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A MODEL OF PHYSICAL REASONING IN INFANCY*

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*This research was supported by grants from the Guggenheim Foundation, the University of Illinois Center for Advanced Study, and the National Institute of Child Health and Human Development (HD-21104 and HD-28686). I would like to thank Jerry DeJong, Judy Deloache, and Steve Reznick for helpful comments and suggestions; Elizabeth Cullum for her help with the data analyses; and Andrea Aguiar, Elizabeth Cullum, Lincoln Craton, Julie DeVos, Marcia Graber, Myra Gillespie, Valerie Kolstad, Laura Kotovsky, Amy Needham, Helen Raschke, and the undergraduate assistants at the Infant Cognition Laboratory at the University of Illinois for their help with the data collection. I would also like to thank the parents who kindly agreed to have their infants participate in the research.

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I. INTRODUCTION

A long-standing concern of infancy research has been the description of infants' knowledge about the physical world. Traditionally, this research tended to focus on infants' understanding of occlusion events. When adults see an object occlude another object, they typically assume that the occluded object continues to exist behind the occluding object. Piaget (1952, 1954) was the first to examine whether infants hold the same assumption. He concluded that it is not until infants are about 9 months of age that they begin to appreciate that objects continue to exist when masked by other objects. This conclusion was based mainly on analyses of infants' performance in manual search tasks. Piaget noted that, prior to about 9 months of age, infants do not search for objects they have observed being hidden. If an attractive toy is covered with a cloth, for example, young infants make no attempt to lift the cloth and grasp the toy, even though they are capable (beginning at about 4 months) of performing each of these actions. Piaget took this finding to suggest that young infants do not yet understand occlusion events and wrongly assume that objects cease to exist when concealed by other objects.

In subsequent years, numerous reports were published confirming Piaget's (1952, 1954) observation that young infants typically fail to search for hidden objects (for reviews of this early research, see Gratch, 1977; Harris, 1987; Schuberth, 1983). Piaget's *interpretation* of his observation, however, was eventually questioned. Researchers came to realize that young infants might perform poorly in search tasks, not because of incorrect beliefs about occlusion events, but because of difficulties associated with the planning of means–end search sequences (e.g., Baillargeon, Graber, DeVos, & Black, 1990; Baillargeon, Spelke, & Wasserman, 1985; Bower, 1974; Diamond, 1991). This concern led investigators to seek alternative methods for exploring infants' beliefs about occluded objects, methods that did not require infants to perform means–end action sequences.

A well-established finding in infancy research—infants' tendency to

look longer at novel than at familiar stimuli (see Banks, 1983; Fagan, 1984; Olson & Sherman, 1983; Spelke, 1985, for reviews)—suggested an alternative method for investigating infants' intuitions about occlusion events. In a typical experiment, infants are presented with two test events: a possible and an impossible event. The possible event is consistent with the belief that objects continue to exist when occluded; the impossible event, in contrast, violates this belief. The rationale is that if infants possess such a belief, they will perceive the impossible event as more novel or surprising than the possible event and will therefore look reliably longer at the impossible than at the possible event.

Using this violation-of-expectation method, investigators have demonstrated that, contrary to traditional claims, even very young infants appreciate that objects continue to exist when occluded (see Baillargeon, 1993; Harris, 1989; Spelke, Breinlinger, Macomber, & Jacobson, 1992, for recent reviews). Described next are two experiments, conducted with very different events, that illustrate this conclusion.

In the first experiment (Baillargeon et al., 1990), 5.5-month-old infants watched the familiarization and test events depicted in Figure 1. At the start of the possible test event, the infants saw two covers placed side by side: on the left was a clear plastic cover, and on the right was a cage. A toy bear was visible inside the cage. After a few seconds, a screen was raised to hide the covers from view. Next, a gloved hand reached behind the screen's right edge twice in succession, reappearing first with the cage and then with the

