelty of an object's position or by effects of the stronger principle of continuity. Additional individual difference analyses, described in the Appendix, were undertaken to investigate further the possibility that knowledge of inertia develops gradually. Most of the findings of these analyses support the thesis that knowledge of inertia emerges slowly over the second six months of life (see Appendix).

GENERAL DISCUSSION

The present experiments shed light on infants' knowledge of continuity and of inertia, they provide support for the thesis that knowledge of objects develops around constant core principles, and they raise questions concerning the relation between the early-developing knowledge and action. We consider each of these points in turn.

Infants' knowledge of continuity

Both past and present experiments provide evidence that the continuity principle guides infants' reasoning about object motion throughout most of the first year. Infants have reacted to violations of this principle at ages ranging from 2.5 months (Spelke et al., 1992) to 10 months (Xu & Carey, 1992; Experiment 4). They have reacted to continuity violations not only in events involving rolling objects but also in events involving falling, rotating, and hand-held objects (Baillargeon, 1987; Spelke et al., 1992; Wynn, 1992), events in which one object moved successively behind two occluders (Baillargeon & Graber, 1988; Spelke & Kestenbaum, 1986; Xu & Carey, 1992; see also Baillargeon & Graber, 1987), and events in which an object was retrieved from a container (Baillargeon et al., 1990). When an event that is inconsistent with the continuity principle is superficially more familiar, infants' response to the inconsistency of the event overrides their response to its superficial familiarity (e.g., Baillargeon, 1987; Spelke et al., 1992). The continuity principle therefore appears to be a strong and consistent guide to infants' reasoning about objects.

The findings of Experiment 4, of the experiments by Spelke et al. (1992), and of the analyses reported in the Appendix suggest no change in reactions to event outcomes that are inconsistent with the continuity principle across the age range from 2.5 to 10 months. These experiments provide no evidence that knowledge of the continuity principle becomes deeper or stronger during the second half of the first year. This principle appears to guide physical reasoning throughout most of the infancy period.

Infants' knowledge of inertia

The development of knowledge of inertia contrasts with the development of knowledge of continuity in all the above respects. First, knowledge of inertia appears to emerge relatively late in infancy. In none of the present experiments did 4.5- or 6-month-old infants look longer at a non-linear event outcome than at a linear event outcome, even when the two outcomes were of equal superficial novelty. Similarly, 4- and 6-month-old infants in previous studies looked no longer at event outcomes in which a rapidly moving object appeared to stop moving abruptly and spontaneously, contrary to inertia (Spelke et al., 1992; Spelke, Simmons, Breinlinger, Jacobson, & Macomber, submitted). Young infants' failure to look longer at outcomes that are inconsistent with inertia cannot be attributed to inadequacies of the method or displays, because of the successful findings of similar studies testing infants' knowledge of continuity. In the present experiments, in particular, 6-month-old infants showed a reliably greater looking preference for an event outcome presenting a continuity violation than for an otherwise similar outcome presenting an inertia violation. A plausible interpretation of these findings is that young infants do not appreciate that a linearly moving object will continue in linear motion in the absence of obstacles.

Second, older infants' knowledge of inertia appears to be fragile. As a group, the 8- and 10-month-old infants looked reliably longer at the non-linear event outcome than at the linear outcome when the two outcome positions were equally novel. At 8, 10 and 12 months, however, infants showed no looking preference for a non-linear event outcome when that outcome was superficially more familiar. Ten-month-old infants' preference for a superficially familiar event outcome that was inconsistent with inertia was markedly lower than their preference for a similar event outcome that was inconsistent with continuity. Moreover, infants showed no greater preference for an event outcome that was inconsistent with both continuity and inertia than for an event outcome that was inconsistent with continuity alone. These failures to respond to violations of inertia again cannot be attributed to general inadequacies of the present experimental method or displays. Older infants' reactions to events inconsistent with inertia appear to be easily obscured by reactions to other aspects of the events.

