Developmental Science 2:3 (1999), pp 339–362

PAPER

Perception and understanding of effects of gravity and inertia on object motion

In-Kyeong Kim[1] and Elizabeth S. Spelke[2]

1. *La Sierra University, USA*
2. *Massachusetts Institute of Technology, USA*

Abstract

Experiments using a preferential looking method, a perceptual judgment method, and a predictive judgment method investigated the development, from 7 months to 6 years of age, of sensitivity to the effects of gravity and inertia on inanimate object motion. The experiments focused on a situation in which a ball rolled off a flat surface and either continued in linear motion (contrary to gravity), turned abruptly and moved downward (contrary to inertia), or underwent natural, parabolic motion. When children viewed the three fully visible motions, both the preferential looking method and the perceptual judgment method provided evidence that sensitivity to inertia developed between 7 months and 2 years, and that sensitivity to gravity began to develop after 3 years. When children predicted the future location of the object without viewing the motions, the predictive judgment method provided evidence that sensitivity to gravity had developed by 2 years, whereas sensitivity to inertia began to develop only at 5–6 years. These findings suggest that knowledge of object motion develops slowly over childhood, in a piecemeal fashion. Moreover, the same system of knowledge appears to be tapped both in preferential looking tasks and in judgment tasks when children view fully visible events, but a different system may underlie children's inferences about unseen object motions.

Human adults are sensitive to a variety of effects of gravity and inertia on the motions of objects. In particular, a hand-held object that is released in mid-air looks natural only if it begins to move downward, an object that falls freely looks natural only if it undergoes appropriate acceleration (Shanon, 1976), and an object that rolls off a cliff looks natural only if it moves downward on a parabolic path (Kaiser, Proffitt & McCloskey, 1985).

What are the origins of this sensitivity? Gravity and inertia have constrained the motions of objects throughout the history of the earth, and humans and other animals have evolved a variety of sensory and motor mechanisms that take account of their effects (Howard, 1982; Schone, 1984). It is therefore possible that humans have also evolved perceptual and cognitive mechanisms that are sensitive to effects of gravity and inertia. Alternatively, human adults have a lifetime of experience observing objects, and they may have learned about natural object motions. One goal of the present research is to investigate these contrasting possibilities through studies of infants and children.

Despite their sensitivity to the naturalness of perceived physical events, adults are prone to error if they must infer the path or acceleration of a moving object that is hidden (Shanon, 1976; McCloskey, 1983). Moreover, adults often give mistaken explanations for the motions of objects and make erroneous predictions about future object motions (e.g. Piaget, 1976; Clement, 1982). These observations suggest that the tacit conceptions underlying adults' perception of object motion are distinct from the explicit conceptions that underlie their predictions, judgments and explanations.

What are the origins of the gap between implicit and explicit knowledge of object motion? Studies of school-aged children provide evidence that the explicit knowledge guiding judgments about object motion sometimes differs from the implicit knowledge guiding actions on objects in children as young as 5 years. Indeed, the same child may act so as to propel an object correctly, and

Address for correspondence: Elizabeth S. Spelke, E10-246, Department of Brain and Cognitive Sciences, MIT, Cambridge, MA 02139, USA.

then report erroneously on the conditions that guided her actions (Piaget, 1976; Krist, Fieberg & Wilkening, 1993).

Some previous research with infants also suggests a discrepancy between the knowledge that guides actions on visible objects and the knowledge that guides inferences about hidden objects. When infants reach for a continuously visible moving object, their reaches are 'predictive' i.e. aimed ahead of the object's currently visible position, and guided by inertia (von Hofsten, Vishton, Spelke, Rosander & Feng, 1998). In contrast, when infants view an object that moves behind an occluder, their looking preferences between events in which the object reappears at different positions suggests no sensitivity to inertia (Spelke, Katz, Purcell, Ehrlich & Breinlinger, 1994). These findings suggest that the gap between action and judgment extends back to infancy, but they are not decisive for two reasons. First, it is unclear whether preferential looking tasks tap the same kind of knowledge as the verbal judgment tasks given to adults (see Bertenthal, 1996, and Spelke, Breinlinger, Macomber & Jacobson, 1992, for discussion). Second, the studies assessing infants' predictive reaching for fully visible objects used somewhat different events and presentation conditions than those assessing infants' preferential looking at partly occluded objects, and so they cannot be compared directly. A second goal of the present research is to explore the possible divergence between preferential looking methods and verbal judgment methods, as well as the possible divergence between perceptions of and judgments about constraints on object motion, through systematic comparisons of the early development of sensitivity to object motion across different kinds of tasks.

A third goal of this research is to investigate the nature of human knowledge of gravity and inertia. Diverse conceptions of object motion have been expressed in the history of science (Duhem, 1954; Kuhn, 1970, 1977) and by contemporary science students (Champagne, Klopher & Anderson, 1980; Clement, 1982). In the history of physics, theories of force, acceleration and velocity have been subject to continuous innovation. Aristotelians, impetus theorists, and classical and relativistic physicists have offered different explanations for object motion and different descriptions of how objects move under particular conditions. Studies of contemporary college students have been interpreted by some investigators as suggesting that students reason intuitively as impetus theorists did (McCloskey, 1983). Other investigators, however, have proposed that students' reasoning is based on piecemeal knowledge rather than on any general conceptions of object motion (diSessa, 1983).

The present research aims to shed light on this issue by investigating the development of sensitivity to effects of gravity and inertia on the path of motion of an object that moves off a supporting surface, and by comparing children's performance in this situation to their performance in a situation studied previously, in which an object moved on an inclined, supporting surface with either appropriate or inappropriate acceleration (Kim & Spelke, 1992). If a single conception of gravity underlies infants' reactions to moving objects in both situations, then infants should become sensitive to the natural path of motion for an unsupported object at the same age at which they were found to become sensitive to the natural acceleration of a partially supported object: between 5 and 7 months of age (Kim & Spelke, 1992). If piecemeal knowledge underlies humans' commonsense understanding of effects of gravity and inertia, in contrast, then understanding may emerge at different times in these different situations.

This research focused on the development of sensitivity to gravity and inertia in one situation. If a ball rolls down a ramp and then off its edge, it continues to move forward while also moving downward at a steadily accelerating speed. The forward and downward motions combine to form a parabolic path. Experiments 1–5 investigated 7-month-old infants' sensitivity to this effect of gravity and inertia in fully visible events, using Kim and Spelke's (1992) preferential looking method. The findings of all these experiments were negative, providing evidence that the sensitivity to gravity and inertia shown in Kim and Spelke's studies reflected limited, piecemeal knowledge of objects. Experiments 6–8 next investigated sensitivity to the same events at 2 years of age, providing evidence for emerging sensitivity to inertia but not gravity. Experiments 9–12 investigated how this sensitivity develops in 3- to 6-year-old children, both with the preferential looking method and with a verbal judgment method assessing children's perception of the naturalness of observed object motions. The two methods provided evidence for the same developmental changes in sensitivity to inertia and gravity, suggesting slow piecemeal development of a single system of perceptual knowledge. Finally, Experiment 13 investigated the development of sensitivity to inertia and gravity, in 2- to 6-year-old children, by means of a different verbal judgment task assessing children's predictions about the future position of an object whose motion they have not seen. This last experiment provided evidence for a different developmental sequence, suggesting that the divergence between perception and judgment found in adults begins early in development.

Sensitivity to gravity and inertia in 7-month-old infants

Overview

Experiments 1–5 were based on the methods and findings of Kim and Spelke (1992). In Kim and Spelke's experiments, separate groups of 5- and 7-month-old infants were habituated to two different events in which a ball rolled downward or upward on a ramp with appropriate acceleration, speeding up as it moved downward or slowing down as it moved upward. Then infants were tested with events in which the ramp was inclined in the opposite direction and the ball rolled with acceleration which was either novel but appropriate or familiar but inappropriate. At 5 months, infants looked longer at the novel, appropriate acceleration pattern, suggesting that they discriminated the two motions but were not sensitive to the inappropriateness of upward accelerating or downward decelerating motion in this situation. At 7 months, in contrast, infants looked longer at the familiar but now inappropriate acceleration pattern, providing evidence for sensitivity to the effect of gravity in this situation. Between 5 and 7 months, infants appeared to begin to implicitly expect a downwardly moving object to accelerate and an upwardly moving object to decelerate.

The present experiments were undertaken to investigate the generality of 7-month-old infants' sensitivity to the effects of gravity on a moving object. We used the method and stimuli of Kim and Spelke (1992), with one change. Instead of testing infants with a ball rolling on a full ramp with two different patterns of acceleration, each of the present studies tested infants with a ball rolling on a truncated ramp and then continuing on two different paths. If 7-month-old infants have developed a general sensitivity to gravity, then they might expect gravity to influence the path as well as the acceleration of object motion. If infants' sensitivity to gravity is more piecemeal, in contrast, then infants might fail to expect gravity to influence an object's path of motion.

As in Kim and Spelke (1992), the infants in Experiments 1–5 first were habituated to an object undergoing natural motion in a straight line. In different experiments, the object either moved laterally on a slanted or horizontal planar surface, or it was released in mid-air and fell vertically. After habituation, infants were tested with events in which the object rolled off a slanted or horizontal cliff and either underwent natural motion on a parabolic path or underwent unnatural motion. In Experiments 1–4, the unnatural motion consisted of a continuation of the object's previous, linear path of motion: a path that is inconsistent with the effects of gravity on an object in free fall. In Experiment 5, the unnatural motion consisted of an abrupt turn as the object rolled off the surface, followed by vertical, downward motion: a path that is inconsistent with the effects of inertia. Looking times to the test events were compared, on the assumption that infants who were sensitive to the naturalness of the object's parabolic motion would look longer at the test displays with unnatural motion.

Experiment 1

Infants were habituated to a videotaped event in which a ball rolled on a slanted ramp with constant, natural acceleration. Then they were tested with events in which the right half of the ramp was removed, the ball rolled down and off the ramp, and the ball continued either on a parabolic path (novel but natural) or on a straight line as during habituation (familiar but inconsistent with gravity). If infants are sensitive to the effect of gravity on the unsupported ball's motion, they will look longer at the test event presenting the linear motion.

Method

Subjects Participants were six male and six female infants ranging in age from 6 months 15 days to 7 months 15 days ($M = 6$ months 28 days). Three additional infants were eliminated from the experiment because of experimenter error (one), distraction by a sibling (one), or distraction by a parent (one).

Displays The experiment used two introductory displays, one habituation display, and two test displays, all videotaped in color on a VHS cassette system (see Figures 1 (a) and 3). At the infant's distance (60 cm from the center of the screen), the ball subtended 2.5°, and it moved at an average speed of 20°/s. For the habituation display, a green, planar, supporting surface was slanted 15° downwards from left to right. A yellow styrofoam ball decorated with blue sparkles was introduced by a hand at the far left, upper end of the inclined ramp, was placed on the ramp and released, and rolled down the ramp and off the screen. The ball rolled for 1.3 s; the entire event lasted 4.5 s and occurred repeatedly. Before the habituation sequence, there was one introductory display, in which an experimenter tapped on the surface of the ramp to be used for the habituation trial.