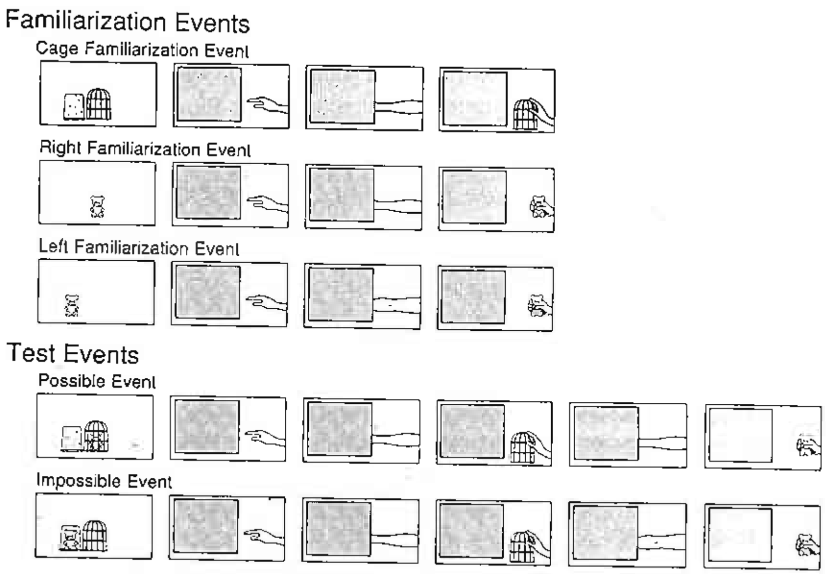

Fig. 1. Schematic drawing of the test events used in Baillargeon et al. (1990).

bear. The impossible test event was identical to the possible event except that the bear was under the clear cover at the start of the event and thus still should have been inaccessible to the hand after the cage was removed. The three familiarization events shown prior to the test events were designed to acquaint the infants with the hand's actions in removing the cage and the bear (see Figure 1).

A second group of 5.5-month-old infants was tested in a control condition in which the clear cover was replaced by a clear, shallow container. In one test event, the bear sat in the container, with its head and upper body protruding above the rim; in the other test event, as before, the bear was under the cage. In this condition, the bear was always accessible to the hand after the cage was removed.

The infants in the experimental condition looked reliably longer at the impossible than at the possible event, whereas the infants in the control condition tended to look equally at the events they were shown. These results indicated that the infants (a) believed that the bear, cage, and clear cover or container continued to exist and retained their locations after they were hidden by the screen; (b) understood that the hand and the bear could not move through the clear cover; and hence (c) were surprised in the impossible event to see the hand reappear from behind the screen holding the bear. Baseline trials with the bear under the cover or cage or in the container provided further support for this interpretation.

The results of this first experiment indicated that, by 5.5 months of age, infants believe that objects continue to exist when occluded. The next experiment asked whether 3.5-month-old infants possess the same belief (Baillargeon & DeVos, 1991). The infants were habituated to a toy carrot that slid back and forth along a horizontal track whose center was occluded by a screen; the carrot disappeared at one edge of the screen and reappeared, after an appropriate interval, at the other edge (see Figure 2). On alternate trials, the infants saw a short or a tall carrot slide along the track. Following habituation, the midsection of the screen's upper half was removed, creating a large window. The infants then saw a possible and an impossible test event. In the possible event, the short carrot moved back and forth along the track; this carrot was shorter than the window's lower edge and so did not appear in the window when passing behind the screen. In the impossible event, the tall carrot moved along the track; this carrot was taller than the window's lower edge and hence should have appeared in the window but did not in fact do so.

The results showed that the infants tended to look equally at the short- and the tall-carrot habituation events, but looked reliably longer at the impossible than at the possible test event. These results indicated that the infants (a) believed that each carrot continued to exist and retained its height behind the screen; (b) appreciated that each carrot could not

