Cognition, 51 (1994) 107–129
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Calibration-based reasoning about collision events in 11-month-old infants

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Received August 27, 1992, final version accepted August 9, 1993

Abstract

Previous research indicates that, when a moving object collides with a stationary object, infants expect the stationary object to be displaced. The present experiment examined whether infants believe that the size of the moving object affects how far the stationary object is displaced. In the experiment, 11-month-old infants sat in front of a horizontal track; to the left of the track was an inclined ramp. A wheeled toy bug rested on the track at the bottom of the ramp. The infants in the midpoint condition were first familiarized with an event in which a medium-sized cylinder rolled down the ramp and hit the bug, causing it to roll to the middle of the track. Next, the infants saw one of two test events. In both events, novel cylinders were introduced, and the bug now rolled to the end of the track. The two test cylinders were identical to the familiarization cylinder in material but not in size: one was larger (large-cylinder event) and one was smaller (small-cylinder event) than the familiarization cylinder. The infants in the endpoint condition saw the same familiarization and test events as the infants in the midpoint condition except that the bug rolled to the end rather than to the middle of the track in the familiarization event. The infants in the midpoint condition looked reliably longer at the small- than at the large-cylinder event, whereas the infants in the endpoint condition tended to look equally at the two events. These results indicated that the infants (a)

This research was supported by a grant from the National Institute of Child Health and Human Development (HD-21104) to the second author. We thank Jerry DeJong for insightful comments; Elizabeth Cullum, Kevin Miller, and Stanley Wasserman, for their help with the data analyses; and Lincoln Craton, Myra Gillespie, Valerie Kolstad, Amy Needham, and the undergraduate students working in the Infant Cognition Laboratory at the University of Illinois for their help with the data collection. We also thank the parents who kindly agreed to have their infants participate in the studies.

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SSDI 0010-0277(93)00580-Z

believed that the size of the cylinder affected the length of the bug's displacement and (b) used the familiarization event to calibrate their predictions about the test events. After watching the bug roll to the middle of the track when hit by the medium cylinder, the infants were surprised to see the bug roll to the end of the track with the small but not the large cylinder. After watching the bug roll to the end of the track when hit by the medium cylinder, however, the infants were not surprised to see the bug do the same with either the small or the large cylinder. Parallel results were obtained with adult subjects. The present findings have implications for research on the nature and development of infants' physical reasoning as well as for assessments of causal reasoning in infancy.

Introduction

A long-standing concern of cognitive psychology has been the description of adults' and children's reasoning about physical events (e.g., Carey, 1985; Clement, 1982; Gelman, 1990; Gentner & Gentner, 1983; Karmiloff-Smith & Inhelder, 1975; Keil, 1990; McCloskey, 1983; Michotte, 1963; Siegler, 1978; Vosniadou & Brewer, 1989). Within the realm of infancy, researchers have also sought to characterize infants' physical world. Piaget (1952, 1954) was the first to explore the development of infants' physical knowledge. His findings led him to conclude that young infants understand very little of the physical events that take place about them. However, recent experiments conducted with more sensitive methods have revealed that, contrary to what Piaget and his followers believed, young infants are capable of sophisticated physical reasoning (see Baillargeon, 1993, in press; Baillargeon, Kotovsky, & Needham, in press; and Spelke, Breinlinger, Macomber, & Jacobson, 1992, for recent reviews).

Several of these recent experiments have focused on young infants' ability to reason about collision events between a moving and a stationary object (e.g., Baillargeon, 1986; Baillargeon & DeVos, 1991; Cohen & Oakes, 1992; Kotovsky, 1992; Kotovsky & Baillargeon, 1993; Leslie & Keeble, 1987; Oakes, 1992; Oakes & Cohen, 1990). One of these experiments, for example, examined whether 5.5-month-old infants expect a stationary object to be displaced when hit by a moving object (Kotovsky, 1992). The infants sat in front of a horizontal track; to the left of the track was an inclined ramp. The infants were habituated to a large cylinder that rolled down the ramp; small stoppers prevented the cylinder from rolling onto the track. Following habituation, the infants saw two test events. In both events, the cylinder rolled down the ramp as before, but a wheeled toy bug now stood on the track. In one event, the bug was positioned a short distance from the ramp; no collision therefore took place between the cylinder and the bug, which remained stationary. In the other event, the bug was positioned directly at the bottom of the ramp; though hit by the cylinder, the bug again remained stationary, as in the no-collision event.

A second group of 5.5-month-old infants was tested in a control condition similar to the experimental condition except that a right-angle partition was placed inside the apparatus. This partition filled the space between the bug and the right wall of the apparatus, preventing the bug's displacement.

The infants in the experimental condition looked reliably longer at the collision than at the no-collision event, whereas the infants in the control condition tended to look equally at the two test events. Together, these results indicated that (a) the infants in the experimental condition expected the bug to be displaced when hit by the cylinder and were surprised that it was not and (b) the infants in the control condition understood that the bug could not be displaced when hit by the cylinder because the wall partition blocked its path.

The results of this experiment suggested that young infants expect a stationary object to be displaced when hit by a moving object. The present research built on these initial findings. It asked whether infants not only believe *that* the stationary object should be displaced, but also are able to judge *how far* it should be displaced.

The present research

Consider what would happen if adult subjects were shown the collision event described in the last section and asked how far the bug would be likely to be displaced when hit by the cylinder. The answer to this question clearly depends on a multiplicity of factors that include the weight of the bug and cylinder, the smoothness of the ramp and track, and so on. Lacking information about these variables, most adults would be reluctant to hazard a guess as to the probable length of the bug's displacement (an informal survey in which naive subjects were pressed for an answer yielded estimates ranging from the bug rolling a few centimeters to its crashing full speed through the far wall of the apparatus).

Consider now what would happen if, prior to being asked how far the bug was likely to roll when hit by the large test cylinder, adults were shown that the bug travelled to the middle of the track when hit by a smaller cylinder.[1] Adults would then no doubt expect the bug to roll past the middle of the track when hit by the larger test cylinder.

Adults often engage in the form of physical reasoning in which information

[1] Most adults would recognize that the length of the bug's displacement depended on the cylinder's weight, or more precisely mass, rather than size. However, when cylinders of difference sizes but identical material are used, size and weight can be expected to covary, so that the one can provide a useful index of the other. In what follows we will refer only to the size of the cylinders; we will discuss in the Conclusion whether the infants relied on the size or weight of the cylinders in their predictions.

from one event is used to calibrate predictions about other events. Consider, for example, how most of us perform when testing mechanical devices (e.g., the brakes of a rented car, the sharpness of a new knife, the volume of an unfamiliar sound speaker, the temperature of the hot water faucet in a hotel room). We apply a certain amount of pressure or move the control to a certain level, assess the outcome, and then modify our behavior to achieve the desired effect.