For the test events, the ramp was cut in half, and the color of the ramp was changed to red to elicit infants' attention to the change. In one of the test events, the ball

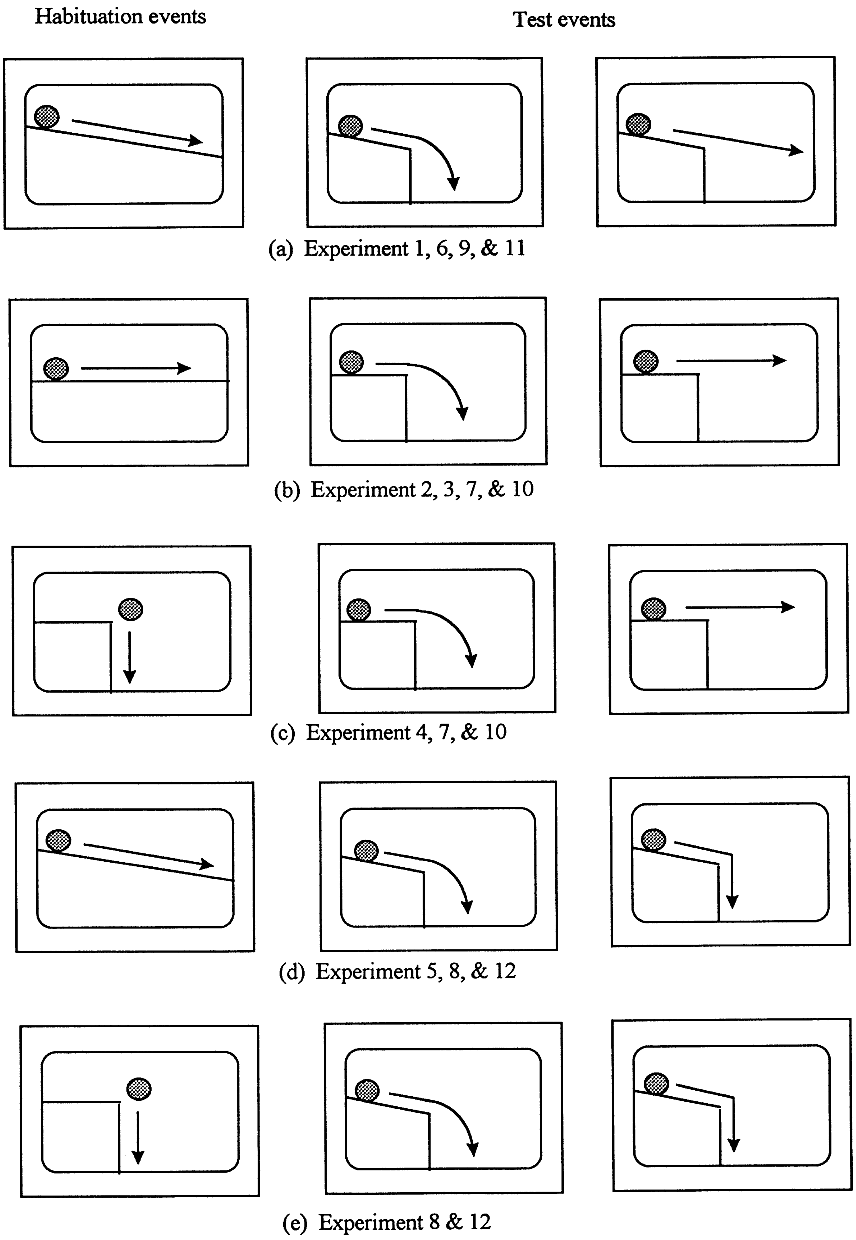

Figure 1 *Schematic depiction of the events used for Experiments 1–12.*

was released as before, rolled down the truncated ramp, and then fell from the edge of the ramp on a parabolic path (natural). In the other test event, the ball was released and then rolled straight across the screen as if it was still being supported by a complete ramp (unnatural). It actually rolled on a pair of fishing wires, which were not visible on the video image. For the test events, the ball moved for 1.3 s, each complete event lasted 6 s, and the events again occurred repeatedly. Before the test trials, there was an introductory display showing an experimenter who tapped on the surface of the truncated ramp and waved her hand to show there was nothing but empty space to the right of the ramp.

Twelve adults naive to the purpose of the present studies rated the naturalness of the habituation and test events in this experiment. For each event, the motion of the ball was repeated three times. The events were shown in counterbalanced order across subjects, within a larger set of eight displays. After the presentation of an event, a subject was asked to rate whether the motion appeared natural or unnatural on a scale from 1 (very natural) to 5 (very unnatural).

Figure 2 shows the average ratings for the three events. All subjects rated the habituation event (Figure 2(b)) and the parabolic test event (Figure 2(c)) as very natural, and all subjects rated the straight test event (Figure 2(g)) as very unnatural. The ratings for each of these events differed significantly from the neutral rating of 3: respective values for $t(22) = 23.0$, 11.73 and 9.75; all $p < 0.001$.

Design Each infant was presented with the same habituation display followed by the same two test displays in alternation. Half the infants of each sex were presented first with the linear test display; the remaining infants were presented first with the parabolic test display.

Procedure Infants first were presented with the introductory display with the full ramp for about 10 s. The habituation sequence immediately followed. After the last habituation trial, infants were presented with the introductory display with the half ramp for about 10 s, and then the test sequence followed. During the test sequence, infants were presented with the two test displays in alternation for a total of six trials. Interobserver agreement averaged 0.93.

Results

Mean looking times for the habituation and test trials are shown in Figure 3. Log-transformed looking times were subjected to a 2 (Test order) by 3 (Test trial pair) by 2 (Test event: straight vs parabolic) analysis of variance (ANOVA). There was a significant effect of Test order, $F(1, 10) = 10.87$, $p < 0.01$: infants looked longer at the test sequence when the parabolic test event was presented first. This effect was complicated by a Test order by Test event interaction, $F(1, 10) = 25.33$, $p < 0.01$, and a Test trial pair by Test event interaction, $F(2, 20) = 3.51$, $p < 0.05$: infants looked longer at whichever test event was presented first, and they looked longer at the straight event in the first trial pair and at the parabolic event in the third pair. However, there was no main effect of Test event, $F(1, 10) = 2.32$, $p = 0.16$.

Discussion

After familiarization with an event in which a ball rolled downward on an inclined plane, 7-month-old infants showed no preference between the straight and parabolic test events. Thus, the experiment provides no evidence that infants perceived the correct parabolic motion as more natural.

It is possible, however, that the present test was too stringent. Like the natural test event, the unnatural test event in the present experiment presented a motion that was both downward and forward: thus, both test motions were consistent with aspects of inertia and gravity. Infants might have perceived both of these events as more natural than an event in which an unsupported object underwent no downward motion. It is possible, therefore, that the infants understood that the object should move forward and downward, but failed to appreciate that the forward and downward motions should combine to form a parabolic path.

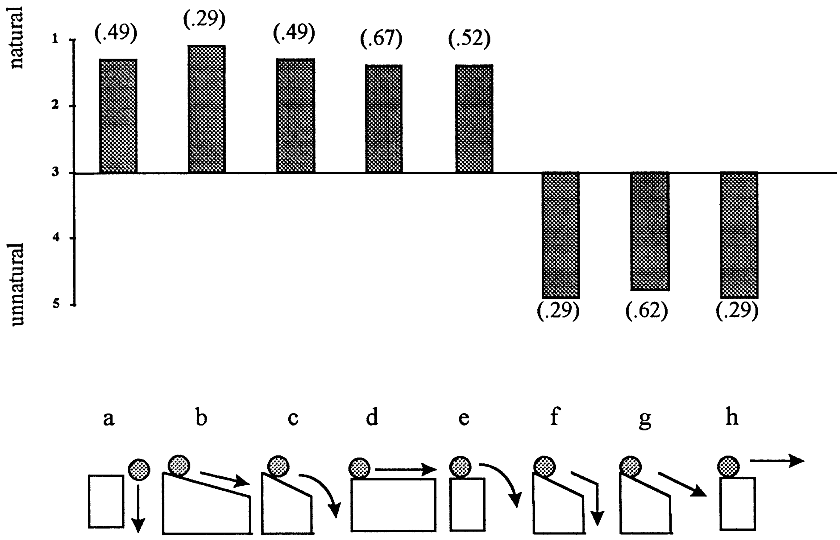

Figure 2 *Adults' judgments of the naturalness of each of the events presented to infants and children in Experiments 1–12 (standard deviations in parentheses).*

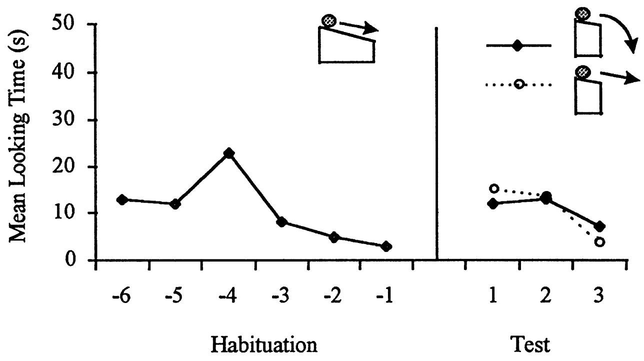

Figure 3 Mean looking times during the last six habituation trials and the six test trials by the infants in Experiment 1.

Accordingly, Experiment 2 presented infants with an unnatural event in which an unsupported object underwent no downward motion at all, in order to investigate whether infants expect motion downward rather than horizontal motion through the air.

Experiment 2

Experiment 2 was identical to Experiment 1 except for the horizontal inclination of the surface in the habituation and test events. Seven-month-old infants were habituated to a videotaped event in which a ball rolled on a horizontal surface at a natural, nearly constant velocity. Then, for the test events, the surface was cut in half, the ball was set in motion on the surface, and after rolling off the surface it either followed a parabolic path (unfamiliar but natural) or rolled straight across the screen (familiar but inconsistent with gravity). If infants appreciated that the object should move downward after losing its support, then they were expected to look longer at the test event with the linear motion.

Method

The method was the same as in Experiment 1 except as follows. Participants were eight infants, four males and four females, ranging in age from 6 months 15 days to 7 months 15 days ($M = 7$ months 0 days). No infant failed to complete the experiment.

The displays are depicted schematically in Figures 1 (b) and 4. For the habituation display, a green horizontal plane covering the bottom half of the screen was used. A ball was tapped by a hand at the far left end of the plane, and the ball rolled at a constant velocity across and off the screen. The ball rolled for 1.1 s, and one entire event lasted 3.7 s. For the test displays, a red truncated plane covering the bottom left quadrant of the screen was used, the ball was tapped as before, and it either rolled off the plane on a parabolic path (natural) or followed the same linear trajectory across the screen as during habituation (unnatural). In both test events, the ball moved for 1 s and one entire event lasted 3.7 s. Except for the inclination of the plane, the tapping of the ball, and the duration of the events, all the events were the same as in Experiment 1.

The habituation and test events were presented to adults who rated their naturalness along with the events from Experiment 1 (see Figure 2). The habituation event (Figure 2 (d)) and the parabolic test event (Figure 2 (e)) were rated as very natural by adults, whereas the straight test event (Figure 2 (h)) was rated as very unnatural. All the ratings differed from the neutral value of 3: respective values of $t(22) = 7.71$, 9.95 and 23.0; all $p < 0.001$.

Inter-observer agreement averaged 0.94.

Results

Mean looking times for the habituation and test trials are shown in Figure 4. The data were analyzed as in Experiment 1. The ANOVA yielded no significant effects. In particular, there was no main effect of Test event, $F(1, 6) < 1$.

Discussion

After familiarization with an event in which a ball rolled on a flat plane, 7-month-old infants looked equally at the parabolic event and straight event. The experiment therefore provides no evidence that 7-month-old infants expect an unsupported, moving object to move downward on a parabolic path rather than horizontally through the air.

The present findings present an interesting contrast with the research of Kim and Spelke (1992). Because Experiments 1 and 2 used the same method as the

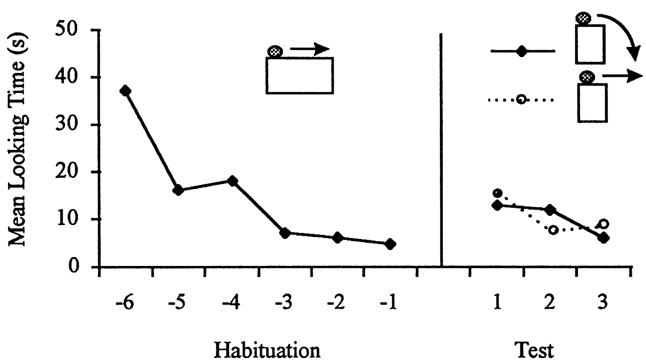

Figure 4 *Mean looking times during the last six habituation trials and the six test trials by the infants in Experiment 2.*

experiments of Kim and Spelke (1992), infants' failure to look longer at the events with linear motion suggests that infants' sensitivity to the novelty of object motions that violate effects of gravity and inertia depends on piecemeal knowledge rather than on sensitivity to general physical constraints on objects. Nevertheless, there is one procedural difference between these two sets of experiments that complicates their comparison: In the present experiments, the object was released by a hand and then rolled off-screen, whereas in Kim and Spelke's (1992) experiments the object was released by a hand and then caught, at the opposite side of the screen, by a second hand. It is possible that events in which an object comes visibly to rest on-screen are easier for infants to understand than are events in which an object moves completely from view. Experiment 3 was conducted to test this possibility and to provide a more direct comparison between the present experiments and those of Kim and Spelke (1992).