Finally, knowledge of inertia appears to develop slowly. An extended process of development is suggested by the discrepancy between the findings of Experiment 5 and Experiments 2 and 3, by the high variability and unclear developmental changes observed in Experiment 5, and by the individual difference analyses reported in the appendix. These experiments do not permit us to say "when" knowledge of inertia develops; they suggest, indeed, that this question is ill-founded (see Fischer & Bidell, 1991; Munakata, 1992). Mature knowledge of inertia may depend on an accumulation of expectations about the behavior of objects. These expectations may begin to emerge in infancy, and they may continue to develop thereafter.

Research with older children provides further evidence that knowledge of inertia grows slowly and in a piecemeal fashion. In one series of experiments, children were asked how a ball would move after rolling off a platform (Kim & Spelke, 1991). Three- and 4-year-old children judged with near unanimity that the ball would abruptly change direction and move straight downward, contrary to inertia. In contrast, some 5-year-olds and most 6-year-olds correctly judged that the ball would move smoothly after leaving the platform, continuing in forward motion while beginning to move downward. In another series of experiments using a slightly different task, the straight-down prediction was the modal judgment given by 6-year-old children; it declined in frequency thereafter (Kaiser et al., 1985). These findings suggest that an understanding of inertia continues to develop well into childhood.

The developmental ordering of the emergence of knowledge of continuity and inertia conforms to the principle that the earliest developing psychological mechanisms encompass the most reliable constraints on external objects (Kellman, 1993). All material objects, animate and inanimate, move on connected paths. In contrast, not all freely moving objects move smoothly. The inertia principle is violated by self-propelled objects including people, animals, and machines. Because some of the external forces that act on objects are not easily perceivable, moreover, the inertia principle appears to be violated by many events involving inanimate objects, such as falling leaves and slamming doors. The continuity principle therefore is a more reliable guide to reasoning, and it may provide a more solid foundation for the development of knowledge.

The core knowledge thesis

The findings of these experiments are consistent with the thesis that common sense knowledge of the physical world develops by enrichment around constant core principles. Although a variety of early-developing actions on objects are accommodated to inertia and not to continuity, the reasoning of infants, like that of adults, accords more strongly with the continuity principle. It remains possible that counterexamples to the core knowledge thesis will be found as infants' physical reasoning is tested further: infants may be found to reason about objects in accord with principles (other than inertia) that are peripheral to or absent from mature physical conceptions, or they may show no signs of reasoning about objects in accord with yet untested principles that are central to mature conceptions. The present research nevertheless casts doubt on possibly the most striking apparent counterexample to the core knowledge thesis outside the realm of scientific theory-building, arising from studies of the development of action in infancy (e.g., Fischer & Bidell, 1991; Gopnik, 1988; Piaget, 1952, 1954).

What are the origins of core knowledge? One possibility is that this knowledge derives from infants' abilities to learn about regularities in their perceived environment (e.g., Mandler, 1992; McClelland, 1992). On this view, the principle of continuity is learned earlier than the principle of inertia because it is exhibited more clearly in the events that infants perceive. A second possibility is that core knowledge derives from biologically based cognitive mechanisms, perhaps shaped by evolution (e.g., Gelman, 1990; Sperber, in press). A consideration of infants' perceptual capacities seems to us, as to others (e.g., Piaget, 1954), to cast doubt on the first possibility: neither the continuous existence nor the spatiotemporally connected motions of objects appear to be evident in the highly discontinuous and partial views of the world provided by an infant's perceptual systems. Mature perceptual systems, moreover, do not appear to be constrained to accord with the continuity principle: adults can easily perceive events in which an object vanishes or passes through a barrier, even though we believe that objects do not behave in these ways (Leslie, 1988). If a deep regularity underlies the behavior of significant entities in a species' surroundings, and if that regularity is not clearly exhibited in the events that members of the species perceive, conditions appear favorable for the evolution of cognitive mechanisms encompassing the regularity. Knowledge of the continuity principle may have emerged through such a process.