Recent results suggest that children, like adults, can use information from prior events to calibrate their predictions about subsequent events (Zelazo & Shultz, 1989). The experiment examined adults' and 9- and 5-year-olds' ability to predict how far stationary objects were likely to be displaced when hit by moving objects. The subjects watched events in which blocks slid down a ramp and collided with other blocks at the bottom of the ramp. The number of blocks at the top and at the bottom of the ramp was varied, and the subjects were asked to predict how far the bottom blocks would be displaced. Prior to the test trials, the subjects were given two demonstration trials. In one, six blocks were placed at the top of the ramp and one at the bottom; in the other, one block was placed at the top of the ramp and six at the bottom. After seeing these two calibration trials, the subjects were able to systematically reason about the outcome of the test events. Most of the adults and the 9-year-olds took into account the number of blocks at both the top and the bottom of the ramp in their predictions. The 5-year-olds were somewhat less successful, though half of the children gave evidence of systematically attending to the number of blocks at the top of the ramp.

The present research addressed two questions. First, it asked whether infants believe that, in a collision event between a moving and a stationary object, the size of the moving object affects the length of the stationary object's displacement. Second, it examined whether infants can use information from prior collision events to calibrate their predictions about the outcome of other collision events. Subjects were 10- to 12-month-old infants. The infants were first familiarized with a collision event in which a medium-sized cylinder caused a bug to travel either to the middle or to the end of a track. The medium cylinder was then replaced by a smaller or a larger cylinder, and the experiment tested whether the infants relied on the familiarization event to reason about the small- and the large-cylinder events.

How likely was it that the infants in the experiment would use their representation of the familiarization event to predict the length of the bug's displacement in the small- and the large-cylinder events? Recent results indicate that, when reasoning about the interaction of two objects, even young infants can recruit additional objects as reference points (Baillargeon, 1991, 1993). In a series of experiments, for example, 4.5- and 6.5-month-old infants watched events in which a box was placed in the path of a rotating screen (Baillargeon, 1991); the experiments examined whether the infants could predict at what point the screen should reach the occluded box and stop. The infants tended to look equally when the screen stopped either against the occluded box (possible event) or after rotating through the top 50% of the space occupied by the occluded box (impossible event), as though they perceived both stopping points to be consistent with the box's height and location. However, the infants had no difficulty detecting the 50% violation when a second, identical box was placed to the right of the box behind the screen. This second box stood out of the screen's path and thus remained visible throughout the test events; the screen stopped when aligned with the top of the second box in the possible event, but rotated past the top of the visible box in the impossible event. Interestingly, the second box enhanced the infants' performance only when it was positioned in the same fronto-parallel plane as the box behind the screen. When the second box was placed to the right and slightly in front of the box behind the screen, so that the screen rotated past the top of the visible box in both the impossible and the possible events, the infants tended to look equally at the two test events. Together, these results suggested that the infants used an alignment strategy to detect the 50% violation: they reasoned that the screen would contact the top of the occluded box when aligned with the top of the visible box.

The results of these and other experiments (e.g., Baillargeon, 1991, 1993) suggest that even young infants are able to devise reasoning strategies involving the use of physically available reference points. Given such results, it seemed plausible that infants would also be able to engage in reasoning based on reference points demonstrated in prior events.

Design

The infants in the experiment were randomly assigned to one of two conditions: the midpoint or the endpoint condition. The infants in the *midpoint* condition sat in front of a horizontal track; to the left of the track was an inclined ramp (see Fig. 1). A toy bug stood on the track at the bottom of the ramp. The infants first saw a familiarization event in which a blue medium-sized cylinder rolled down the ramp and hit the bug, causing it to roll to the middle of the track. Next, the infants saw one of two test events. In both events, new cylinders were introduced. Both cylinders now caused the bug to roll to the end of the track; the bug stopped only when it hit the right wall of the apparatus. In one event (large-cylinder event), the cylinder was a yellow cylinder *larger* than the familiarization cylinder. In the other event (small-cylinder event), the cylinder was an orange cylinder *smaller* than the familiarization cylinder.

The infants in the *endpoint* condition saw familiarization and test events identical to those shown to the infants in the midpoint condition, with one exception (see Fig. 2). In the familiarization event, the bug rolled to the end of the track when hit by the medium-sized cylinder.