Experiment 3

Experiment 3 presented the same events as Experiment 2, with one exception: after the hand released the ball on the left side of the screen and the ball rolled rightward across the screen, a second hand caught it on the right side of the screen. The spatial and temporal characteristics of these events were as similar as possible to those of Kim and Spelke (1992), in which a ball rolled on a full ramp inclined either downward or upward. As in Experiment 2, however, the ball rolled on a full, horizontal ramp during the habituation sequence and rolled on a truncated ramp during the test, on either a linear or a parabolic path.

Method

The method was the same as in Experiments 1 and 2 except as follows. Participants were eight infants, three males and five females, ranging in age from 6 months 15 days to 7 months 15 days ($M = 7$ months 2 days). One additional infant was eliminated because of experimental error.

The displays are depicted schematically in Figure 5. For the habituation event, a ball was tapped by a hand at the left end of the plane, was caught by a second hand at the right end of the plane, was held briefly, and then carried off the screen. For each test event, the ball was tapped and then was caught by a second hand at the final position (parabolic or straight-across path), held briefly, and then carried off the screen. For all three events, the ball moved for 1.2 s, and one entire event lasted 5 s. All events occurred repeatedly. Inter-observer agreement averaged 0.96.

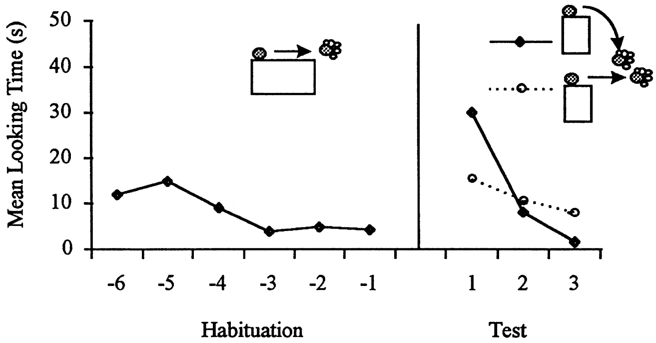

Figure 5 *Mean looking times during the last six habituation trials and the six test trials by the infants in Experiment 3.*

Results

Mean looking times for the habituation and test trials are shown in Figure 5. The ANOVA showed only a significant effect of Test trial pair, $F(2, 12) = 10.20$, $p < 0.005$: looking time declined over successive pairs of test trials. There was no main effect of Test event, $F(1, 6) = 1.88$, $p > 0.2$.

A second ANOVA with the additional between-subjects factor of Experiment compared the test trial looking patterns in Experiments 2 and 3. This analysis showed again the effect of Test trial pair, $F(2, 24) = 11.91$, $p < 0.001$, but no other significant effects. In particular, there was no interaction of Experiment and Test event, $F(1, 12) = 1.67$, $p > 0.2$.

Discussion

After habituation to an event in which a ball rolled on a flat plane, 7-month-old infants showed no preference between the straight and parabolic test events. Longer exposure to the ball's final position did not enhance infants' sensitivity to the naturalness of its path of motion.

In three experiments, therefore, 7-month-old infants showed no preference between a natural event in which an object rolled off a surface and underwent parabolic motion and an unnatural event in which the object continued in linear motion. The results provide no evidence that 7-month-old infants expect an object that rolls off a cliff to move downward, relative to the straight-across path, in accord with the effects of gravity on object motion.

The present results contrast with those of Kim and Spelke (1992), who used very similar events and the same method as Experiment 3. Although 7-month-old infants appear to expect, on some level, that an object will accelerate when it moves downward and decelerate when it moves upward on an inclined plane, they do not appear to expect that an object will begin to move on a parabolic path when it moves off a plane and begins to fall freely.

Nevertheless, it is possible that infants indeed expect an object to move downward when it loses its support, but that Experiments 1–3 failed to reveal this expectation because they presented infants with too stringent a test of sensitivity to effects of gravity. These experiments pitted the superficial familiarity of the test events against their physical naturalness, because the motion of the habituation event was the same as that of the unnatural test event. It is possible, therefore, that infants responded both to the naturalness and to the superficial familiarity of object motion. Note that this possibility cannot explain the difference between the present experiments and those of Kim and Spelke (1992), which also pitted the superficial familiarity of test events against their physical plausibility. Nevertheless, the next experiment tested infants' sensitivity to gravity further by investigating infants' reactions to horizontal and parabolic motions after habituation to an event in which an object appeared in free fall, such that the two test motions were both novel.

Experiment 4

Seven-month-old infants were habituated to a videotaped event in which a ball underwent a vertical, free-fall motion. Then, for the test event, a ball rolled on a plane and continued to follow a parabolic path (natural) or a straight path (inconsistent with gravity).

Method

The method was the same as in Experiment 1 except as follows. Participants were 12 infants, six males and six females, ranging in age from 6 months 15 days to 7 months 15 days ($M = 7$ months 3 days). Two additional infants were eliminated because of fussiness.

The displays are depicted schematically in Figures 1 (c) and 6. For the habituation display, there was a green rectangular-shaped, truncated ramp, which covered the left bottom quarter of the screen. A hand held a ball at the right side of the ramp, and released it. The ball underwent a free fall and disappeared off the screen. The ball fell for 0.43 s, and one entire event lasted 3.7 s. This event was rated as very natural by adults, a rating that differed from the neutral value of 3, $t(22) = 11.73$, $p < 0.001$ (Figure 2 (a)). The test displays were the same as in Experiment 2. Inter-observer agreement averaged 0.95.

Results

Mean looking times for the habituation and test trials are shown in Figure 6. Although the infants tended to look longer at the test event with the straight path, this tendency was not significant, $F(1, 10) = 2.63$, $p = 0.13$. The only significant effect in the analysis was a main effect of Test trial pair, $F(2, 20) = 5.96$, $p < 0.01$: looking time declined on successive pairs of test trials.

Discussion

After habituation to an event in which a ball underwent a free-fall motion, 7-month-old infants showed no significant preference for the straight over the parabolic test events. Like Experiments 1–3, therefore, Experiment 4 provides no evidence that 7-month-old infants are sensitive to the natural, parabolic path of motion of an object that rolls off a supporting surface.

In summary, four experiments failed to provide evidence that 7-month-old infants are sensitive to the effect of gravity on the motion of an object that rolls off a supporting surface. It is possible, however, that infants are sensitive to a different aspect of the motion of such an object: They may implicitly appreciate that the object's motion is subject to inertia. Accordingly, the next experiment investigated 7-month-old infants' sensitivity to the effects of inertia on object motion in the same situation as Experiment 1.

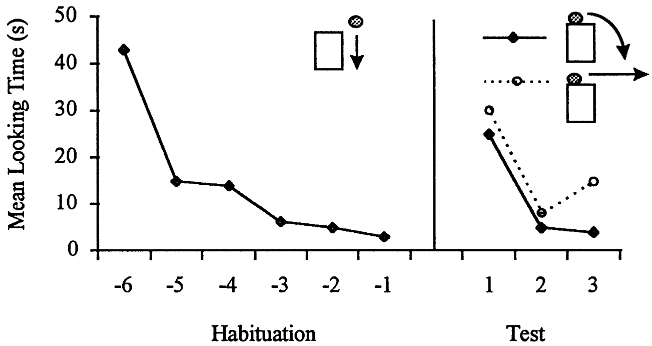

Figure 6 *Mean looking times during the last six habituation trials and the six test trials by the infants in Experiment 4.*

Experiment 5

Seven-month-old infants were habituated to a video-taped event in which a ball rolled on a slanted ramp at a constant acceleration. Then, for the test events, the ramp was cut in half as before, the ball rolled down and off the ramp, and then the ball either continued on a parabolic path (natural) or turned and moved straight downward (inconsistent with inertia). If infants are sensitive to the effects of inertia in this situation, they will look longer at the straight-down test event because the ball abruptly ceases to move forward after leaving the ramp.

Method

The method was the same as in Experiment 1 except as follows. Participants were 12 infants, seven males and five females, ranging in age from 6 months 15 days to 7 months 15 days ($M = 6$ months 29 days). No infant failed to complete the experiment.

The displays are depicted schematically in Figures 1 (d) and 7. The familiarization event and the natural test event were the same as in Experiment 1. For the unnatural test event, the ball rolled on the ramp until it reached its edge, and then it made a sudden turn and moved straight downward. This event was made through the video editing, by combining a segment in which the ball rolled down on the ramp with a segment in which it underwent a straight-down free-fall motion. The ball moved for 1.3 s, and a complete event lasted 6 s. This event was rated as very unnatural by adults, a rating that differed from the neutral value of 3, $t(22) = 23.0$, $p < 0.001$ (Figure 2 (f)). Inter-observer agreement averaged 0.95.

Results

Mean looking times for the habituation and test trials are shown in Figure 7. The data were analyzed as in Experiment 1 and showed no significant effects. In particular, there was no main effect of Test event, $F(1, 10) < 1$.

Discussion

After familiarization with an event in which a ball rolled downward on an inclined plane, 7-month-old infants looked equally at the parabolic event and straight-down event. Even though the infants in this experiment were habituated to an event presenting a different path of motion than either of the test events, infants did not respond to the straight-down motion as unnatural or unexpected, relative to the parabolic motion. The

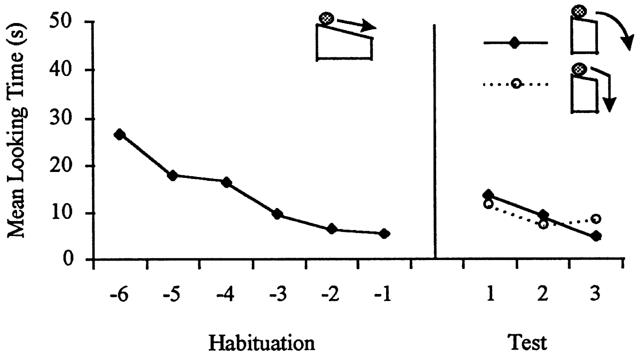

Figure 7 *Mean looking times during the last six habituation trials and the six test trials by the infants in Experiment 5.*

experiment therefore provides no evidence that 7-month-old infants are sensitive to the effects of inertia on the motion of a ball that rolls off a cliff.

Discussion of the studies of 7-month-old infants

After habituation to the natural, linear motion of an object rolling on a planar surface, 7-month-old infants were presented with the same object undergoing the same motion on a truncated surface, rolling off the surface, and continuing either on a natural parabolic path or on a path inconsistent with gravity (continued linear motion) or inertia (abrupt turning downward). The infants did not respond to either the linear or the abruptly turning path of motion as unexpected or unnatural, relative to the natural, parabolic path of motion. The experiments therefore provide no evidence that infants are sensitive to the naturalness of the correct parabolic motion in this situation.

This conclusion might be questioned on three grounds. First, it is based entirely on negative findings, but negative findings could result from the use of an insensitive method or inadequate displays. In the present case, however, the method is the same as that of Kim and Spelke (1992), which yielded positive findings with infants in the same subject population. The displays, moreover, are very similar to those of Kim and Spelke (1992) and evoked clear judgments of naturalness/unnaturalness from adults (see Figure 2). Although one can never conclude that children lack a given ability, the present findings suggest strongly that infants who view a ball rolling on an inclined plane are more sensitive to the effects of gravity and inertia on the object's acceleration than to the effects of gravity and inertia on the object's path of motion.

Second, our experiments might be criticized because they only tested infants' reactions to three paths of falling motion, whereas there are infinitely many possible paths an object could follow, and the correct parabolic path would be different depending on the initial force and other factors. It is possible, therefore, that infants had an expectation about the motion of the object but that we failed to test this expectation because we presented no test events that corresponded to it. We believe, however, that the motions presented during the habituation trials of Experiments 1–3 and 5 render this possibility unlikely. In Experiments 1 and 5, we specified for infants the initial acceleration of the object by using the same slanted plane in the habituation and test events, and in Experiments 2 and 3 we specified the initial force with which the object was hit on the horizontal plane by hitting the object with the same force during habituation and test. All the experiments therefore gave infants the opportunity to pick up the relevant information about the object's velocity and acceleration during the habituation trials. Although it is possible that infants had a specific, erroneous expectation about the motion of the object that failed to correspond to any of the test events, this possibility appears unlikely, because such an expectation would fail to accord both with the natural motions of objects and with the actual motions infants viewed during the habituation period.