The modularity of early reasoning

The present findings have an unsettling consequence: infants' knowledge of objects does not appear to be accessible as a guide to many of infants' most frequent and important actions on objects. Although knowledge of the continuity principle is revealed in infants' patterns of preferential looking, this knowledge does not appear to guide visual tracking and visual search for objects (e.g., Moore et al., 1978), object-directed reaching (Hofsten et al., 1993), learned means–ends behaviors (Munakata, 1992), or manual search for hidden objects (Piaget, 1954). Symmetrically, although the present experiments show no evidence for knowledge of inertia before 6 months of age, many of the above object-directed actions appear to be accommodated to inertial properties of object motion well before that time. These findings call into question the assumption that infants' actions are guided by their knowledge.

More generally, the present findings accord with mounting evidence that early-developing mechanisms for perceiving, acting, and reasoning are modular (Gallistel & Gelman, 1992; Hermer, 1993; Karmiloff-Smith, 1992; Prasada, 1993; see also Fodor, 1983; Rozin, 1976; Sperber, in press). Modular visuomotor mechanisms, attuned both to constraints on objects and to constraints on sensorimotor systems, may permit infants to track and reach for visible objects more rapidly and effectively than their reasoning processes would otherwise permit (see Fodor, 1983). Modular mechanisms of physical reasoning, attuned to different constraints on objects, may permit infants to develop a system of physical knowledge that centers on objects' most fundamental properties (see Kellman, 1993). To the extent that the demands on infants' sensorimotor and cognitive systems are different, we should not expect one system to be built upon the other (*contra* Piaget, 1952) or both systems to draw on a common foundation.

If initial reasoning depends on modular cognitive mechanisms, and if the initial systems of knowledge embodied in those mechanisms are largely inaccessible as guides to action, then human development would seem to result in an increase in the interconnectedness and the accessibility of different systems (Hermer, 1993;

Karmiloff-Smith, 1992; Rozin, 1976). The developmental processes that make early knowledge accessible, linking children's thoughts to one another and to their actions, remain to be explored.

References

Aslin, R.N. (1981). Development of smooth pursuit in human infants. In D.F. Fisher, R.A. Monty, & J.W. Senders (Eds.), *Eye movements: cognition and visual perception*. Hillsdale, NJ: Erlbaum.

Atran S. (1990). *Cognitive foundations of natural history: towards an anthropology of science*. Cambridge, UK: Cambridge University Press.

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

Baillargeon, R. (1987). Object permanence in 3.5- and 4.5-month-old infants. *Developmental Psychology*, *23*, 655–664.

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

Baillargeon, R. (1993). The object concept revisited: new directions in the investigation of infants' physical knowledge. In C.E. Granrud (Ed.), *Visual perception and cognition in infancy*. Carnegie-Mellon Symposia on Cognition, Vol. 23. Hillsdale, NJ: Erlbaum.

Baillargeon, R., & DeVos, J. (1991). Object permanence in young infants: further evidence. *Child Development*, *62*, 1227–1246.

Baillargeon, R., & Graber, M. (1987). Where's the rabbit? 5.5-month-old infants' representation of the height of a hidden object. *Cognitive Development*, *2*, 375–392.

Baillargeon, R., & Graber, M. (1988). Evidence of location memory in 8-month-old infants in a non-search AB task: further evidence. *Developmental Psychology*, *24*, 502–511.

Baillargeon, R., Graber, M., De Vos, J., & Black, J.C. (1990). Why do young infants fail to search for hidden objects? *Cognition*, *36*, 255–284.

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

Ball, W.A., & Tronick E. (1971). Infant responses to impeding collision: optical and real. *Science*, *171*, 818–820.

Bornstein, M.H. (1985). Habituation of attention as a measure of visual information processing in human infants: summary, systematization, and synthesis. In G. Gottlieb & N.A. Krasnegor (Eds.), *Measurement of audition and vision in the first year of life*. Norwood, NJ: Ablex.