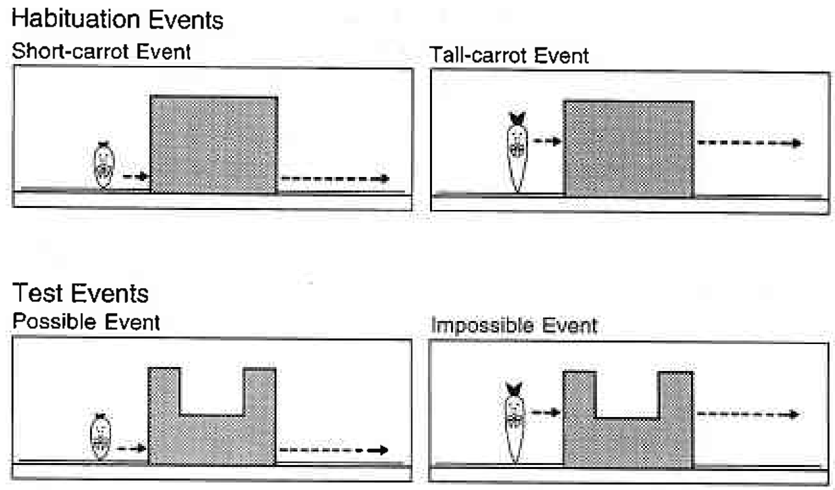

Fig. 2. Schematic drawing of the test events used in Baillargeon and DeVos (1991).

disappear at one end of the screen and reappear at the other end without having traveled the distance behind the screen; and hence (c) were surprised in the impossible event that the tall carrot failed to appear in the screen window.

The results of the two experiments described earlier, and of many related experiments (see Baillargeon, 1993, and Spelke et al., 1992, for recent reviews), demonstrated that, contrary to what had traditionally been claimed, even young infants believe that objects continue to exist when masked by other objects. Such a conclusion encouraged researchers to explore other facets of infants' physical world. If infants possessed intuitions about occlusion phenomena, the reasoning went, it seemed likely that they possessed intuitions about other physical phenomena as well. Accordingly, experiments were conducted, using the same violation-of-expectation method that had been used successfully with occlusion phenomena, to investigate infants' understanding of a wide range of additional phenomena, such as support (e.g., Baillargeon & Hanko-Summers, 1990; Needham & Baillargeon, 1993, 1995; Spelke et al., 1992), collision (e.g., Kotovsky & Baillargeon, 1994; Leslie & Keeble, 1987; Oakes & Cohen, 1990), unveiling (e.g., Baillargeon & DeVos, 1995a, 1995b), arrested-motion (e.g., Baillargeon, 1987a, 1987b, 1991; Baillargeon et al., 1985; Spelke et al., 1992), containment (e.g., Caron, Caron, & Antel, 1988; Kolstad & Baillargeon, 1995a, 1995b), and displacement (e.g., Kim & Spelke, 1992; Spelke, Katz, Purcell, Ehrlich, & Breinlinger, 1994) phenomena. Unlike the initial experiments on occlusion phenomena, however, whose findings had tended to be generally positive, these subsequent experiments yielded more complex patterns of results: Infants demonstrated successful reasoning at different ages for different phenomena, for different aspects of the same phenomenon, and for different tasks examining the same facet of a phenomenon.

Attempts to make sense of these patterns of successes and failures (many of which are described later) have led my collaborators and me to develop a multifactor model of infants' physical reasoning (e.g., Baillargeon, in press-a, in press-b; Baillargeon, Kotovsky, & Needham, in press). The model assumes that in order to explain infants' reasoning about a particular physical phenomenon, one must consider two broad classes of factors: phenomenon-specific factors and phenomenon-general factors. Phenomenon-specific factors include (a) the knowledge infants have acquired about the phenomenon, and (b) the strategies infants are able to use in reasoning about the phenomenon. Phenomenon-general factors have to do with infants' overall perceptual and information-processing abilities and include a host of factors such as (a) how well infants can perceive events; (b) what information infants are likely to attend to and encode when shown events; and (c) how long infants are able to retain the information they have encoded about events. Phenomenon-general factors apply in the same manner across phenomena: Infants' ability to gauge depth relations, for example, remains constant whether infants are observing support or unveiling events. Phenomenon-specific factors, on the other hand, frequently yield different performances across phenomena. To illustrate, young infants possess sophisticated intuitions about support but not unveiling events. The two classes of factors are discussed later, along with supporting experimental evidence. Before undertaking this discussion, however, I briefly describe the general procedure used in our experiments.

II. A NOTE ABOUT PROCEDURE

All of the experiments presented in this chapter made use of the violation-of-expectation method described in the introduction. In each experiment, the infant sat on a parent's lap in front of an apparatus consisting of a large display box. The parent was asked to remain calm and neutral and to close his or her eyes during the test trials.