Third, these experiments contain no baseline measures of preference for parabolic, linear, and abruptly turning motions, independent of the physical plausibility of these events. It is possible, therefore, that infants had an intrinsic preference for parabolic motion, and that this preference offset their novelty reactions to the unnatural test events. This possibility reveals an inherent limitation of experiments using the preferential looking method to test for infants' sensitivity to the naturalness of different paths of object motion. It is not possible to test for stimulus preferences among different paths of motion independent of the physical plausibility of those paths of motion. For example, one could present infants with an object that underwent linear, parabolic, and abruptly turning motion while rolling on a single, continuous horizontal surface. On such a surface, however, the linear motion would be natural and the other motions would be unnatural. Because there is no situation in which linear, turning, and parabolic motions are equally natural, no pure baseline conditions can be run in these experiments.

Although we cannot conduct meaningful baseline conditions for the present experiments, a consideration of infants' visual preferences in other, related experiments for which baseline measures are possible casts doubt on the thesis that infants are sensitive to the naturalness of parabolic motion but that their sensitivity is masked by a baseline preference for that motion. In the experiments by Kim and Spelke (1992), for example, infants were found to have a general preference for accelerating object motion over decelerating object motion. Nevertheless, this preference did not prevent their also exhibiting a robust preference for a decelerating motion that was natural and inconsistent with the downward force of gravity, relative to an accelerating or decelerating motion that was natural. In experiments by Gergely, Nadasdy, Csibra and Biro (1995), infants were presented with test displays involving one linear motion and one curved motion, as in the present studies. Because the investigators' focus was on animate, goal-directed motions, they were able to create conditions in which both the linear and the curved motions were natural, as well as conditions in which one motion was natural and the other was not. Infants showed a robust visual preference for the unnatural motions, suggesting that any baseline preference for curvilinear motion was outweighed by infants' reactions to the naturalness or unnaturalness of events. Although we cannot be certain that the present situation is free of baseline preferences, we believe it is noteworthy that five experiments, using a method that has produced clear positive findings in other studies (Kim & Spelke, 1992), all failed to provide evidence that 7-month-old infants are sensitive to the natural, parabolic path of motion of an object that rolls off a supporting surface. Either such sensitivity is absent, or it is too weak to override an (unknown) intrinsic preference for parabolic motion. In either case, comparison of the present findings with those of Kim and Spelke (1992) suggests that sensitivity to object motion develops in a piecemeal fashion in infancy.

In view of the negative findings with 7-month-old infants and the limitations of the preferential looking method for probing those findings further, the remaining experiments investigated 2- to 6-year-old children's perception and reasoning about the path of a falling object. Preference-for-novelty tests are still possible with older children, and they were conducted at 2 and 3 years of age. In addition, 3- to 6-year-old children's judgments about the same visible object motions were elicited to provide information about their explicit conceptions of object motion and to allow tests for a discrepancy between perception and judgment.

Sensitivity to gravity and inertia in 2-year-old children

Overview

Two-year-old children were tested with the events presented in Experiments 1–5, using a variation of the preferential looking method from those experiments, tailored to this age. Experiment 6 used the events of Experiment 1 and investigated whether 2-year-old children implicitly appreciate that an object that rolls off an inclined supporting surface should increase its downward motion and follow a parabolic path. Because the findings of Experiment 6 were negative, Experiment 7 used the events of Experiment 2 and investigated whether such children implicitly appreciate that an object that rolls off a horizontal supporting surface should begin to move downward, in accord with gravity. Finally, Experiment 8 used the events of Experiment 5 and investigated whether 2-year-old children implicitly appreciate that an object that rolls off a supporting surface should continue in some forward motion, in accord with inertia.

Experiment 6

Experiment 6 was a replication, with modifications, of Experiment 1. Two separate groups of 2-year-old children were familiarized, on three trials, either with an event in which a ball rolled on a full inclined plane with an accelerating motion, as in Experiment 1, or with an event in which a ball was released beside a truncated plane and underwent a vertical free-fall motion, as in Experiment 4. Then all the infants were tested with the two test events of Experiment 1, in which the ball rolled off the truncated plane and continued to move either on a parabolic path (natural) or on a straight path (inconsistent with gravity). As in the experiments with infants, looking times to the test displays were measured and compared to determine whether the children tended to look longer at the unnatural test motion.

Method

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

Subjects Participants were 13 male and three female children ranging in age from 2 years 1 month to 2 years 11 months ($M = 2$ years 6 months). Two additional children were tested and eliminated from the experiment because of experimenter error (one) or parental interference (one).

Displays and design Half the children were familiarized with the habituation display of Experiment 1 and half with the habituation display of Experiment 4. All the children were tested with the test displays of Experiment 1, with half the children in each familiarization condition viewing the unnatural test display first. Prior to familiarization and test, children viewed the appropriate introductory displays from Experiments 1 and 4.

Procedure Before starting the experiment, the experimenters played with the child to familiarize him or her with the new environment. After 5 to 10 minutes of play, he or she went for the experiment with a parent. The child was seated on a booster seat with his or her eyes 30 inches from the same TV screen used with infants. The parent was asked to stand behind the child so that he or she felt secure but was asked not to talk or look at the display.

As in the experiments with infants, children were presented with a videotaped introductory display for about 10 s. Then they were shown three trials of the familiarization display. (Three trials were used rather than a full habituation sequence because 2-year-old children appeared to become bored with the events more quickly than infants.) Then the children were shown the second introductory display, and finally they were tested with parabolic and straight test events as in the studies with infants.

Inter-observer agreement averaged 0.92.

Results

Mean looking times for the familiarization and test trials are shown in Figure 8. Log-transformed looking times were subjected to a 2 (Familiarization condition) by 2 (Test order) by 3 (Test trial pair) by 2 (Test event: parabolic vs straight) ANOVA. The analysis revealed main effects of Familiarization condition, $F(1, 12) = 6.44$, $p < 0.05$, and Test trial pair, $F(1, 12) = 26.19$, $p < 0.001$: children in the free-fall familiarization condition looked significantly longer during the test sequence than those in the straight-across condition, and all children tended to look longest on the first pair of test trials. There was no effect of Test event, $F(1, 12) < 1$: children looked equally at the events that were consistent versus inconsistent with gravity. A separate analysis with free-fall familiarization condition group only again revealed no effect of Test event, $F(1, 7) < 1$.

Discussion

Like 7-month-old infants, the 2-year-old children who were presented with a ball that rolled off a cliff showed no preference for an unnatural, linear motion over a natural, parabolic motion. The experiment therefore provides no evidence that the children were sensitive to the effect of gravity in this situation. The next experiment accordingly tested whether 2-year-old chil-

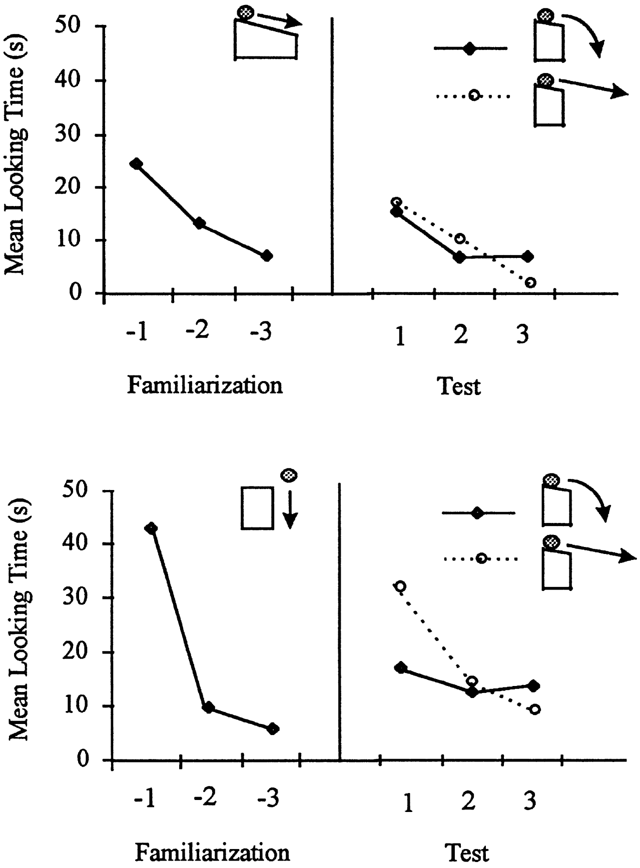

Figure 8 *Mean looking times during the last three familiarization trials and the six test trials by the 2-year-old children in Experiment 6.*

dren are sensitive to gravity in the simpler situation of Experiment 2, in which an object rolls off a horizontal cliff and either continues in horizontal motion or begins to move downward.

Experiment 7

Experiment 7 was a replication of Experiments 2 and 4 with older children. Separate groups of 2-year-old children were familiarized with an event in which a ball either rolled on a flat plane, undergoing fully horizontal motion, or fell through the air to the side of a truncated plane, undergoing vertical, free-fall motion. Then all the children were tested with events in which the ball rolled off the flat, truncated plane and continued either on a parabolic path (natural) or on a linear, horizontal path (unnatural). If 2-year-old children expect an object to begin to move downward when it loses its support, then the children should have looked longer at the unnatural linear test event.

Method

The method was the same as Experiment 6, except as follows. Participants were 15 male and nine female children ranging in age from 1 year 9 months to 2 years 10 months ($M = 2$ years 3 months). Three additional children failed to complete the experiment because of lack of interest (one) or parental interference (two). Displays were the same as Experiments 2 and 4.

Results

Looking times during the familiarization and test trials are presented in Figure 9 and were analyzed as in Experiment 6. There was no significant difference between the two familiarization groups, $F(1, 22) < 1$. The only significant finding in the analysis was a main effect of Test order, $F(1, 20) = 29.75$, $p < 0.001$: looking time declined over successive pairs of test trials. In particular, there was no effect of Test event,

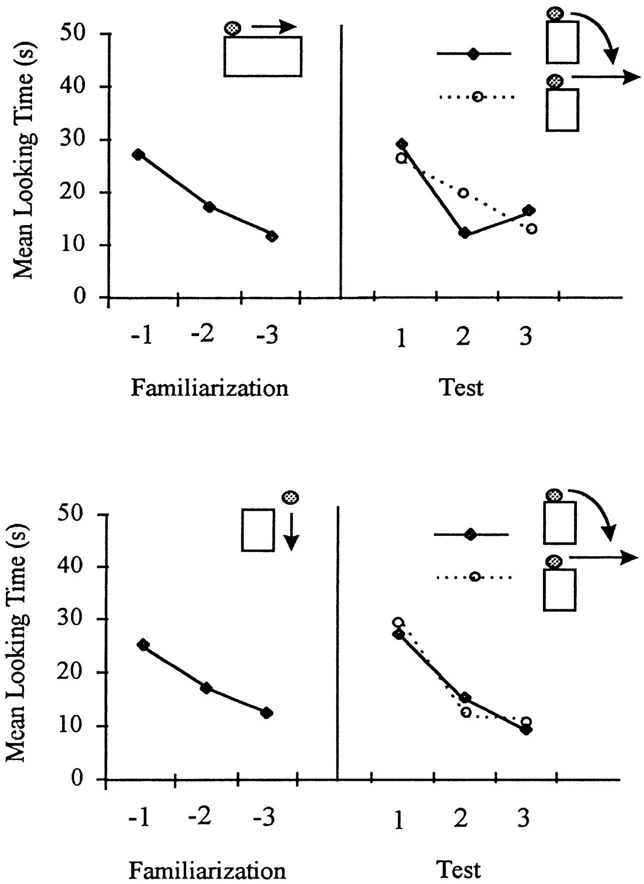

Figure 9 *Mean looking times during the last three familiarization trials and the six test trials by the 2-year-old children in Experiment 7.*

$F(1, 20) < 1$: children showed no looking preference for the unnatural event.

Discussion

Two-year-old children showed no reliable looking preferences between events in which a ball rolled off a horizontal cliff and continued in natural parabolic motion or unnatural linear motion. Their looking patterns, like those of the 7-month-old infants in Experiments 2–4, therefore provide no evidence that 2-year-old children are sensitive to this effect of gravity on object motion. The next experiment investigated whether 2-year-old children are sensitive to the effect of inertia on object motion in this situation.

Experiment 8

Experiment 8 was a replication of Experiment 5 with older children. Separate groups of 2-year-old children first were familiarized with events in which an object rolled on an inclined plane or fell through the air, as in Experiment 6, and then were tested with events in which the object rolled off a truncated inclined plane and either continued on a parabolic path (natural) or turned abruptly and moved on a straight-down path (inconsistent with inertia). If 2-year-old children are sensitive to inertia, they should look longer at the unnatural event. If they fail to understand this effect, they should look equally at the two test events.