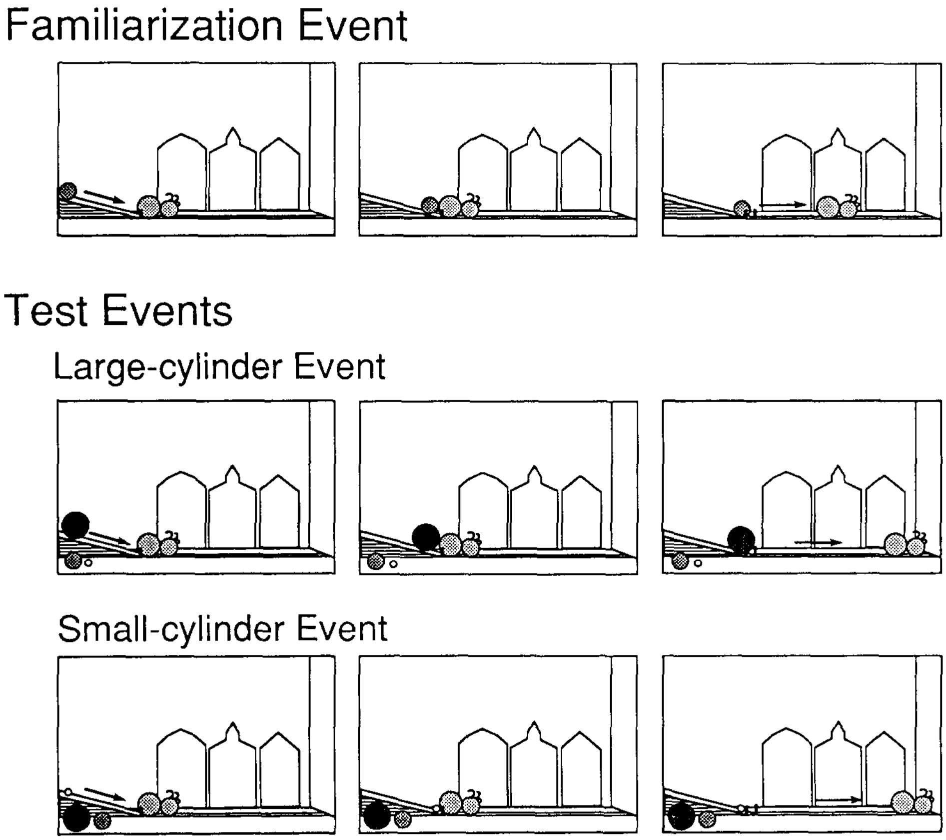
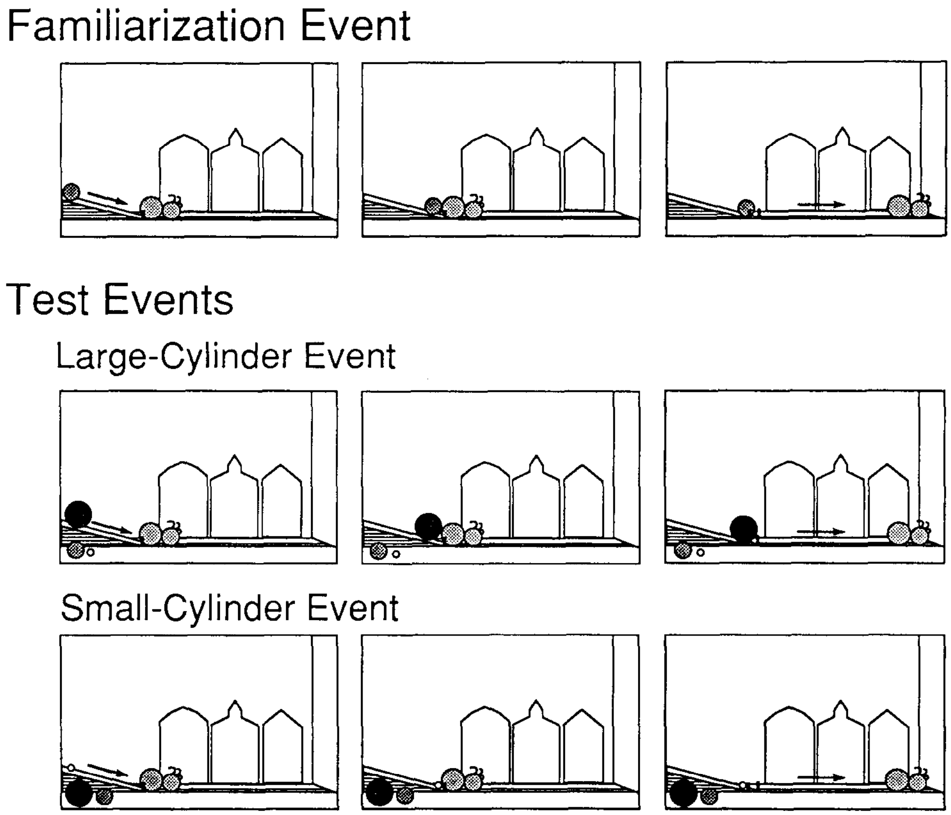


Figure 1. *Schematic drawing of the events shown to the infants in the midpoint condition.*

Our reasoning was as follows. If the infants in the experiment (a) believed that the size of the cylinder affected the length of the bug's trajectory and (b) were able to use the familiarization event to calibrate their predictions about the outcome of the test events, then two predictions followed. The first prediction was that the infants in the midpoint condition should expect the bug to roll past the middle of the track when hit by the larger but not the smaller cylinder. The infants should therefore be surprised or puzzled in the small-cylinder event to see the bug roll to the end of the track. Because infants' surprise at an event typically manifests itself by prolonged attention to the event (e.g., Spelke, 1985), we expected that, if the infants were surprised by the small-cylinder event, they would look reliably longer at it than at the large-cylinder event. The second prediction was that the infants in the endpoint condition (a) should expect the bug to roll to the end of the track when hit by the large cylinder and (b) should find it acceptable that the bug rolled to the end of the track when hit by the small cylinder (since in the familiarization event the bug stopped only when it hit the



Familiarization Event

Test Events

Large-Cylinder Event

Small-Cylinder Event

Figure 2. *Schematic drawing of the events shown to the infants in the endpoint condition.*

right wall of the apparatus, it was conceivable that it should do the same with the small cylinder; as reported below, adults who observed this event typically found it consistent with the familiarization event). The infants should therefore look about equally at the large- and the small-cylinder events, because neither event would seem surprising.

Method

Subjects

Subjects were 60 healthy, full-term infants ranging in age from 10 months, 0 days to 12 months, 4 days (M = 10 months, 29 days). An additional 4 infants were eliminated from the experiment, 3 because of experimenter error and 1 because of equipment failure. Parents were contacted by letters and follow-up phone calls.

They were offered reimbursement for their transportation expenses, but were not compensated for their participation.

Half of the infants were randomly assigned to the midpoint condition and half to the endpoint condition. Furthermore, within each condition, half of the infants watched the small-cylinder event, and half watched the large-cylinder event (midpoint condition: small-cylinder group, $M = 11$ months, 2 days, large-cylinder group, $M = 11$ months, 4 days; endpoint condition: small-cylinder group, $M = 10$ months, 27 days, large-cylinder group, $M = 10$ months, 25 days).

Apparatus

The apparatus consisted of an unpainted wooden box 122.5 cm high, 152 cm wide, and 52 cm deep that was mounted 80.5 cm above the room floor. The infant faced an opening 52.5 cm high and 150 cm wide in the front wall of the apparatus. The back wall of the apparatus was covered with pink poster board and was decorated with brightly colored pictures of a barn, a church, and a house (see Fig. 1). The three buildings were arranged in a row 8.5 cm above the floor of the apparatus. The barn was positioned 50 cm from the left wall and the house 1 cm from the right wall. Immediately below the three buildings was an opening 8.5 cm high and 91 cm long that was partially concealed by a dark blue fringe. During the experiment, the opening was used by a left hand wearing a cream-colored glove 65.5 cm long to reach into the apparatus and reposition the bug.

A wooden ramp 56 cm long and 13.6 cm wide stood against the left wall of the apparatus, below an opening 21 cm high and 15 cm wide that was filled with a white fringe. The ramp was covered with black contact paper and was positioned 28 cm from and parallel to the front of the apparatus. At the top of the ramp was a plateau 7.6 cm high and 16 cm long; the ramp itself sloped downward at an 11° angle. The sides of the ramp were covered with panels of wood 0.5 cm thick that were cut to protrude 0.75 cm above the ramp. These side panels prevented the cylinders from rolling off the ramp. The ramp and its side panels were mounted on a strip of particle board 0.7 cm thick, 15.5 cm wide, and 56 cm long. At the bottom of the ramp and located 10.5 cm apart were two upright metal posts that prevented the cylinders from rolling onto the track. Each post was 10.5 cm high and 1.25 cm in diameter and was covered with black felt.