Bower, T.G.R. (1982). *Development in infancy* (2nd ed.) San Francisco: Freeman.

Bower, T.G.R., Broughton, J., & Moore, M.K. (1971). The development of the object concept as manifested in tracking behavior of infants between 7 and 20 weeks of age. *Journal of Experimental Child Psychology*, *11*, 182–193.

Bower, T.G.R., & Paterson, J.G. (1973). The separation of place, movement, and time in the world of the infant. *Journal of Experimental Child Psychology*, *15*, 161–168.

Carey, S. (1985). *Conceptual change in childhood*. Cambridge, MA: Bradford/MIT Press.

Carey, S. (1988). Conceptual differences between children and adults. *Mind and Language*, *3*, 167–181.

Carey, S. (1991). Knowledge acquisition: enrichment or conceptual change? In S. Carey & R. Gelman (Eds.), *Epigenesis of mind: essays on biology and cognition* (pp. 1257–1291). Hillsdale, NJ: Erlbaum.

Carey, S., Klatt, L., & Schlaffer, M. (1992). *Infants' representations of objects and nonsolid substances*. Unpublished manuscript, MIT.

Carey, S., & Spelke, E.S. (in press). Domain specific knowledge and conceptual change. In L.A. Hirschfeld & S.A. Gelman (Eds.), *Domain specificity in cognition and culture*. Cambridge, UK: Cambridge University Press.

Colombo, J., Mitchell, D.W., & Horowitz, F.D. (1988). Infant visual behavior in the pairedcomparison paradigm: test–retest and attention–performance relations. *Child Development*, *59*, 1198–1210.

Colombo, J., Mitchell, D.W., O'Brien, M., & Horowitz, F.D. (1987). Stability of visual habituation during the first year of life. *Child Development*, *58*, 474–487.

Cooke, N.J., & Breedin, S.D. (1990, November). *Implicit knowledge about motion*. Poster presented at the 31st Annual Meeting of the Psychonomic Society, New Orleans, LA.

Darlington, R. (1990). *Regression and linear models*. New York: McGraw-Hill.

Fantz, R.L. (1961). The origin of form perception. *Scientific American*, *204*, 66–72.

Fischer, K.W., & Bidell, T. (1991). Constraining nativist inferences about cognitive capacities. In S. Carey & R. Gelman (Eds.), *Epigenesis of mind: essays on biology and cognition* (pp. 199–236). Hillsdale, NJ: Erlbaum.

Fodor, J.A. (1983). *The modularity of mind*. Cambridge, MA: Bradford/MIT Press.

Franklin, A. (1976). *The principle of inertia in the middle ages*. Boulder, CO: Colorado Associated University Press.

Gallistel, C.R., & Gelman, R. (1992). Preverbal and verbal counting and computation. *Cognition*, *44*, 43–74.

Gelman, R. (1990). First principles organize attention to and learning about relevant data: number and the animate–inanimate distinction as examples. *Cognitive Science*, *14*, 79–106.

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

Halloun, I.A., & Hestenes, D. (1985). Common sense concepts about motion. *American Journal of Physics*, *53*, 1056–1065.

Harris, P.L. (1975). Development of search and object permanence during infancy. *Psychological Bulletin*, *82*, 332–344.

Harris, P.L. (1983). Infant cognition. In M.M. Haith & J.J. Campos (Eds.), *Handbook of child psychology: Vol. 2. Infancy and developmental psychobiology*. New York: Wiley.

Hermer, L. (1993). A geometric module for spatial orientation in young children. *Proceedings of the fifteenth annual meeting of the Cognitive Science Society*. Hillsdale, NJ: Erlbaum.

Hofsten, C. von (1980). Predictive reaching for moving objects by human infants. *Journal of Experimental Child Psychology*, *30*, 369–382.