Method

Participants were 12 male and 12 female children ranging in age from 1 year 11 months to 2 years 8 months ($M = 2$ years 3 months). Three additional children were eliminated from the experiment because of parental interference (two) or other distractions (one). Familiarization displays were the same as in Experiment 6, test displays were the same as in Experiment 5, and the procedure was the same as in Experiments 6 and 7. Inter-observer agreement averaged 0.92.

Results

Mean looking times for the familiarization and test trials are shown in Figure 10. Log-transformed looking times were analyzed as in Experiments 6 and 7 and revealed a significant effect of Test event, $F(1, 20) = 19.76$, $p < 0.001$: 2-year-old children looked reliably longer at the straight-down event than at the parabolic event. Children exhibited a significant preference for the straight-down event both after familiarization with the free-fall motion, $F(1, 10) = 10.51$, $p < 0.05$, and after familiarization with the straight-across motion, $F(1, 10) = 9.25$, $p < 0.05$. The only other significant effect was a main effect of Test trial pair, $F(1, 20) = 17.17$, $p < 0.005$: looking time declined over the test sequence.

Discussion

After familiarization with either slanted linear or free-fall motion, 2-year-old children looked longer at a test event in which the ball rolled off a cliff, abruptly turned, and continued on a straight-down path than at an event in which it rolled off the cliff and continued in parabolic motion. Despite the superficial familiarity to the straight-down event for the infants familiarized to free-fall motion, children responded to the straight-down event as more novel or unexpected. They seemed to perceive the parabolic event as more familiar or expected

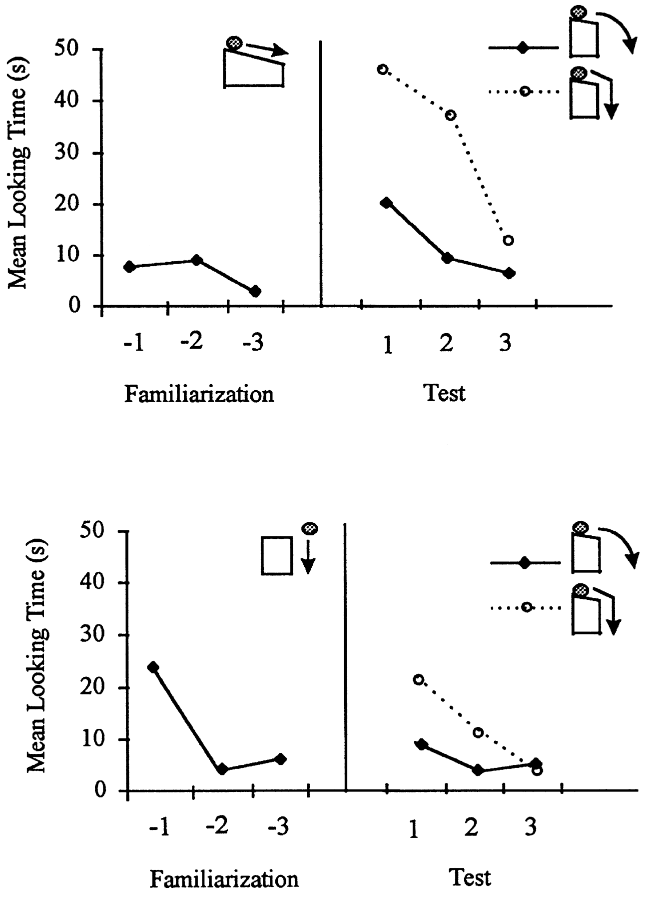

Figure 10 *Mean looking times during the last three familiarization trials and the six test trials by the 2-year-old children in Experiment 8.*

than the abruptly turning event in which the object began to move straight downward.

This experiment provides evidence that infants are sensitive to one effect of inertia on the motion of an object that rolls off a supporting surface: the object should continue in forward motion of some kind and not turn abruptly downward. Together with Experiment 5, the studies suggest that this sensitivity develops between 7 months and 2 years of age. This suggestion is consistent with the findings of Spelke *et al.* (1994), using a preferential looking method with partly occluded displays, who found that sensitivity to the effect of inertia on the motion of an object on a horizontal plane begins to develop only after 6 months of age and is not complete at 12 months. It contrasts with the findings of experiments using a predictive reaching method, however: By 6 months, infants aim their reaching for a fully visible, moving object, at positions that are consistent with the continued forward motion of the object (von Hofsten *et al.*, 1998). Sensitivity to inertia appears to develop slowly, and perhaps in a task-specific manner.

Discussion of the studies of 2-year-old children

Experiments 6, 7 and 8 provide evidence that 2-year-old children have developed some knowledge about the behavior of an object that rolls off a supporting surface and continues moving in free fall, but they suggest that the children's knowledge is not complete. Although such an object is expected to continue in some forward motion, both natural parabolic motion and unnatural linear motion appear to be equally acceptable to the children. These findings underscore the gradual, piecemeal nature of children's developing knowledge of constraints on object motion.

The positive findings of Experiment 8 contrast with the negative findings of Kaiser *et al.* (1985), using older children and a different method. Children aged $4\frac{1}{2}$ to 12 years were asked to predict the trajectory of a ball rolled off the edge of a table and that of a ball dropped from a moving model train. Most preschool and kindergarten children judged that the ball would fall straight down. This erroneous judgment contrasts with 2-year-old children's successful performance in Experiment 8, suggesting a divergence between children's perception and judgments. Nevertheless, the experiments by Kaiser *et al.* (1985) differed from Experiment 8 in a number of respects, including the age of the subjects and specific features of the displays. In the next experiments, we compare children's perceptions and judgments more directly, using the same displays for both tasks.

The negative findings of Experiments 6 and 7 contrast with the findings from our initial study with adults, who viewed the same events presented to children and judged their naturalness. Because adults find the continued linear motion to be unnatural (Figure 2), the negative findings with 2-year-old children suggest that knowledge of object motion continues to develop after 2 years of age. Nevertheless, the study with adults used a different measure than Experiments 6–8 (verbal judgment rather than preferential looking), complicating the comparison across studies. Experiments 9–13 address this problem.

Finally, the negative findings of Experiments 6 and 7 contrast with the findings of experiments by Hood (1995), investigating 2- to 4-year-old children's sensitivity to gravity in events in which a ball traveled downward through a curved tube. Hood presented children with events in which a ball was dropped into a curved, opaque tube. Asked where the ball landed, children pointed reliably to a position directly below its point of release, suggesting sensitivity to the effect of gravity on the object's motion. Children's performance in Hood's experiment, like infants' successful performance in the experiments of Kim and Spelke (1992) and others, further suggests that sensitivity to gravity develops in a piecemeal fashion. Nevertheless, the experiments by Hood used different displays and a different measure than the present studies, making comparisons across the studies problematic. The next experiments investigate the continued development of sensitivity to constraints on object motion using the same set of perception and judgment tasks with children aged 3–6 years.

Perception and judgments about effects of gravity and inertia in 2- to 6-year-old children

The final experiments explore the task-specific, piecemeal nature of children's knowledge more directly, in older children. Three different tasks were used to test 3- to 6-year-old children's sensitivity to the effects of gravity and inertia on the motion of an object that rolls off a cliff. In Experiments 9, 10, 11 and 12, children were presented with the videotaped events from the previous experiments, they participated in the same preferential looking experiments as did the 2-year-old children in Experiments 6–8, and they were also asked, at the end of the study, which events presented motion that was 'silly'. In Experiment 13, children in five age groups, from 2 years to 6 years, were presented with a real ball and three-dimensional truncated cliff and were asked to predict where the ball would land after rolling off the cliff.

Experiment 9

Experiment 9 investigated whether 3- to 4-year-old children implicitly appreciate that a ball moving downward on a slanted surface should increase its downward motion if it moves off the surface. The experiment used the same method as Experiment 6, with one innovation: at the end of the preferential looking experiment, children were shown each of the test events for one final, brief viewing and were asked which event presented motion that was unnatural.

Method

The method was the same as in Experiment 6 except as follows. Participants were five female and 11 male children ranging in age from 3 years 1 month to 4 years 10 months ($M = 3$ years 9 months). Three additional children failed to complete the experiment because of experimenter error. Children were presented with the same familiarization and test events (straight-across and parabolic motions) as in Experiment 6, following exactly the same looking time procedure as for that experiment. After viewing the test events on six trials, they were shown each test display for one final time and were asked which was 'okay' and which was 'silly'.

Results

Mean looking times for the test trials are shown in Figure 11. Log-transformed looking times were analyzed as in Experiments 6–8 and revealed only a main effect of Test trial pair, $F(1, 12) = 8.97$, $p < 0.05$, indicating that looking time declined over the series of test trials. There was no effect of Test event, $F(1, 12) < 1$.

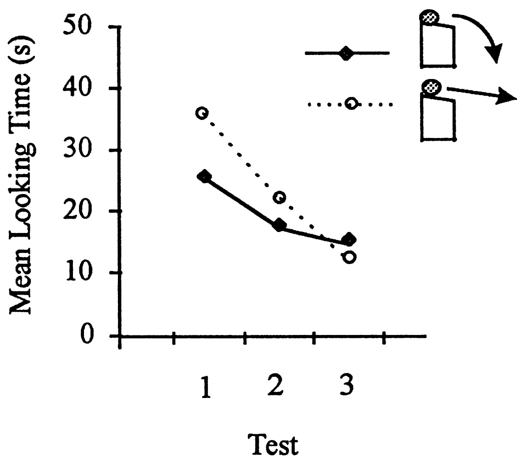

Figure 11 *Mean looking times during the six test trials by the 3- to 4-year-old children in Experiment 9.*

On the judgment task, eight children said the unnatural event was silly, and eight children said that the natural event was silly; binomial $p > 0.4$. Those who said the unnatural event was silly were no more likely to show a visual preference for the unnatural event than those who said the natural event was silly (respectively, four and five of the eight children giving each judgment looked longer at the unnatural event).

Discussion

Experiment 9 provided no evidence that 3- to 4-year-old children implicitly expect an object moving downward on a slanted surface to increase its downward motion when it moves off the surface. Neither the looking time method nor the judgment method provided evidence for any consistent reaction to the impossible, linear test event. Like 7- and 24-month-old infants, 3-year-old children therefore show no signs of sensitivity to this effect of gravity on object motion. Accordingly, the next experiment investigated whether 3- to 4-year-old children implicitly expect a horizontally moving object to begin moving downward when it loses its support.

Experiment 10

The next experiment used the method of Experiment 9 with the events of Experiments 2, 4 and 7, events in which an object rolled off a horizontal surface and either began to move downward on a parabolic path (natural) or continued in horizontal motion (contrary to gravity).

Method

Participants were eight male and six female children ranging in age from 3 years 1 month to 4 years 10 months ($M = 3$ years 8 months). No subject was eliminated from the sample. The method was the same as Experiment 9.

Results

Mean looking times for the test trials are shown in Figure 12 and were analyzed as in Experiment 9. The analysis revealed a main effect of Test trial pair, $F(1, 10) = 40.95$, $p < 0.001$, indicating that children looked longer on the earlier test trials, but no effect of Test event, $F(1, 10) = 1.81$, $p > 0.2$.

On the judgment measure, eight children said the unnatural (straight-across) event was silly, four said the natural event was silly, one said that neither event was silly, and one refused to answer the question. Although these responses tended to go in the correct direction,

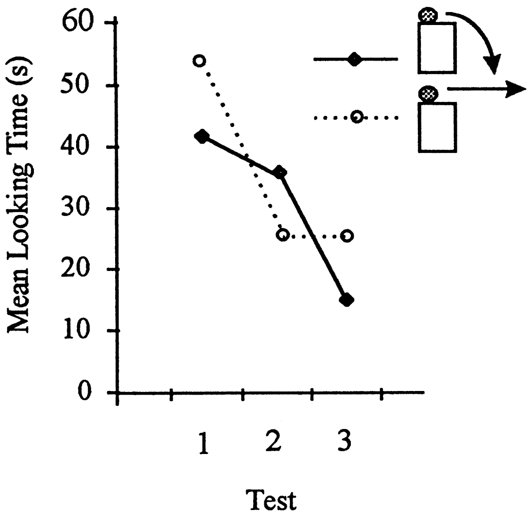

Figure 12 *Mean looking times during the six test trials by the 3- to 4-year-old children in Experiment 10.*

they did not differ significantly; $p = 0.19$, binomial test. Judgments and preferential looking patterns again showed no systematic relation: longer looking at the unnatural test event was shown by five of the eight children who said the unnatural event was silly and by three of the four children who said the natural event was silly.