Three cylinders of different diameters and colors were used in the experiment. All three cylinders were 13.4 cm long and were made of the same plastic piping material. The largest cylinder was 11.4 cm in diameter and was painted bright yellow. The medium-sized cylinder was 5.9 cm in diameter and was painted light blue. Finally, the smallest cylinder was 2.7 cm in diameter and was painted bright orange. The cylinders were sent down the ramp by a right hand wearing a black glove 61.5 cm long; the hand entered the apparatus through the opening in the left wall at the top of the ramp.

Centered at the bottom of the ramp was a model train track 5 cm wide. The track was 96 cm long and covered the full length of the apparatus from the bottom of the ramp to the right wall. The track rested on a strip of particle board 0.7 cm thick and 15.5 cm wide that was covered with black felt.

A brightly colored toy bug 15 cm high, 22 cm long, and 13 cm wide was mounted on model train wheels. The bug consisted of two styrofoam balls decorated with long blue fur; the front, smaller ball sported eyes and antennae, and the rear, larger ball was partly covered with a white flounced skirt (the bug actually looked darling). When the bug was placed at the bottom of the ramp, its rear portion extended between the two posts. Although it appeared as though the cylinders squarely hit the bug when they rolled to the bottom of the ramp, they in fact did little more than contact the bug's fur and skirt, with an impact insufficient to cause the bug to move. Fortunately, the limited nature of the contact was virtually impossible to detect: even adult observers failed to notice it, despite repeated viewings (see below).

When in position at the bottom of the ramp, the rear portion of the bug rested against a metal lever 0.6 cm wide and 0.6 cm deep that protruded 3 cm above the floor of the apparatus, between the two posts. The lever was controlled by two micro-switches set in the floor of the ramp. The switches were positioned 4 and 7 cm from the bottom of the ramp; the small and medium cylinders triggered the first switch, and the large cylinder the second switch. When triggered, the switches activated a solenoid located beneath the floor of the apparatus; the solenoid in turn operated the lever that rested against the bug. Controls attached to the solenoid made it possible for an experimenter to independently vary which switch would trigger the solenoid and how much power the lever would receive. With this system, any cylinder could thus be made to propel the bug any distance.

The infants were tested in a brightly lit room. Four 40 W clip-on lights were attached to the front and side walls of the apparatus to provide additional light. Two muslin-covered frames, each 183 cm high and 71 cm wide, stood at an angle on either side of the apparatus. These frames served to isolate the infants from the experimental room. At the end of each trial, a muslin-covered frame 63 cm high and 150 cm wide was lowered in front of the opening in the front wall of the apparatus.

Events

Two experimenters worked in concert to produce the events. The first wore the black glove and manipulated the cylinders; the second wore the cream-colored glove and manipulated the bug. Numbers in parentheses indicate the time taken to perform the actions described.

Midpoint condition

Familiarization event. At the beginning of the trial, the medium cylinder rested on the floor of the apparatus, 5.5 cm (at its closest point) in front of the ramp and 33 cm (again, at its closest point) from the left wall. The cylinder lay at an angle so that one of its ends faced the infant. To start, the black hand tapped on the cylinder at the rate of approximately three taps per second. When the computer signaled that the infant had looked at the cylinder for 4 cumulative seconds, the black hand grasped the cylinder and deposited it at the top of the ramp (2 s). The black hand then released the cylinder, which rolled down the ramp (2 s). When the cylinder hit the posts at the bottom of the ramp, the bug was propelled down the track and slowed to a stop at about the middle of the track, approximately 45 cm from the bottom of the ramp (1 s). After a 4 s pause, the black hand, which had been resting at the top of the ramp, reached down the ramp and lifted the cylinder back to the top of the ramp (2 s). Next, the cream-colored glove entered the apparatus through the opening in the back wall, grasped the bug's face (1 s), gently pushed the bug back to the bottom of the ramp (2 s), and exited the apparatus (1 s). The black hand then released the cylinder once again, beginning a new event cycle. Each cycle (except for the initial cycle, in which the cylinder was first tapped and then deposited at the top of the ramp) thus lasted about 13 s. Cycles were repeated without pause until the computer signaled that the trial had ended (see below). When this occurred, an experimenter lowered the curtain in front of the apparatus.

Small-cylinder test event. The small-cylinder test event was similar to the familiarization event with several exceptions. First, at the start of the trial, the large and the small cylinders lay about 2 cm from and parallel to the medium cylinder (markings on the apparatus floor ensured that the cylinders were positioned consistently across trials). The cylinders were placed in descending size order with one end facing the infant, to facilitate size comparisons. Second, the small cylinder was used instead of the medium cylinder in the event. Third, the bug was propelled to the end rather than to the middle of the track. The bug took approximately 2 s to travel the length of the track, and stopped only when it hit its head against the right wall of the apparatus. Because the bug now rolled along the track for 1 s longer and to a farther point than in the familiarization event, two changes were made to ensure that the total length of each event cycle remained 13 s, as in the familiarization event. One change was that the bug rested at its stopping point for only 3 s instead of 4 s; the other change was that the cream-colored hand pushed the bug faster so as to still return it to the bottom of the ramp in 2 s.

Large-cylinder test event. The large-cylinder test event was identical to the small-cylinder test event, except that the large cylinder was substituted for the small cylinder.

Endpoint condition

Familiarization event. The familiarization event shown to the infants in the endpoint condition was identical to that shown to the infants in the midpoint condition, except that the bug traveled to the end rather than to the middle of the track, just as it did in the test events.

Small- and large-cylinder test events. The small- and the large-cylinder test events shown to the infants in the endpoint condition were identical to those shown to the infants in the midpoint condition.

Adult ratings

In order to correctly assess the infants' responses to the test events, it seemed important to determine how naive adults perceived these events. Two questions were of particular interest. First, how did adults perceive the small- and the large-cylinder events if shown no prior familiarization event? Second, were adults' perceptions of the small- and the large-cylinder events different if they were first shown the midpoint or the endpoint familiarization event?

To address the first question, 24 undergraduate students ($M = 19.0$ years) were tested; half were shown the small- and half the large-cylinder event.[2] Each event was presented for 60 s and was performed in the manner indicated above with one exception: at the start of the trial, the black hand tapped the small or the large cylinder for 4 s before grasping it and placing it at the top of the ramp. At the end of the trial, the subject completed a form in which they were asked (a) to rate how surprising the event was on a scale of 1 to 6, where 1 was "not at all surprising" and 6 was "very surprising", and (b) to describe the event. Analysis of the subjects' ratings indicated that they viewed the small- ($M = 3.2$) and the large- ($M = 3.4$) cylinder events to be equally acceptable, $F(1, 22) = 0.14$. The vast majority of the subjects readily accepted the events as plausible collision events. Thus, 21 of the subjects stated, for example, that the cylinder "pushed",

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[2] Unlike the infants, the adult subjects were not allowed to manipulate the cylinders prior to the experiment.