Hofsten, C. von (1983). Catching skills in infancy. *Journal of Experimental Psychology: Human Perception and Performance*, *9*, 75–85.

Hofsten, C. von, & Rosander, K. (1993a). *The early development of eye–head tracking of a moving visual field*. Unpublished manuscript.

Hofsten, C. von, & Rosander, K. (1993b). *Perturbation of target motion during tracking*. Unpublished manuscript.

Hofsten, C. von, Spelke, E.S., Feng, X., & Vishton, P. (submitted). *Predictive reaching for partly occluded objects*. Poster submitted to the International Society of Infant Studies, Paris.

Hofsten, C. von, Spelke, E.S., Vishton, P., & Feng, X. (1993, November). *Principles of predictive catching in 6-month-old infants*. Paper presented at the 34th Annual Meeting of the Psychonomic Society, Washington, DC.

Kaiser, M.K., Jonides, J., & Alexander, J. (1986). Intuitive reasoning about abstract and familiar physics problems. *Memory & Cognition*, *14*, 308–312.

Kaiser, M.K., McCloskey, M., & Proffitt, D.R. (1986). Development of intuitive theories of motion: curvilinear motion in the absence of external forces. *Developmental Psychology*, *22*, 67–71.

Kaiser, M.K., Proffitt, D.R., & McCloskey, M. (1985). The development of beliefs about falling objects. *Perception and Psychophysics*, *38*, 833–839.

Kaiser, M.K., Proffitt, D.R., Whelan, S.M., & Hecht, H. (1992). The influence of animation on dynamical judgments. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 669–690.

Karmiloff-Smith, A. (1992). *Beyond modularity*. Cambridge, MA: Bradford/MIT Press.

Kellman, P.J. (1993). Kinematic foundations of infant visual preception. In C.E. Granrud (Ed.), *Visual preception and cognition in infancy*. Carnegie-Mellon Symposia on Cognition, Volume 23. Hillsdale, NJ: Erlbaum.

Kim, I.K., & Spelke, E.S. (1991, April). *Perception and understanding of effects of gravity and inertia* *on object motion*. Paper presented at the Society for Research in Child Development, Seattle, WA.

Kitcher, P. (1988). The child as parent of the scientist. *Mind and Language*, *3*, 217–228.

Kuhn, T.S. (1962). *The structure of scientific revolutions*. Chicago: University of Chicago Press.

Kuhn, T.S. (1977). A function for thought experiments. In T.S. Kuhn (Ed.), *The essential tension*. Chicago: University of Chicago Press.

Leslie, A. (1988). The necessity of illusion: perception and thought in infancy. In L. Weiskrantz (Ed.), *Thought without language*. Oxford: Clarendon Press.

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

Mandler, J.M. (1992). How to build a baby II: Conceptual primitives. *Psychological Review*, *99*, 587–604.

McClelland, J. (1992). *Parallel distributed processing: implications for cognitive development*. Invited address, International Congress of Psychology, Brussels.

McCloskey, M. (1983). Naive theories of motion. In D. Gentner & A.L. Stevens (Eds.), *Mental models* (pp. 299–324). Hillsdale, NJ: Erlbaum.

McCloskey, M., Washburn, A., & Felch, L. (1983). Intuitive physics: The straight-down belief and its origin. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *9*, 636–649.

Moore, M.K., Borton, R., & Darby, B.L. (1978). Visual tracking in young infants: Evidence for object identity or object permanence? *Journal of Experimental Child Psychology*, *25*, 183–198.

Moore, M.K., & Meltzoff, A.M. (1978). Object permanence, imitation, and language development in infancy: toward a neo-Piagetian perspective on communicative and cognitive development. In F.D. Minifie & L.L. Lloyd (Eds.), *Communicative and cognitive abilities: early behavioral assessment*. Baltimore, MD: University Park Press.

Munakata, Y. (1992). *Rethinking object permanence: a gradualistic account*. Presented at the annual joint University of Pittsburgh–Carnegie Mellon University conference.