Discussion

Like Experiment 9, Experiment 10 provides no clear evidence that 3- to 4-year-old children react to the perceptible motion of an object as more unnatural if the object continues in linear motion after leaving a supporting surface, relative to natural parabolic motion. Nevertheless, Experiment 10 showed a trend in the correct direction on the judgment measure, suggesting that sensitivity to the effects of gravity may be developing over this age range. Experiment 11 therefore tested 5- and 6-year-old children in the same situation as Experiment 9.

Experiment 11

Experiment 11 investigated whether 5- to 6-year-old children implicitly appreciate that an object that rolls off a slanted cliff should increase its downward motion.

Method

The experiment used the same method as Experiment 9. Participants were nine male and six female children ranging in age from 5 years 0 months to 6 years 11 months ($M = 5$ years 9 months). One additional participant was eliminated because of experimenter error.

Results

Mean looking times for the test trials are shown in Figure 13 and were analyzed as in Experiment 9. The analysis revealed a significant effect of Test trial pair, $F(1, 11) = 16.37$, $p < 0.005$: looking time declined over the series of test trials. In addition, there was a marginally significant effect of Test event, $F(1, 11) = 3.37$, $p = 0.09$: children tended to look longer at the unnatural linear motion.

On the judgment measure, 11 children said that the unnatural event was silly, and four said the natural event was silly. This difference was marginally significant; $p < 0.06$, binomial test.

A further 2 (Age) by 2 (Habituation condition) by 2 (Test order) by 3 (Trial pair) by 2 (Test event) analysis compared the looking times of the 5- to 6-year-old children in Experiment 11 with to those of the 3- to 4-year-old children in Experiment 10. The results showed a main effect of Test event, $F(1, 21) = 4.56$, $p < 0.05$: children looked longer at the unnatural event. There was also a main effect of Trial pair, $F(1, 21) = 45.85$, $p > 0.001$, and an interaction of Test event by Test order, $F(1, 21) = 4.86$, $p < 0.05$. Both effects reflected the decline in looking over the series of test trials. There was no interaction of Age by Test event, $F(1, 21) < 1$. Five- to 6-year-old children's looking times for the natural and unnatural events were not significantly different from those of 3- to 4-year-old children.

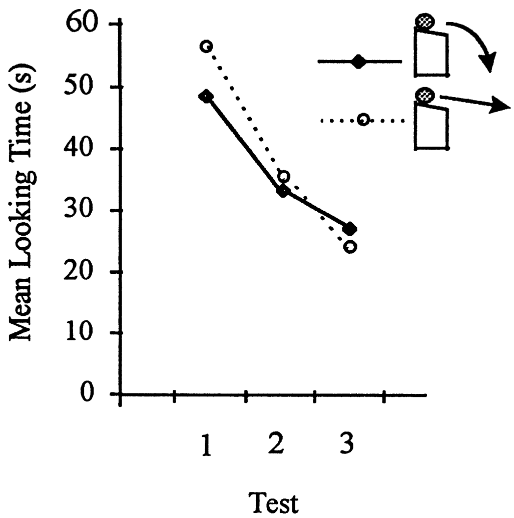

Figure 13 *Mean looking times during the six test trials by the 5- to 6-year-old children in Experiment 11.*

A final analysis compared the judgments of the 5- to 6-year-old children in Experiment 11 with those of the 3- to 4-year-old children in Experiment 10. Overall, 19 children in the two studies judged that the unnatural event was silly whereas eight judged that the natural event was silly – a significant difference, $p < 0.02$, binomial test. Judgments at the two ages did not differ, $p > 0.20$, Fisher exact test.

Discussion

The findings of Experiment 11, together with those of Experiments 1–10, suggest that sensitivity to the natural parabolic trajectory of the ball begins to develop between 3 and 6 years of age. Five- to 6-year-old children tended to judge that the unnatural linear motion was sillier than the natural parabolic motion, and they tended to look longer at the unnatural test event. Although neither tendency was strong enough to reach significance within this sample, both tendencies were significant when the data from the 5- to 6-year-old children were combined with those of the 3- to 4-year-old children in Experiment 10, who were tested with the same events. In contrast, 7-month-old infants and 2-year-old children showed no sensitivity to the effects of gravity in these events when they were tested with the preferential looking method. These findings suggest that sensitivity to one effect of gravity is emerging between 2 and 6 years of age, with 3–4 years as a time of transition.

Nevertheless, this suggestion must be qualified by two questions about the present methods. First, concerning the judgment task, do children show gradually emerging reactions to the violation of gravity because their sensitivity to the relevant effects of gravity emerges slowly or because the judgment task itself only slowly becomes a sensitive measure of children's knowledge? Perhaps the 3- to 6-year-old children in the present studies had highly consistent reactions of surprise to the unnatural test event, but their responses were not highly consistent within each age group because children did not understand our questions about the naturalness of object motion or failed to communicate their answers effectively. Second, concerning the looking time method, why did children not show more robust sensitivity to the effects of gravity in their looking times? Does the weakness of the looking preferences within each of the two age groups stem from the weakness of children's sensitivity to gravity, or from limits to our preferential looking method at these ages?

Experiment 12 was undertaken, in part, to address both these questions. In Experiment 12, 3- to 4-year-old children were presented with the events of Experiments 5 and 8, events in which an object's motion either was natural or failed to accord with inertia. As in Experiments 8–10, looking times were measured to the natural and unnatural events. As in Experiments 9–11, judgments about the naturalness of object motion were elicited as well. Because the 2-year-old children in Experiment 8 had shown robust reactions to the impossible test event, we reasoned that 3- and 4-year-old children also would be sensitive to this event. Their reactions on the preferential looking and judgment tasks therefore could serve as a measure of the effectiveness of the tasks. If the judgment method is relatively insensitive at the ages we have tested, then 3- to 4-year-old children should fail to show sensitivity to inertia by the judgment method. If the preferential looking method is less effective at older than at younger ages, because older children are less engaged by the events and therefore show consistent looking patterns, then 3- to 4-year-old children should fail to show sensitivity to inertia by the preferential looking method. In contrast, if a given method is appropriate at this age, then 3- to 4-year-old children, like the younger children in Experiment 8, should give evidence of sensitivity to inertia when tested by that method.

Experiment 12

Method

Experiment 12 used the events of Experiment 8 and the method of Experiments 9–11. Participants were seven male and eight female children ranging in age from 3 years 0 months to 4 years 10 months ($M = 3$ years 11 months). No further subjects were tested and eliminated.

Results

Mean looking times for the test trials are shown in Figure 14 and were analyzed as in the previous experiments. The analysis revealed no significant effects: in particular, no effect of Test event, $F < 1$. On the judgment test, ten children said the unnatural (straight-down) event was silly, three said the natural event was silly, and two refused to answer. Analysis of those children giving answers revealed a reliable difference in children's judgments for the two events, $p < 0.05$, binomial test. Longer looking at the unnatural event was shown by five of the ten children who said the unnatural event was silly and by one of the three children who said the natural event was silly.

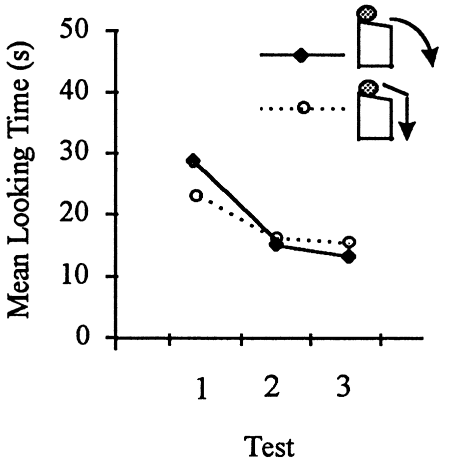

Figure 14 *Mean looking times during the six test trials by the 3- to 4-year-old children in Experiment 12.*

Discussion

The 3- to 4-year-old children in this experiment looked equally at an event in which an object that rolled off a cliff continued in natural parabolic motion and an event in which the object changed its motion abruptly and fell straight downward, contrary to inertia. In contrast, the children reliably judged that the first event was 'okay' and the second event was 'silly'. The children therefore showed sensitivity to inertia by the judgment measure but not by the preferential looking measure.

Concerning the preferential looking measure, the present findings contrast with those of Experiment 8: 2-year-old children, tested with the same preferential looking method and events, looked reliably longer at the test event that was inconsistent with inertia. It is unlikely that this age difference reflects any decline with age in sensitivity to inertia, both because such a decline would be inherently implausible, given children's experience with naturally moving objects, and because the older children showed continued sensitivity to inertia by the judgment measure. We conclude that the present version of the preferential looking method, used with the present displays, is less sensitive at the older age. Older children's increased restlessness and impatience with the simple repeated events of this study probably account for this age difference.

The present findings cast light on the findings from the preferential looking method in Experiments 10 and 11. As a group, the 3- to 6-year-old children in those experiments judged significantly that the linear test event was less natural than the parabolic event, and the children showed consistent looking preferences between the events, but neither tendency was strong. Given the present evidence that the preferential looking method is less sensitive at older ages, the weak findings from that method in Experiments 10 and 11 probably stem from limits on the present preferential looking method rather than from limits on 5- to 6-year-old children's sensitivity to gravity.

The present findings also cast light on the gradual development of sensitivity to gravity suggested by children's judgments in Experiments 10 and 11. Although the 3- to 6-year-old children together showed significant judgments in accord with gravity, their judgments also were not consistent enough to be significant at either age alone. We noted previously that this finding, by itself, could reflect either the slow development of sensitivity to gravity or an increase, with age, in the sensitivity of the judgment task. In the present experiment, however, 3- to 4-year-old children gave consistent judgments about the naturalness of object motion in relation to inertia, casting some doubt on the latter possibility. We conclude that sensitivity to the effect of gravity on the motion of an object that rolls off a cliff increases gradually over the preschool years.

Finally, the present findings support the principal conclusions from Experiments 1–8: children's sensitivity to the effects of gravity and inertia on a moving object that loses its support develop slowly, with sensitivity to inertia preceding sensitivity to gravity. In Experiments 6–8, 2-year-old children tested with the preferential looking method looked longer at an unnatural event in which an object abruptly turned after rolling off a cliff, contrary to inertia, but they looked no longer at an unnatural event in which the object continued in linear motion, contrary to gravity. In Experiments 9, 10 and 12, 3- to 4-year-old children tested with the judgment method showed sensitivity to the unnaturalness of the abrupt turning of the object, contrary to inertia, but as a group they did not show consistent reactions to the unnaturalness of the continued linear motion of the object, contrary to gravity. The common patterns of findings across these studies suggest that both the preferential looking method and the judgment method tap a common system of knowledge of object motion. Both methods, however, assess children's reactions to fully visible object motions. Does the same system of knowledge guide children's predictions or inferences about object motions that are not directly visible?

Experiment 13

The final experiment investigated 3- to 5-year-old children's understanding of object motion using a different judgment task, focusing on their predictions about the future motion of an object. Children were presented with a real three-dimensional slanted ramp with the shape of the truncated ramp in the test events of Experiments 1 and 6–8. A hand-held ball was placed at the high end of the ramp, where it was released and allowed to roll down the ramp, but it was caught at the end of the ramp and so underwent no free fall. Children were asked where the ball would land if it were not caught and instead rolled off the ramp.

If subjects had judged without constraint where the object would land, then the present task would differ from the previous ones in two general respects: it would assess predictions about motions the child had not seen rather than reactions to perceived motions, and it would present the child with a much larger number of response options (essentially an infinite number, because the ball could land anywhere). Because we wished to focus on the first difference, we attempted to make the response options available to children in Experiment 13 more similar to those available to children in Experiments 9–12. Accordingly, children were shown just three locations where the ball could land, each corresponding to one of the three motions tested in the previous experiments. Children were told the ball would land in one of these three positions and were asked to choose the correct one.