The infant's looking behavior was monitored by two observers who watched the infant through peepholes in large cloth-covered frames on either side of the apparatus. The observers could not see the test events from their viewpoints, and they were not told the order in which the events were presented. Each observer held a button box linked to a computer and depressed the button when the infant attended to the events. Each trial was divided in 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 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. Mean agreement per trial per infant ranged from 89% to 93% across experiments. The computer used the primary observer's looking times to determine the end of the trials (see later).

At the back of the apparatus were two (or sometimes three) experimenters who worked together to produce the test events. The actions of each experimenter followed precise, second-by-second scripts that were practiced until they were performed smoothly and accurately. A metronome helped the experimenters adhere to the scripts.

Each infant was tested according to the same general procedure. Prior to the experiment, while its goal was explained to the parent, the infant was encouraged to manipulate for a few minutes some or all of the objects used in the experiment. Next, the parent and the infant were brought to the test room and were seated in front of the apparatus. In some experiments, the infant first received familiarization or habituation trials to acquaint him or her with some aspects of the test events (e.g., objects' possible locations or trajectories). In this chapter, trials are referred to as familiarization trials if the infant received a fixed number of trials (this number varied from 1 to 6 across experiments).[1] In contrast, trials are referred to as habituation trials if the infant was given trials until he or she either (a) satisfied a habituation criterion of a 50% or greater decrease in looking time on three consecutive trials, relative to the looking time on the first three trials, or (b) completed a maximum number of habituation trials (which was typically nine trials).

Following the familiarization or habituation trials, the infant watched two test events on alternate trials until he or she completed three (or sometimes two or four) pairs of test trials. An infant assigned to an experimental condition typically saw a possible and an impossible test event, and an infant assigned to a control condition saw two possible test events. In either case, the order of presentation of the test events was counterbalanced across infants. In each test trial, unless otherwise noted, the test event was repeated continuously until the computer signaled the end of the trial. A given trial ended when the infant either (a) looked away from the event for 2 (or sometimes 1) consecutive seconds, or (b) looked at the event for a maximum number of seconds (usually 60). When a trial ended,

[1]For the sake of brevity, no mention will be made in the chapter of the familiarization trials infants received when only one or two trials were given. Such trials typically involved showing infants the objects used in the test events.

an experimenter lowered a curtain in front of the apparatus. During the intertrial interval, the test objects were quickly returned to their starting positions; the curtain was then lifted to begin a new trial.

Finally, the number of infants tested in each condition ranged from 12 to 20 across experiments. The infants' looking times at the test events were compared by means of analyses of variance and, if appropriate, planned comparisons. Results are reported as reliable if the *p* values associated with them were equal to or smaller than .05.

III. PHENOMENON-SPECIFIC FACTORS IN INFANTS' PHYSICAL REASONING

It was proposed earlier that to account for infants' reasoning about a given physical phenomenon, one must consider two broad classes of factors: phenomenon-specific factors that concern infants' expertise with the phenomenon under investigation, and phenomenon-general factors that reflect infants' basic perceptual and information-processing abilities. In this section of the chapter, I focus on two phenomenon-specific factors that have been shown to affect infants' reasoning about a phenomenon: (a) the knowledge infants have acquired about the phenomenon, and (b) the strategies infants are able to use in reasoning about the phenomenon.

A. Infants' Physical Knowledge

How does infants' knowledge about a physical phenomenon develop? Recent investigations in our laboratory suggest that infants' intuitions develop according to a consistent pattern that recurs across ages and phenomena. Specifically, it appears that when learning about a phenomenon infants first form a preliminary, all-or-none concept that captures the essence of the phenomenon but few of its details. In time, this initial concept is progressively elaborated. Infants slowly identify discrete and continuous variables that are relevant to the initial concept, study their effects, and incorporate this accrued knowledge into their reasoning, resulting in increasingly accurate predictions over time.

To illustrate the distinction between initial concepts and variables, I will summarize experiments on the development of infants' knowledge about support, collision, and unveiling phenomena.