"bumped", "struck", or "hit" the bug, "causing" it to roll to the end of the track; the remaining 3 subjects gave less precise descriptions. None of the subjects made reference to the switches and the lever and their possible roles in the bug's motion.

The second question of interest was whether the adults would rate the small- and the large-cylinder events differently if they were first shown the midpoint or the endpoint familiarization event. To address this question, 48 undergraduate students were tested ($M = 19.3$ years). Half of the subjects were shown the midpoint and half the endpoint familiarization event for 60 s.[3] Next, half of the subjects in each condition watched the small- and half watched the large-cylinder event, again for 60 s. The ratings of the subjects in the two conditions were analyzed by means of a 2 × 2 analysis of variance, with condition (midpoint or endpoint condition) and event (small- or large-cylinder event) as between-subjects factors. The Condition × Event interaction was significant, $F(1, 44) = 6.21$, $p < .02$. Planned comparisons revealed that the adults in the midpoint condition perceived the small-cylinder event ($M = 3.8$) as reliably more surprising than the large-cylinder event ($M = 1.9$), $F(1, 44) = 11.35$, $p < .002$, whereas the adults in the endpoint condition tended to view the small- ($M = 1.9$) and the large- ($M = 2.0$) cylinder events as equally surprising, $F(1, 44) = 0.02$. The adults' descriptions of the small- and the large-cylinder events confirmed the patterns suggested by their ratings. After watching the bug roll to the middle of the track when hit by the medium cylinder, most subjects reported surprise at seeing the bug roll to the end of the track with the small cylinder. Thus, 11 of the 12 subjects described the event as "surprising", "unexpected", or "confusing", and/or referred to the inconsistent fact that the bug rolled farther with the small than with the medium cylinder. A very different pattern was found in the descriptions given by the other subjects. None of the subjects in the midpoint condition who saw the large-cylinder event referred to this event as surprising. Furthermore, only 5 of the 24 adults in the endpoint condition reported being surprised by the events, in all cases for reasons having nothing to do with the bug's travelling to the end of the track (e.g., one subject found the event "surprising because [he] expected to see something new"!).

Together, these data suggested that the adults readily made use of the familiarization event they were shown to calibrate their predictions about the small- and the large-cylinder events. After watching the bug travel to the *middle*

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[3] An additional analysis was performed to compare the ratings of the subjects who saw the midpoint ($M = 2.5$) and the endpoint ($M = 3.0$) familiarization events with those of the subjects who saw only the small- ($M = 3.2$) and the large- ($M = 3.4$) cylinder test events. The differences between the groups were not reliable, $F(3, 68) = 0.93$. These results suggest that, in the present experimental situation, the subjects' ability to predict the length of the bug's displacement was so poor that all of these events were judged to be acceptable, even though some of them were physically inconsistent (e.g., the bug rolling to the middle of the track with the medium cylinder, but to the end of the track with the small cylinder).

of the track with the medium cylinder, the subjects were surprised to see the bug roll to the end of the track with the small but not the large cylinder. In contrast, after watching the bug roll to the *end* of the track with the medium cylinder, the adults were not surprised to see the bug roll to the end of the track with either the small or large cylinder.

A note about speed. Because the bug traveled at the same speed whenever it rolled to the end of the track, many of the test events involved speed violations. Thus, (a) the bug traveled faster than it should have in the small-cylinder event shown to the subjects in the midpoint and the endpoint conditions and (b) the bug traveled slower than it should have in the large-cylinder event shown to the subjects in the endpoint condition. Indeed, the only event in which no speed violation occurred was the large-cylinder event shown to the adults in the midpoint condition, in which the bug traveled both faster and farther than in the familiarization event. However, subjects appeared impervious to these speed violations. A contrast comparing the ratings of the large-cylinder event by the adults in the midpoint condition ($M = 1.9$) with the ratings of the large- ($M = 2.0$) and the small- ($M = 1.9$) cylinder events by the adults in the endpoint condition yielded no significant difference, $F(1, 44) = 0.007$. These data suggested that these three events were perceived as equally unsurprising, despite the fact that the last two events involved a speed violation, whereas the first event did not. Examination of the subjects' descriptions of the events pointed to the same conclusion. Very few subjects (4 out of 48) ever commented on the speed at which the bug traveled in their descriptions of the events. Of the 12 subjects in the midpoint condition who saw the small-cylinder event, only 1 mentioned the bug's speed (saying he was "puzzled why the smaller one caused the bug to go farther and faster"), though all 12 referred to the distance the bug traveled. Similarly, of the 24 subjects in the endpoint condition, only 3 mentioned the speed at which the bug traveled. Two of these subjects noted that the bug's speed was the same as in the familiarization event (e.g., "the bug did not appear to go any faster"); the remaining subject distorted his perception of the bug's speed to fit the predicted outcome ("the speed of the object that hit the wall was faster"). The distance the bug traveled was thus a far more salient aspect of the events for the subjects than the speed at which it traveled. This finding was not unexpected since the changes in the bug's distance were easier to assess and remember (relative either to the apparatus or to the subject's position in front of the apparatus) than the changes in the bug's speed.

Procedure

Prior to the beginning of the experiment, each infant was allowed to manipulate the three cylinders for a few seconds while the parents filled out consent forms. During the experiment, the infant sat on the parent's lap in front of the apparatus, facing the middle of the track. The infant's head was approximately 80 cm from the track. The parent was asked not to interact with the infant while the experiment was in progress, and to close his or her eyes during the test trial.

The infant's looking behavior was monitored by two observers who watched the infant through peepholes in the cloth-covered frames on either side of the apparatus. Each observer held a button connected to a DELL computer and depressed the button when the infant attended to the events. Each trial was divided into 100 ms intervals, and the computer determined in each interval whether the two observers agreed on the direction of the infant's gaze. Interobserver agreement was measured for 46 of the 60 infants and was calculated for each trial on the basis of the number of intervals in which the computer registered agreement, out of the total number of intervals in the trial. Agreement averaged 98% per trial per infant. The looking times recorded by the primary observer were used to determine when a trial had ended (see below). Because observers could determine from available sound cues in each trial (a) which cylinder was used and (b) how far the bug rolled, special steps were taken to ensure that the primary observer remained blind to the condition to which each infant was assigned. Specifically, different primary observers were used to monitor the infant's looking times in the familiarization and the test trials. During the familiarization phase of the experiment, one of the primary observers left the experimental room so that the sounds that accompanied the bug's displacement could not clue him or her as to the infant's test condition.