Method

Subjects Participants were (a) two male and six female children ranging in age from 2 years 1 month to 2 years 11 months (mean 2 years 7 months), (b) five male and three female children ranging in age from 3 years 3 months to 3 years 11 months (mean 3 years 6 months), (c) two male and six female children from 4 years 3 months to 4 years 11 months (mean 4 years 7 months), (d) three male and five female children from 5 years to 5 years 11 months (mean 5 years 3 months), and (e) four male and four female children from 6 years 2 months to 6 years 11 months (mean 6 years 6 months).

Displays Figure 15 depicts the display used in this experiment. A ramp of red foamboard (41 cm wide × 66.5 cm high) slanted by 15° was attached by white inverted L-shaped foamboard (49 cm wide and 61 cm high). In that L-shape, three holes (10 cm in diameter) were made on the final position of the straight, parabolic, or straight-down path: the distances between the edge of the ramp and the centers of the holes were 5 cm, 30 cm and 55 cm (45 cm in height), respectively.

Procedure A child was seated in front of the display and was shown the red ramp and the three holes in the L-shape. A yellow Nerf ball (6 cm in diameter) was placed at the left top of the ramp; it was released by the experimenter's right hand and caught at the right end of the ramp by the experimenter's left hand. The child was presented this same event four times. Then the child was asked to point to which hole the ball would land in after rolling off the edge of the ramp. His or her answer was recorded.

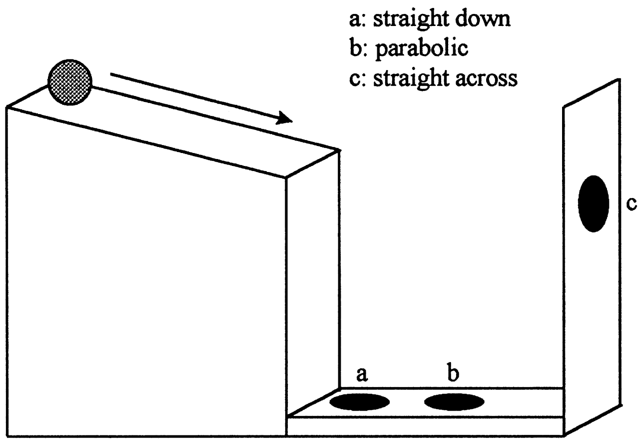

Figure 15 *Schematic depiction of the apparatus used for Experiment 13.*

Results

Figure 16 presents the percentage of participants of each age group who gave each of the three answers. Eight out of eight children tested at 2, 3 and 4 years chose the straight-down position: each binomial $p < 0.001$. At 5 years, four children chose the straight-down position, three chose the parabolic position, and one chose the straight-across position, binomial $p > 0.20$. At 6 years, seven children chose the correct, parabolic position and one chose the straight-down position, binomial $p < 0.005$. Comparisons across the different ages revealed a significant change between 4 and 5 years, $\chi^2(2) = 5.3$, $p < 0.05$, and between 4 and 6 years, $\chi^2(1) = 12.44$, $p < 0.005$, but not between 5 and 6 years, $\chi^2(2) = 4.4$, $p = 0.11$.

Discussion

The 2-, 3- and 4-year-old children consistently judged that the ball would land in the straight-down hole, as if they expected the object to move straight downward. Although this expectation shows some sensitivity to gravity, it shows no sensitivity to inertia: the younger children did not judge that the object would continue moving forward as it fell. In contrast, the 6-year-old

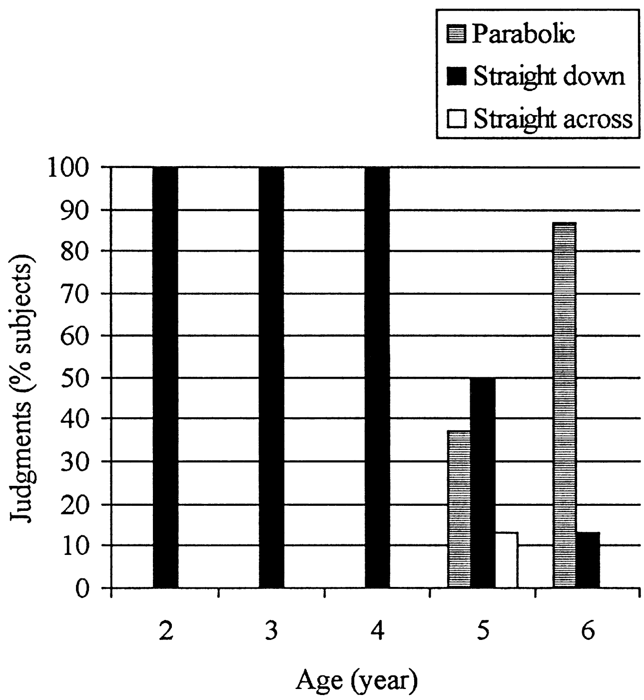

Figure 16 *Percentage of children judging that the ball would land in the correct parabolic location, the straight-down location (contrary to inertia) or the straight-across location (contrary to gravity) at each age from 2 to 6 years.*

children consistently judged that the ball would land in the parabolic hole, as if they expected the object to move both forward and downward. Five years appears to be a transitional age between the younger and older pattern.

The present experiment replicates the finding of Kaiser *et al.* (1985) that young children tend to predict that an object that moves off a support will begin to move straight downward, contrary to inertia. In the present study, however, children gave correct predictions, in accord with inertia, at a younger age than in Kaiser *et al.*'s (1985) study, where many children continued to make straight-down predictions well into the early school years. Procedural differences between these experiments may account for their different findings. First, we presented children with a freely moving object that was caught by a hand before rolling off a cliff, whereas Kaiser *et al.* presented a ball that rolled inside a clear plastic tube and stopped at the end of the tube because the end was blocked. Children's judgments about object motion may be less accurate in the latter situation (see Hood, 1995). Second, we constrained children's predictions to three locations by presenting three fixed indentations that a ball could enter and asking them to choose the one where the ball would land. In contrast, Kaiser *et al.* (1985) presented a movable cup and asked children to place the cup at the place where they judged the ball would land. Our task may have facilitated children's judgments both by calling their attention to the correct parabolic location and by limiting their choices.

The present experiment has two limitations. First, because the experiment does not assess children's prediction about the exact landing point of the object but only their choice among three candidate locations, it is not a sensitive measure of bias in children's judgments. It is possible, for example, that the older children would have underestimated the object's landing position if given a less constrained task (see Krist *et al.*, 1993). Nevertheless, children's answers revealed clear consistency within four of the five ages and a clear developmental change across the ages. The consistency of children's answers suggests that the questions were simple enough for even the youngest children to understand, allowing comparisons of children's perceptions and inferences about object motion at ages as young as 2–3 years.

A more serious limitation of this experiment is that it did not focus on the object's path of motion but only on its final position. For this reason, children's choice of the parabolic hole does not necessarily imply that they expected the object to move on a parabolic path: they might have expected it to follow a different path to this final position. We cannot conclude, therefore, that 6-year-old children expected the object to undergo parabolic motion. Nevertheless, we can infer from their judgments that the 6-year-old children had come to appreciate that the object should move both forward and downward, in some manner, after rolling off the cliff.

Discussion of Experiments 9–13

Experiments 9–13 investigated children's developing sensitivity to effects of gravity and inertia on the motion of a ball that rolls off a support, by means of two new methods: a perceptual judgment method in which children report whether a given visible motion looks normal or 'silly', and a predictive judgment task in which the ball and support are presented but motion off the support is never seen, and children are asked to predict where the ball would land if it rolled off the support. Children given the perceptual judgment task also were tested with the preferential looking method, both to ensure that their exposure to the events was comparable to that of the children in the previous experiments and to allow comparison of the results obtained with different methods. Unfortunately, the findings of these experiments cast doubt on the usefulness of the preferential looking method with children above 3 years of age, at least for the present displays. The 3- to 4-year-old children in Experiment 12 showed no reliable looking preference between the natural motion and the motion inconsistent with inertia, contrary both to their judgments about the naturalness of these events and to the looking preferences of the 2-year-old children in Experiment 8. In contrast, both judgment methods gave consistent and interpretable findings across all the ages tested: from 3 to 6 years for the perceptual judgment task and from 2 to 6 years for the predictive judgment task. We focus on these findings.

By the perceptual judgment task, children showed clear sensitivity to inertia at the youngest age tested. At 3 to 4 years, they judged reliably that the natural parabolic motion was normal whereas the unnatural motion in which the object abruptly turned downward was not. These findings accord with the findings of Experiment 8 using the preferential looking method. They suggest that sensitivity to inertia is well established in young children, when the children view fully visible events.

In addition, the perceptual judgment task provides evidence that sensitivity to gravity develops slowly from 2 to 6 years. When children were presented with a ball that rolled off a slanted ramp and continued in either natural parabolic motion or unnatural linear motion, they tended to judge reliably that the parabolic motion was more natural both at 3–4 years and at 5–6 years, but this tendency was not significant at 3–4 years, marginally significant at 5–6 years, and significant only when the two ages were combined. Because the judgment task gives reliable findings at the younger age when it is used to assess children's sensitivity to inertia (Experiment 12), the weaker findings obtained when it is used to assess sensitivity to gravity do not plausibly stem from limits to the method itself. Instead, 3–4 years appears to be a transitional period for the development of sensitivity to gravity in the present situation. Like the findings of the preferential looking experiments, these findings suggest that sensitivity to inertia develops before sensitivity to gravity for the present events and that sensitivity to gravity develops slowly, in a piecemeal fashion.

The findings of the predictive judgment task differed from those of both the preferential looking experiments and the perceptual judgment task in some striking respects. First, the youngest children tended to respond merely at chance on the tasks presenting fully visible motion (Experiments 1–7 and 9), but young children unanimously gave the wrong response on the predictive judgment task. This finding suggests that children were not simply confused or uncertain, but rather misconceived the object's motion on the predictive judgment task. Second, children's responses at all ages showed sensitivity to gravity. At 2, 3 and 4 years of age, children unanimously predicted that the object would move straight downward, in accord with gravity but contrary to inertia. At no age did children tend to judge that the object would continue in linear motion, despite the fact that half the children in Experiment 9 reported, when presented with this motion, that linear motion looked more natural than the correct parabolic motion. Third, children's predictions showed sensitivity to inertia only at the oldest age tested – 6 years – with 5 years appearing to be a transitional age between a pure response to gravity and a response to gravity and inertia. Whereas sensitivity to inertia developed before sensitivity to gravity on the perceptual judgment task, the reverse pattern was obtained on the predictive judgment task.

The contrasting developmental patterns observed on the two judgment tasks provide evidence for a 'double dissociation', over development, in children's performance. These patterns cannot be explained by proposing that one task is simply more sensitive than the other or that knowledge of one physical constraint is simply stronger than knowledge of the other constraint. Rather, the perceptual judgment task appears to be a more sensitive measure of knowledge of inertia, whereas the predictive judgment task appears to be a more sensitive measure of knowledge of gravity. We consider the possible significance of this double dissociation in the General discussion.

The findings from the predictive judgment task complement those of Kaiser *et al.* (1985), Hood (1995) and Krist *et al.* (1993). Like the children in Hood's (1995) experiment and like the youngest children in Kaiser *et al.*'s experiments, the 2- to 5-year-old children in Experiment 13 tended to predict that the ball would fall straight downward after losing its support. Like the children in Krist *et al.*'s (1993) experiments, these children showed a discrepancy between their predictive judgments about where the ball would land and other measures of their knowledge (perceptual judgments in our experiments, predictive actions in Krist *et al.*'s experiments).

Finally, the findings of the predictive judgment task complement Hood's findings concerning children's judgments about object motions in relation to gravity and solidity (1994; Hood, Uller & Carey, 1996). Hood presented 2- to 4-year-old children with a display studied by Spelke *et al.* (1992) with infants, in which a ball was dropped behind a screen and either landed on the first surface in its path (consistent with solidity and gravity) or landed on the second surface in its path (inconsistent with solidity). Like the children in Experiment 13, the children in Hood's experiment first were shown the entire display and then were asked to judge the ball's motion without seeing it directly. In contrast to Experiment 13, however, children were not asked to predict the ball's future motion but rather were asked to infer its hidden motion: after the ball was dropped behind the screen, children pointed to the position they judged it to occupy. Children's judgments were consistent with gravity, as in the present experiments. Interestingly, their judgments were not consistent with solidity, in contrast to previous findings with infants using a different task in which the object's initial motion path and final position were visible. Like the present studies, Hood's findings provide evidence for a dissociation between perception and judgment at 2 years of age.