1. Knowledge About Support Phenomena

Initial concept: Contact between the box and platform. Our research on the development of infants' intuitions about support phenomena has

focused on simple problems involving a box and a platform. Our first experiment (Needham & Baillargeon, 1993) asked whether 4.5-month-old infants appreciate that a box can be stable when released *on* but not *off* a platform. The infants saw the possible and impossible events depicted in Figure 3. In the possible event, a gloved hand deposited a box on a platform and then retreated a short distance, leaving the box supported by the platform. In the impossible event, the hand released the box beyond the platform and then retreated, leaving the box suspended in midair with no visible means of support. Additional groups of 4.5-month-old infants were tested in two control conditions. In one, the infants saw the same test events as the infants in the experimental condition except that the hand never released the box, which was therefore continuously supported. In the other control condition, the infants again saw the same test events as the infants in the experimental condition except that the box fell when released by the hand beyond the platform.

The results showed that the infants in the experimental condition looked reliably longer at the impossible than at the possible event, whereas the infants in the two control conditions tended to look equally at the events they were shown. These and other results (see Needham & Baillargeon, 1993) indicated that the infants preferred the impossible event, not because they found the arrangement of the box and the platform in this event more

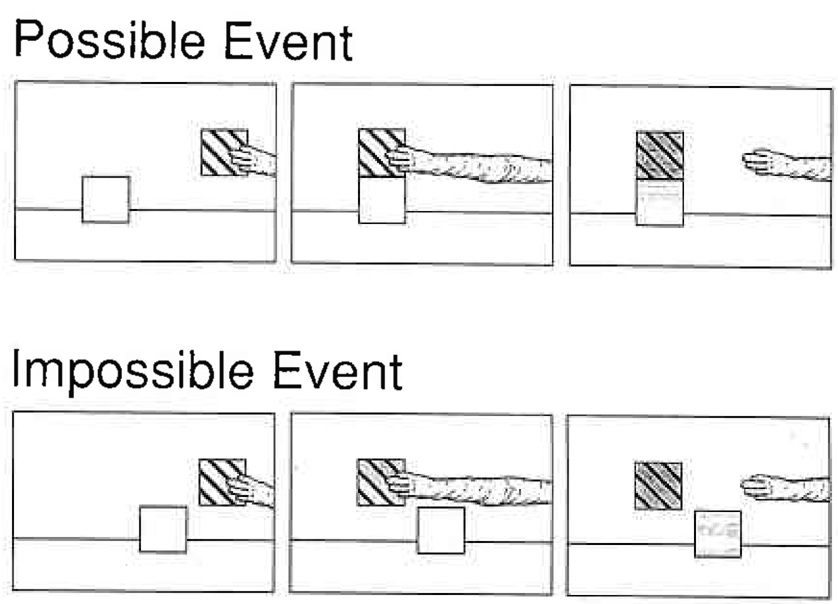

Fig. 3. Schematic drawing of the test events used in Needham and Baillargeon (1993).

pleasing than that in the possible event, and not because they were intrigued to see the hand deliberately release the box beyond the platform, but because they expected the box to fall when let go in mid-air and were surprised that it did not.

The results of this first experiment suggested that by 4.5 months of age, infants expect objects to fall when released in mid-air. The next experiment asked whether 3-month-old infants also possess intuitions about support phenomena (Needham & Baillargeon, 1995). The infants watched test events in which the extended index finger of a gloved hand pushed a box from left to right along the top surface of a platform (see Figure 4). In the possible event, the box was pushed until its leading edge reached the end of the platform. In the impossible event, the box was pushed entirely off the platform and stood suspended in mid-air. Prior to the test events, the infants saw familiarization events that were similar except that a longer platform was used so that the box was always fully supported.

A second group of infants was tested in a control condition identical to the experimental condition except that the hand grasped the box, which was therefore continuously supported. The infants in the experimental condition looked reliably longer at the impossible than at the possible event, whereas the infants in the control condition tended to look equally at the test events they were shown. These results suggested that the infants in the experimental condition expected the box to fall when it was pushed off the platform and were surprised that it did not.