During the familiarization phase of the experiment, the infants in the midpoint and the endpoint condition saw the familiarization event appropriate for their condition on three successive trials. Each trial ended when the infant (a) looked away from the event for 2 consecutive seconds after having looked at it for at least 7 cumulative seconds (beginning at the end of the pretrial, when the cylinder was placed at the top of the ramp) or (b) looked at the event for 60 cumulative seconds without looking away for 2 consecutive seconds. During the test phase, half of the infants in each familiarization condition saw the small- and half saw the large-cylinder event described above on one test trial. The criteria used to determine the end of this trial were the same as for the familiarization trials. The 7 s value for the minimum length of each trial was selected to ensure that the infants had the opportunity to notice how far the bug rolled in each trial.

Results

Familiarization trials

The looking times of the infants in the midpoint and the endpoint conditions during the familiarization trials (see Fig. 3) were compared by means of a

$2 \times 2 \times 3$ analysis of variance (ANOVA), with condition (midpoint or endpoint condition) and event (small- or large-cylinder event) as between-subjects factors and with trial (trial 1, 2, or 3) as within-subject factor. The only significant effect was that of trial, $F(2, 112) = 17.72$, $p < .0001$, indicating that the infants looked reliably less across trials. Differences in the responses of the infants in the midpoint and the endpoint conditions to the small- and the large-cylinder test events were thus unlikely to reflect differences in the infants' responses to the familiarization events.

Test trials

Figure 3 presents the mean looking times of the infants in the midpoint and the endpoint conditions to the small- and the large-cylinder test events. It can be seen that the infants in the midpoint condition looked longer at the small- than at the large-cylinder event, whereas the infants in the endpoint condition tended to look equally at the two events.

The infants' looking times at the test events were analyzed by means of a 2×2 ANOVA with condition and event as between-subjects factors, as in the previous analysis. There was a significant Condition × Event interaction, $F(1, 56) = 4.32$,

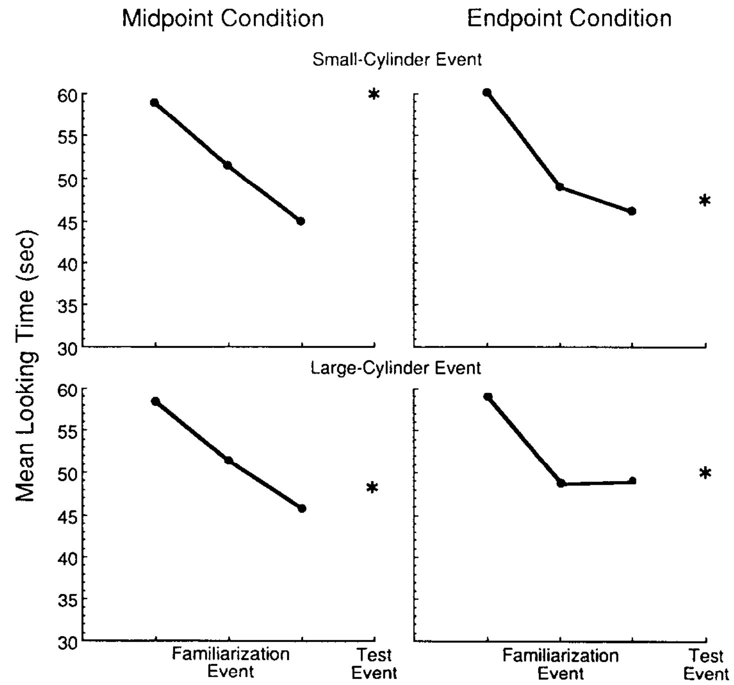

Figure 3. *Looking times of the infants in the midpoint and the endpoint conditions at the familiarization and the test events.*

$p < .05$. Planned comparisons indicated that the infants in the midpoint condition looked reliably longer at the small- ($M = 60.0$) that at the large- ($M = 48.5$) cylinder event, $F(1, 56) = 4.89$, $p < .05$, whereas the infants in the endpoint condition tended to look equally at the two events, $F(1, 56) = 0.53$ (small-cylinder event: $M = 47.5$; large-cylinder event: $M = 51.3$).

Because (a) many of the infants in the experiment (41/60) looked the maximum number of seconds, 60 s, at the test event they were shown and (b) these infants were distributed unevenly across the different conditions, we were concerned that the data violated the homogeneity of variance assumption underlying the ANOVA reported above (e.g., Keppel, 1982). In the midpoint condition, 15/15 and 9/15 infants looked 60 s at the small- and the large-cylinder events, respectively; the corresponding numbers for the infants in the endpoint condition were 7/15 and 10/15. To address this problem, we examined the infants' looking times using the survival analysis technique recommended for data containing both censored observations (i.e., the looking times of the infants who looked 60 s) and uncensored observations (i.e., the looking times of the infants who looked less than 60 s) (McCullagh & Nelder, 1991). The results of this analysis paralleled those of the ANOVA. In the midpoint condition, the infants who saw the small-cylinder event looked reliably longer than those who saw the large-cylinder event, $D(1) = 7.13$, $p < .01$; no such difference was found in the endpoint condition, $D(1) = 0.80$.[4]

Responses to speed violations

Because the adults tested in the midpoint and the endpoint conditions appeared impervious to the speed violations embedded in the test events, we expected the infants in the experiment also to ignore or dismiss these violations. This expectation was confirmed in a contrast comparing the response of the infants in the midpoint condition who saw the large-cylinder event ($M = 48.5$),

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[4] In a final analysis, the infants' looking times at the test events were recoded using a different criterion for ending the trials; specifically, a trial was now judged to have ended when the infant looked away from the event for 1 rather than 2 cumulative seconds. It was hoped that this manipulation would reduce the number of censored observations in the data set. Using this new criterion, 29/60 infants were now found to have looked 60 s at the test event they were shown: 12 of these infants saw the midpoint small-cylinder event, 6 the midpoint large-cylinder event, 4 the endpoint small-cylinder event, and 7 the endpoint large-cylinder event. The infants' recoded looking times were analyzed using a 2 × 2 ANOVA, as before. Planned comparisons again indicated that, in the midpoint condition, the infants who saw the small-cylinder event ($M = 57.7$) looked reliably longer than the infants who saw the large-cylinder event ($M = 42.3$), $F(1, 56) = 7.57$, $p < .05$; in the endpoint condition, in contrast, no significant difference was found between the responses of the infants who saw the small- ($M = 44.0$) and the large- ($M = 42.0$) cylinder events, $F(1, 56) = 0.13$. Similar results were obtained when the infants' recoded looking times were compared by means of the survival analysis technique (midpoint condition, $D(1) = 7.00$, $p < .01$; endpoint condition, $D(1) = 0.00$).

which presented no speed violation, with those of the infants in the endpoint condition to the large- ($M = 51.3$) and the small- ($M = 47.5$) cylinder events, both of which involved a speed violation. This contrast revealed no reliable difference in the infants' responses to the events, $F(1, 56) = 0.03$. It is unclear whether these negative findings stem from the fact that (a) the infants did not expect the size of the cylinder to affect the speed at which the bug traveled or (b) the speed violations were less salient than the distance violation.