General discussion

The present research began with three questions. First, what are the origins of knowledge of effects of gravity and inertia on object motion: does this knowledge begin early in infancy or does it develop more slowly? Second, how does this knowledge grow: do children at some age gain a general understanding of gravity and inertia – an understanding that allows them to make sense of object motion in diverse situations – or do they gradually acquire more piecemeal knowledge of how particular kinds of objects move under particular kinds of circumstances? Third, what are the origins of the gap, found in adults, between our often accurate perceptual sensitivity to constraints on object motion, on one hand, and our often erroneous explicit judgments about object motion, on the other?

Concerning the first two questions, the present experiments provide evidence that sensitivity to the effects of gravity and inertia on object motion develops slowly and in a piecemeal fashion. Although the 7-month-old infants in Kim and Spelke's (1992) experiments perceived the motion of a ball on an inclined plane as more familiar or natural if the ball rolled down the plane with increasing speed or up the plane with decreasing speed, relative to motion downward or upward with the opposite (unnatural) pattern of acceleration, the findings of Experiments 1–5 cast strong doubt on the possibility that this success reflects any general understanding of the effects of gravity and inertia. In Experiments 1–5, 7-month-old infants were presented with events that differed from those of Kim and Spelke (1992) in just one significant respect: during the test trials, the ball rolled downward on a truncated rather than a full plane. If infants were sensitive to the general, combined effects of gravity and inertia, they should have perceived the ball's motion, on leaving the plane, as more natural or familiar if it followed a parabolic path. Contrary to this prediction, infants showed no differential reactions to parabolic, linear or abruptly turning motions of the ball. These findings suggest that infants' successful performance in Kim and Spelke's (1992) experiments depended on local, restricted knowledge about object motion.

The findings of Experiments 6–12 provide further evidence for the gradual, piecemeal development of sensitivity to the effects of gravity and inertia. When 2-year-old children were presented with the same events as the infants in Experiments 1–5, they reacted to the parabolic motion as more familiar or natural than the abruptly turning motion but not as more natural than the continued linear motion. These findings, which show sensitivity to the effect of inertia but not gravity on the continued motion of the ball, suggest that the children were partially but not completely sensitive to the appropriate motion of the ball after it rolled off its support. Finally, when children aged 3–4 and 5–6 years were presented with these events, they reacted to the parabolic motion as more familiar or natural than either of the other two motions, but these findings were reliable only when the two age groups were combined. Sensitivity to the effects of gravity and inertia on the motion of a fully visible ball that rolls off its support therefore appears to develop slowly over the first six years.

Concerning the third question, the findings of the present experiments support two suggestions about the origins and nature of the gap between perceptions of and judgments about object motion. First, this gap does not appear to emerge with the development of expertise from an initially unitary and coherent system of knowledge of object motion, but rather appears to be present from the earliest point in development at which this knowledge is manifest. At the earliest age at which children began to show sensitivity to constraints on the motion of the ball after it left the cliff – 2 years – they already showed qualitatively different patterns of sensitivity to the motion in different task contexts. When presented with fully visible motions, 2-year-old children showed sensitivity to inertia (Experiment 8) but not gravity (Experiments 6 and 7). When presented with the same type of cliff display with no visible motion and asked to judge where the rolling ball would land, 2-year-old children showed sensitivity to gravity but not inertia (Experiment 13). The divergence between perception and judgment found in adults and older children therefore has roots early in development.

Second, the gap found with infants does not appear to reflect a divergence between implicit and explicit knowledge, but rather a gap between the knowledge that guides perception of seen motions versus inferences about unseen motions. The two tasks used in Experiment 13 both assessed children's explicit judgments about object motion, yet they gave divergent findings, with the perceptual judgment task revealing more precocious sensitivity to inertia and the predictive judgment task revealing more precocious sensitivity to gravity. Moreover, the findings of the perceptual judgment task converged with those of the preferential looking task used in Experiments 1–8, with both tasks providing evidence for more precocious sensitivity to inertia.

Other research supports these suggestions. Studies of human infants, assessing their sensitivity to the physical constraints of inertia and continuity (objects move on connected paths), revealed discrepant findings in two different task contexts. When infants were presented with objects that moved from view in preferential looking experiments, their reactions to the reappearance of the objects provided evidence for sensitivity to continuity but not inertia (Spelke *et al.*, 1994; Spelke, Kestenbaum, Simons & Wein, 1996). In contrast, when infants were presented with fully visible objects in predictive reaching experiments, their aiming for the objects provided evidence for sensitivity to inertia but not continuity (von Hofsten, 1980; von Hofsten *et al.*, 1998). Recent experiments suggest, however, that the critical difference between these experiments concerned not the response measure (looking versus reaching) but the presence versus absence of occlusion (Munakata, 1997; von Hofsten, Feng & Spelke, submitted; see also Hood *et al.*, 1996). Different systems of knowledge may guide infants' reactions to fully visible object motions, on one hand, and their extrapolations of partly occluded object motions, on the other.

Studies of human adults with neurological disorders accord with the suggestion, from the present studies, that preferential looking experiments tap the same system of knowledge as explicit judgment tasks. Squire and colleagues (e.g. McKee & Squire, 1993; McDonough, Mandler, McKee & Squire, 1995) tested amnesic adults both with standard tests of explicit memory and with several tests of memory given to infants, including a delayed imitation test and a preferential looking test. Patients who showed an impairment on the standard explicit memory tests also were impaired on the delayed imitation and preferential looking tests. These findings provide converging evidence that novelty reactions in preferential looking experiments are guided by the same system of knowledge as explicit judgments of familiarity and novelty.

Perhaps the most interesting finding to emerge from these experiments concerns the 'double dissociation' between sensitivity to inertia and sensitivity to gravity revealed by the perceptual and the predictive judgment tasks. In studies of neurological patients, some investigators have viewed double dissociations as evidence for two distinct cognitive systems, each of which can be selectively impaired by neurological damage (e.g. Shallice, 1988). Other investigators have suggested that these dissociations may reflect different components of a single cognitive system (see McCarthy & Warrington, 1990, and Caramazza & Shelton, 1998, for discussion). On either interpretation, however, we may draw two lessons from the present findings. First, children's developing knowledge of object motion is not a simple, unitary whole: a given aspect of knowledge may reveal itself on one task and not on another task, even when neither task is simply easier or more sensitive than the other. One therefore cannot conclude, on the basis of a single task, that a child of a given age either 'has' or 'lacks' some aspect of mature knowledge. Second, and more positively, children's developing knowledge of object motion reveals itself in a broad array of tasks and contexts. The present experiments have focused on three such tasks and contexts: preferential looking at fully visible object motions, judgments about the naturalness of fully visible object motions, and judgments about the future position of an object that undergoes a motion that is not seen. Other experiments have focused on other tasks and contexts, including predictive reaching for visible or occluded objects (von Hofsten *et al.*, 1998; submitted), preferential looking at partly occluded motions (e.g. Spelke *et al.*, 1994, 1996), acting to propel an object (Krist *et al.*, 1993) and reporting where an occluded falling object has landed (e.g. Hood, 1995). Exploring the development of physical knowledge in each of these task contexts should provide cognitive psychologists with a rich terrain for exploring the emergence and nature of knowledge of the physical world.

Acknowledgements

We thank Abby Friedman, Kirsten Condry and Evelyn Poey for assistance, and Frank Keil, Carol Krumhansl and Barbara Finlay for advice. The work was supported by a grant from NIH to ESS (R37-HD23103).

References

Bertenthal, B.I. (1996). Origins and early development of perception, action, and representation. *Annual Review of Psychology*, **47**, 431–459.

Caramazza, A., & Shelton, J.R. (1998). Domain-specific knowledge systems in the brain: the animate-inanimate distinction. *Journal of Cognitive Neuroscience*, **10** (1), 1–34.
Champagne, A.B., Klopher, L.E., & Anderson, J.H. (1980). Factors influencing the learning of classical mechanics. *American Journal of Physics*, **48**, 1074–1079.
Clement, J. (1982). Students' preconceptions in introductory mechanics. *American Journal of Physics*, **50**, 66–71.
Duhem, P. (1954). *The aim and structure of physical theory* (P.P. Wiener, trans.). Princeton, NJ: Princeton University Press.
Gergely, G., Nadasdy, Z., Csibra, G., & Biro, S. (1995). Taking the intentional stance at 12 months of age. *Cognition*, **56** (2), 165–193.
von Hofsten, C. (1980). Predictive reaching for moving objects by human infants. *Journal of Experimental Child Psychology*, **30**, 369–382.
von Hofsten, C., Vishton, P., Spelke, E.S., Rosander, K., & Feng, Q. (1998). Principles of predictive action in infancy. *Cognition* **76**, 255–285.
von Hofsten, C., Feng, Q., & Spelke, E.S. (submitted). Predictive head tracking of occluded objects in infancy.
Hood, B.M. (1994). Searching for falling objects in 2-year-olds is different from watching them fall in 4-month-olds. *Infant Behavior and Development*, **17**, 714 (abstract).
Hood, B.M. (1995). Gravity rules for 2- to 4-year-olds? *Cognitive Development*, **10** (4), 577–598.
Hood, B.M., Uller, C., & Carey, S. (1996). Naive physical reasoning in two-year-olds: discrepancies with the infant data. *Infant Behavior and Development*, **19**, 512 (abstract).
Howard, I.P. (1982). *Human visual orientation*. New York: Wiley.
Kaiser, M.K., Proffitt, D.R., & McCloskey, M. (1985). The development of beliefs about falling objects. *Perception and Psychophysics*, **38**, 533–539.
Kim, I.K., & Spelke, E.S. (1992). Infants' sensitivity to effects of gravity on visible object motion. *Journal of Experimental Psychology: Human Perception and Performance*, **18** (2), 385–393.
Krist, H., Fieberg, E.L., & Wilkening, F. (1993). Intuitive physics in action and judgment: the development of knowledge about projectile motion. *Journal of Experimental Psychology: Learning Memory and Cognition*, **19** (4), 952–966.
Kuhn, T.S. (1970). *The structure of scientific revolutions* (2nd edn). Chicago, IL: University of Chicago Press.
Kuhn, T.S. (1977). A function for thought experiments. In T.S. Kuhn (Ed.), *The essential tension*, Chicago, IL: University of Chicago Press.
McCarthy, R.A., & Warrington, E.K. (1990). *Cognitive neuropsychology: A clinical introduction*. New York: Academic Press.
McCloskey, M. (1983). Naïve theories of motion. In D. Gentner & A. L. Stevens (Eds), *Mental models*. Hillsdale, NJ: Erlbaum.
McDonough, L., Mandler, J.M., McKee, R.D., & Squire, L.R. (1995). The deferred imitation task as a nonverbal measure of declarative memory. *Proceedings of the National Academy of Sciences USA*, **92**, 7580–7584.
McKee, R.D., & Squire, L.R. (1993). On the development of declarative memory. *Journal of Experimental Psychology: Learning, Memory and Cognition*, **19**, 397–404.
Munakata, Y. (1997, April). A single, graded knowledge system: the power of weakness to explain task-dependent behavior. Paper presented to the Society for Research in Child Development, Washington, DC.
Piaget, J. (1976). *The grasp of consciousness*. Cambridge, MA: Harvard University Press.
Schone, H. (1984). *Spatial orientation* (C. Strausfeld, trans.). Princeton, NJ: Princeton University Press.
diSessa, A. (1983). Phenomenology and the evolution of intuition. In D. Gentner & A. Stevens (Eds), *Mental models*. Hillsdale, NJ: Erlbaum.
Shallice, T. (1988). *From neuropsychology to mental structure*. New York: Cambridge University Press.
Shanon, B. (1976). Aristotelianism, Newtonianism and the physics of the layman. *Perception*, **5**, 241–243.
Spelke, E.S., Breinlinger, K., Macomber, J., & Jacobson, K. (1992). Origins of knowledge. *Psychological Review*, **99** (4), 605–632.
Spelke, E.S., Katz, G., Purcell, S.E., Ehrlich, S.M., & Breinlinger, K. (1994). Early knowledge of object motion: continuity and inertia. *Cognition*, **51**, 131–176.
Spelke, E.S., Kestenbaum, R., Simons, D., & Wein, D. (1996). Spatiotemporal continuity, smoothness of motion, and object identity in infancy. *British Journal of Developmental Psychology*, **13**, 113–142.

Received: 7 October 1998
Accepted: 10 February 1999