Mundy-Castle, A.C., & Anglin, J. (1969, March). *The development of looking in infancy*. Paper presented at SRCD, Santa Monica, CA.

Needham, A. (1990, April). *3.5-month-old infants' knowledge of support relations*. Paper presented at the 7th International Conference on Infant Studies, Montreal, Canada.

Nelson, K.E. (1971). Accommodation of visual tracking patterns in human infants to object movement patterns. *Journal of Experimental Child Psychology*, *12*, 182–196.

Piaget, J. (1952). *The origins of intelligence in childhood*. New York: International Universities Press.

Piaget, J. (1954). *The construction of reality in the child*. New York: Basic Books.

Prasada, S. (1993, March). *Two-year-olds' inferences about object motion*. Paper presented at the Society for Research in Child Development, New Orleans.

Proffitt, D.R., & Gilden, D.L. (1989). Understanding natural dynamics. *Journal of Experimental Psychology: Human Perception and Performance*, *15*, 384–393.

Proffitt, D.R., Kaiser, M.K., & Whelan, S.M. (1990). Understanding wheel dynamics. *Cognitive Psychology*, *22*, 342–373.

Rozin, P. (1976). The evolution of intelligence and access to the cognitive unconscious. *Progress in Psychobiology and Physiological Psychology*, *6*, 245–279.

Siegel, S., & Castellan, N.J. Jr. (1988). *Nonparametric statistics for the behavioral sciences* (2nd ed.). New York: McGraw-Hill.

Smith, C., Carey, S., & Wiser, M. (1985). On differentiation: A case study of the development of the concepts of size, weight, and density. *Cognition*, *21*, 177–237.

Spelke, E.S., Breinlinger, K., Macomber, J., & Jacobson, K. (1992). Origins of knowledge. *Psychological Review*, *99*, 605–632.

Spelke, E.S., Jacobson, K., Keller, M., & Sebba, D. (submitted). *Developing knowledge of gravity II: Infants' sensitivity to visible object motion*. Manuscript submitted for publication.

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

Spelke, E.S., Simmons, A., Breinlinger, K., Jacobson, K., & Macomber, J. (submitted). *Developing knowledge of gravity I: Infants' sensitivity to hidden object motion*. Manuscript submitted for publication.

Sperber, D. (1991). The epidemiology of beliefs. In C. Fraser (Ed.), *Psychological studies of widespread beliefs*. London: Oxford University Press.

Sperber, D. (in press). The modularity of thought and the epidemiology of representations. In L.A. Hirschfeld & S.A. Gelman (Eds.), *Domain specificity in cognition and culture*. Cambridge, UK: Cambridge University Press.

Wiser, M., & Carey, S. (1983). When heat and temperature were one. In D. Gentner & A. Stevens (Eds.), *Mental models*. Hillsdale, NJ: Erlbaum.

Wynn, K. (1992). Addition and subtraction by human infants. *Nature*, *358*, 749–750.

Xu, F., & Carey, S. (1992). *Infants' concept of numerical identity*. Paper presented at the Boston University Language Acquisition Conference.

Yonas, A. (1981). Infants' responses to optical information for collision. In R.N. Aslin, J.R. Alberts, & M.R. Peterson (Eds.), *The development of perception: Vol. 2. The visual system*. New York: Academic Press.

Appendix: An individual difference analysis of Experiments 4 and 5

Baillargeon (1987, 1990) has suggested an individual difference analysis to test whether infants are in the process of developing understanding of the events presented in preferential looking experiments. Before the age at which knowledge of a given physical principle reaches a stable state, infants' degree of mastery of the principle may be related to the speed at which they process events that exhibit the principle: the greater their mastery of the principle, the faster their processing of such events. Infants' speed of processing an event, in turn, appears to be related to their rate of habituation to that event (Bornstein, 1985; Colombo, Mitchell, O'Brien, & Horowitz, 1987). These findings and assumptions lead to the following prediction: if knowledge of a physical principle is partially developed within a given population of infants, then infants who have mastered the physical principle to a greater extent should habituate more rapidly to events exhibiting the principle (Baillargeon, 1987, 1990; Needham, 1990).