Conclusions

The infants in the midpoint condition looked reliably longer at the small- than at the large-cylinder event, whereas the infants in the endpoint condition tended to look equally at the two events. These results indicate that the infants (a) believed that the size of the cylinder affected the length of the bug's trajectory and (b) were able to use the familiarization event to calibrate their predictions about the test events. Thus, after being shown that the bug rolled to the *middle* of the track with the medium cylinder, the infants were surprised to see the bug travel farther with the smaller but not the larger cylinder. In contrast, after being shown that the bug rolled to the *end* of the track with the medium cylinder, the infants were not surprised to see the bug do the same with either the smaller or the larger cylinder. Such results demonstrate that, by 11 months of age, infants are capable of making sophisticated, calibration-based predictions about collision events. The present research is thus consistent with recent investigations of other facets of infants' physical world, which have also revealed impressive competencies (e.g., Baillargeon, 1993, in press; Baillargeon, Needham, & DeVos, 1992; Kim & Spelke, 1992; Needham & Baillargeon, 1993a, 1993b; Spelke et al., 1992).

The present results suggest at least five directions for future research. The first concerns the development of infants' reasoning about collision events. In the Introduction, we reported a recent finding (Kotovsky, 1992) that infants as young as 5.5 months of age expect a stationary object to be displaced when hit by a moving object. Do 5.5-month-old infants also expect the stationary object to be displaced farther when hit by a larger but not a smaller moving object? Investigations of other areas of infants' physical knowledge have led to the suggestion (Baillargeon, 1993, in press; Baillargeon et al., in press) that, in their initial pass at understanding physical events, infants build preliminary, all-or-none concepts that capture the essence of the events but few of their details. With further experience, these initial concepts are progressively elaborated. Infants slowly identify the variables that are relevant to the events and incorporate this accrued knowledge into their reasoning, resulting in increasingly accurate predictions over time. Some of the evidence that infants first identify initial concepts and only later variables comes from research on the development of infants' intuitions about support (e.g., Baillargeon et al., 1992; Needham & Baillargeon, 1993a, 1993b). These results indicate that, by 3 months of age, infants expect an object to fall if pushed completely off a supporting platform and to remain stable otherwise; at this stage, any contact between the object and the platform is deemed sufficient to ensure the object's stability. Beginning at 6.5 months of age, however, infants realize that the object may fall even when partially supported and that the amount of contact between the object and the platform can be used to judge whether the object will be stable. Will parallel results be obtained in the development of infants' knowledge about collisions, with infants being found to expect a stationary object to be displaced when hit by a moving object *before* they identify the size of the moving object as a variable affecting the length of the stationary object's displacement? To answer this question, further research will need to establish (a) at what age infants begin to expect a stationary object to be displaced when hit by a moving object and (b) at what age infants begin to assume that one of the variables that affects this initial concept is the size of the moving object.

A second line of research that is suggested by the results of the present experiment has to do with infants' own characterization of the variable investigated in the experiment. For ease of description, we have focused throughout the paper on the cylinders' *sizes*; but there is no empirical reason to believe that the infants in the experiment were basing their predictions about the small and the large cylinders on their sizes rather than their *weights*. Recall that the infants were encouraged to manipulate the cylinders prior to the experiment while their parents filled out forms. Although not all of the infants were willing or able to manipulate all of the cylinders (the large cylinder was rather heavy and many infants could not hold it unaided), the infants may still have been able to gather sufficient information about the cylinders' weights to make accurate predictions. One way of determining whether these brief experiences were indeed helpful to the infants would be to conduct the same experiment without allowing the infants first to handle the cylinders. Negative results would suggest that the infants in the present experiment were basing their predictions on the weights rather than the sizes of the cylinders. Positive results, however, would be open to at least two interpretations. One would be that the infants were indeed attending only to the cylinders' sizes. The other interpretation would be that the infants were basing their predictions on the cylinders' weights even though they had not been allowed to manipulate them, either because (a) they had already acquired an expectation that objects of identical material or texture that vary in size typically vary proportionally in weight or (b) they could derive information about the cylinders' weights from the events themselves (e.g., when watching the black hand pick up the cylinders and deposit them at the top of the ramp or when listening to the cylinders roll down the ramp). Additional research is thus needed to ascertain exactly what variable knowledge was revealed in the present experiment. More generally, research is also needed to establish (a) whether infants hold expectations about the relation between objects' sizes and weights; (b) what cues infants are able to use to gather information about objects' weights; and (c) how the answers to these questions change with age.

The line of research we just discussed concerned how infants define the variable investigated in the present experiment. A third, related line of research has to do with how infants characterize the effects of this variable. The infants in the experiment showed clear surprise when the bug rolled farther and faster than it should have, but not when it only rolled faster or slower than it should have, given its behavior in the familiarization events. Further research is needed to establish whether the infants failed to respond to the speed violations because (a) they had no expectation that the size of the cylinder could affect the speed of the bug's displacement or (b) they were unable to detect when the bug traveled faster or slower than it should have. One way of addressing these questions might be to show infants the endpoint familiarization event, but with the bug traveling much more slowly than in the present experiment, so that it would barely reach the end of the track. Would infants then be surprised in the small- but not the large-cylinder event to see the bug speed along the track until it crashed against the distant wall of the apparatus? Although negative results (as is often the case in such situations) would be uninformative, positive results would suggest that, by 11 months of age, infants believe that, in a collision event between a moving and a stationary object, the size of the moving object affects not only the length but also the speed of the stationary object's displacement.

A fourth line of research suggested by the present results has to do with the nature of the strategies the infants used to reason about the size of the cylinder and the length of the bug's displacement. Computational models of everyday physical reasoning (e.g., Forbus, 1984) typically distinguish between quantitative and qualitative strategies. In these models, a strategy is referred to as *quantitative* if it requires subjects to encode and use information about absolute quantities (e.g., object A is "this" large or has traveled "this" far from object B, where "this" stands for some absolute measure of object A's size or distance from B). Conversely, a strategy is referred to as *qualitative* if it requires subjects to encode and use information about relative quantities (e.g., object A is larger than or has traveled farther than object B). It seems likely that the infants in the experiment reasoned qualitatively about the cylinders' sizes, since the cylinders were laid side by side at the start of each event and could easily be compared visually. Had only one cylinder been present in each test event (e.g., the small cylinder in the small-cylinder event), the infants would have been forced to engage in quantitative reasoning, comparing the size of the cylinder before them with their representation of the size of the medium cylinder shown in the familiarization event. It also seems likely that the infants represented the length of the bug's displacement along the track, not in absolute terms (e.g., the bug traveled about "this" far from the ramp), but rather in relative terms. Indeed, there were multiple ways for the infants to qualitatively encode the distance traveled by the bug in each event: relative to the track itself (middle or end), relative to the buildings on the back wall of the apparatus (in front of the church or house), or relative to the infants themselves (in front of the infants or to their right).

Would the infants have been as successful had they been required to reason quantitatively about the size of the cylinder or the length of the bug's displacement? Perhaps not. Sitskoorn and Smitsman (1991) found that 9-month-old infants could judge whether a block could be supported by a box open at the top only when they were able to compare the widths of the block and the box *in a single glance*, as the one was lowered onto the other. When a screen prevented such a comparison, the infants failed the task, even though the block and the box were still visible on either side of the screen. Similarly, Baillargeon (1993) reported that 12.5-month-old infants could determine whether a cloth cover with a small protuberance could hide a small or a large toy dog only when they were able to directly compare the size of the protuberance to that of the dog. When the distance between the two objects was increased, so that they could no longer be compared in a single glance, the infants were unable to perform the task. Such results suggest that, whereas qualitative comparisons between two quantities are readily accomplished, quantitative comparisons in which absolute information about one of the quantities must be supplied from memory pose considerable difficulties. Future research will examine whether the same pattern obtains when infants engage in calibration-based reasoning.[5] Specifically, are infants more likely to succeed in making calibration-based predictions when the relevant information can be encoded qualitatively as opposed to quantitatively? A positive answer to this question would underscore the need for investigating the marked differences in infants' ability to represent, remember, and use qualitative and quantitative information.

Even if infants are found to be far superior at making calibration-based predictions with qualitative as opposed to quantitative information, such a result should not detract from the finding that infants can make such predictions *at all*. As was noted in the Introduction, adults frequently engage in calibration-based reasoning. Such reasoning is especially useful in that it enables adults to predict and control effects (e.g., how quickly a car comes to a stop, how loud a radio sounds, how bright a computer monitor appears, how long it takes to warm up liquids in a microwave oven, how much fat is needed to prevent pancakes from sticking to a pan) in situations in which the precise function relating variables and effects is only imperfectly understood. Because infants' physical knowledge is

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[5] One interesting hypothesis suggested by these speculations is that the infants (and perhaps the adults) were better at reasoning about the length as opposed to the speed of the bug's trajectory because the former could be encoded qualitatively but the latter, in the present context, could not.

much more limited than that of adults, very few functions mapping variables and effects will be well understood. Hence, the fact that infants can engage in calibration-based reasoning – that is, can take advantage of observed outcomes to calibrate future predictions and behaviors – must contribute considerably to their mastery of the physical world.

A final research direction suggested by the results of the present experiment has to do with the assessment of infants' causal reasoning. There is now experimental evidence that infants process causal sequences differently than they do non-causal sequences (Leslie & Keeble, 1987; Oakes & Cohen, 1990). In one experiment, Oakes and Cohen (1990) habituated 6- and 10-month-old infants to one of three events: (a) a causal event in which a moving toy collided with a stationary toy and set it into motion; (b) a non-causal event in which a short delay separated the motion of the first and second toy; and (c) another non-causal event in which a spatial gap separated the motion of the two toys. Following habituation, the infants were presented with the two events not shown in habituation. The results indicated that the 10-month-old infants habituated to the causal event dishabituated to the two non-causal events, whereas those habituated to either of the non-causal events dishabituated only to the causal event. In contrast, the 6-month-old infants tended to look equally at the events. The authors concluded that, by 10 months of age, infants are already able to differentiate between causal and non-causal events.

Additional evidence obtained with a different method suggests that even 6-month-old infants may be sensitive to causality in event sequences. Leslie and Keeble (1987) habituated 6-month-old infants to an animated film depicting either a causal or a non-causal collision event. In the causal event, the infants saw a red brick move from left to right and collide with a green brick, which immediately moved off. The non-causal event was identical except that the movement of the green brick was delayed by 0.5 s. Following habituation, the infants saw the same event in reverse. The authors reasoned that, whereas only spatiotemporal direction was reversed in the non-causal test event, both spatiotemporal and causal direction were reversed in the causal test event. Therefore, if the infants were sensitive to causality, they should dishabituate more to the causal than to the non-causal test event. The results indicated that the infants looked reliably longer when the causal than when the non-causal event was reversed. These and control results suggested that, by 6 months of age, infants are already sensitive to the causal properties of events.

The present research suggests a different, converging approach to the study of causal reasoning in infancy. When adults perceive two events to be causally related, they readily attempt to specify how changes in the first event may affect the second event. When the relation between two events is perceived to be arbitrary, however, modifications of the first event are likely to be dismissed as having little or no bearing on the second event. To illustrate, consider what would happen if a temporal or a spatial gap separated the movements of the cylinder and bug in the familiarization and test events used in the midpoint condition. Adults who watched these events would be unlikely to form any specific expectations as to how far the bug should roll with the small and the large cylinders. If the cylinders were thought *not* to cause the bug's displacement, changes in their sizes would be viewed as irrelevant.

Would infants, like adults, respond to changes in the cylinder's size differentially, depending on whether or not they perceived the cylinder to cause the bug's motion? In the present experiment, the infants in the midpoint condition had a clear expectation that the bug should roll farther along the track when hit by the larger but not the smaller cylinder. Would infants develop the same expectation if given information that, to adults, would suggest that the bug's displacement was not in fact caused by the cylinders? Evidence that infants respond to the changes in the cylinders' size in the causal but not the non-causal condition would provide strong converging support for the claim that infants, like adults, process causal and non-causal event sequences differently.

In daily life, adults are often exposed to events in which relations between variables and effects are only poorly understood. In such situations, adults readily engage in calibration-based reasoning to enhance their ability to predict and control effects. The present research suggests that infants, like adults, are capable of calibration-based reasoning. Such a finding not only expands our understanding of infants' physical reasoning abilities, but also raises challenging questions about the proper characterization of these abilities.

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