In support of this possibility, Baillargeon and her colleagues obtained evidence for relationships between rate of habituation and preference for an inconsistent event in three experiments with young infants (Baillargeon, 1987; Needham, 1990). No such relations were obtained at older ages, when the relevant knowledge appeared to be well established.

To investigate whether knowledge of inertia develops slowly over the course of the first 10 months, we analyzed the correlation between habituation rate and preference for the inconsistent event for the infants in Experiment 5. If knowledge of inertia begins to emerge between 6 and 8 months, continues to develop gradually, and still is not complete at 10 months, then a negative correlation between the rate of habituation measure and the preference-for-inconsistency measure should be observed at 6, 8, and 10 months of age. If knowledge of inertia has not begun to develop at 4.5 months, then no such correlation should be observed at that age.

In addition to these analyses of Experiment 5, we tested for developmental changes in infants' knowledge of continuity by conducting the same individual difference analyses with the data for each of the age groups in Experiment 4. Given the evidence from previous studies for knowledge of continuity both at 2.5 and at 4 months (Spelke et al., 1992), we predicted that no reliable correlations would be obtained either at 6 or at 10 months in Experiment 4.

Method

The measure of rate of habituation was the total looking time during the habituation period. This measure was chosen because duration measures of habituation have proven to be more stable and better predictors of other cognitive variables than have measures such as the number of trials to habituation (Colombo et al., 1987; Colombo, Mitchell, & Horowitz, 1988). For each experiment, the correlation between this measure and preference for the inconsistent event was assessed by means of Spearman's rank-order correlation test.

Results

The findings of the correlational analyses are given in Table 5. In Experiment 4, there was no significant correlation between rate of habituation and preference for the event outcome inconsistent with the continuity principle. The small correlations obtained at each age were opposite in direction to those predicted by the transitional age hypothesis. In Experiment 5, the degree of preference for the event outcome inconsistent with inertia was not inversely correlated with the rate of habituation at 4.5 months or at 8 months. At 6 and at 10 months, the predicted inverse correlation was significant.

Table 5. *Correlations between rate of habituation and proportion of looking at inconsistent outcomes*

(a) Experiment 4 (continuity)	
6 months	.04
10 months	.16
(b) Experiment 5 (inertia)	
$4\frac{1}{2}$ months	.17
6 months	−.58*
8 months	.13
10 months	−.49*

* $p < .05$.

Discussion

All but one of the findings of the correlational analyses accord with our interpretation of the findings presented in the text. In the continuity experiment, there was no correlation between rate of habituation and preference for the inconsistent event outcome either at 6 or at 10 months. These findings accord with the evidence that knowledge of continuity is already well developed by 6 months of age (e.g., Baillargeon & Devos, 1991; Spelke et al., 1992). In the inertia experiment, there was no correlation between rate of habituation and preference for the inconsistent event outcome at 4.5 months. This finding accords with the evidence, from these experiments and others (Spelke et al., 1992, submitted), that knowledge of inertia has not begun to develop at that age. At 6 and at 10 months of age, the predicted correlation was obtained: infants who habituated more rapidly showed a greater test preference for the event outcome inconsistent with inertia. These findings accord with the evidence, from these experiments and others (e.g., Kaiser et al., 1985; Kim & Spelke, 1991), that knowledge of inertia develops slowly and is not complete at 10 months. The one discordant finding from these analyses concerns the data from the 8-month-old infants in Experiment 5: these infants showed no correlation between rate of habituation and preference for the non-linear event outcome.

In summary, the individual difference analyses provide some support for the thesis that knowledge of inertia is developing slowly over the first year. In view of the discordant finding at 8 months and the novelty of the individual difference analysis, however, no strong conclusions can be based on these analyses.