This interpretation was confirmed by the results of another experiment with 3-month-old infants (Needham & Baillargeon, 1995). The infants in this experiment saw the same familiarization and test events as the infants in the experimental condition in the last experiment. Prior to seeing these events, however, the infants received one additional trial similar to the familiarization trials except that the front of the box was removed, creating a large opening (see Figure 5). For half of the infants (hand-in-box condition), a second hand could be seen through the opening, holding the back of the box. For the other infants (empty-box condition), no hand was visible inside the box.

The results indicated that the infants in the empty-box condition looked reliably longer at the impossible than at the possible event, but that the infants in the hand-in-box condition tended to look equally at the two events. Together, these results pointed to two conclusions. The first was that the infants in the empty-box condition preferred the impossible event because they were surprised that the box remained stable after it lost contact with the platform. The second conclusion was that the infants in the hand-in-box condition were able to take advantage of the information given at the start of the experiment to make sense of the impossible event:

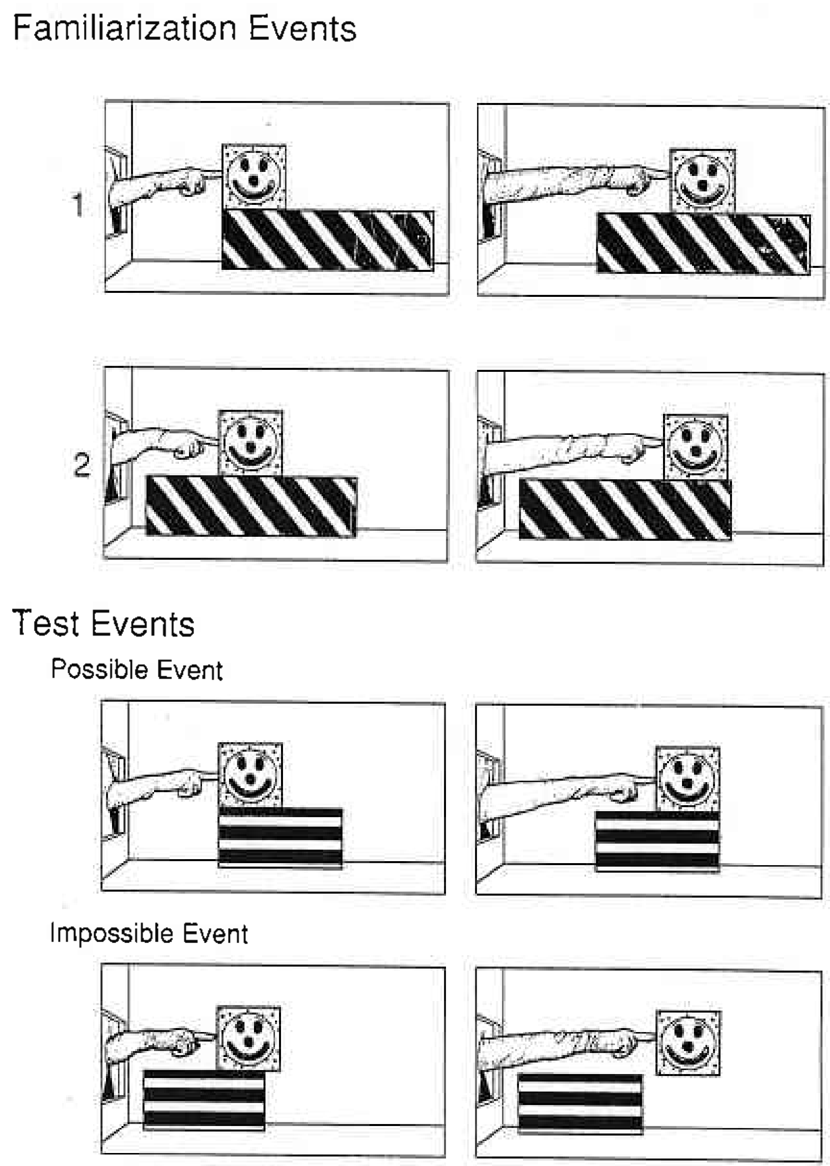

Fig. 4. Schematic drawing of the test events used in Needham and Baillargeon (1995, Exp. 1).

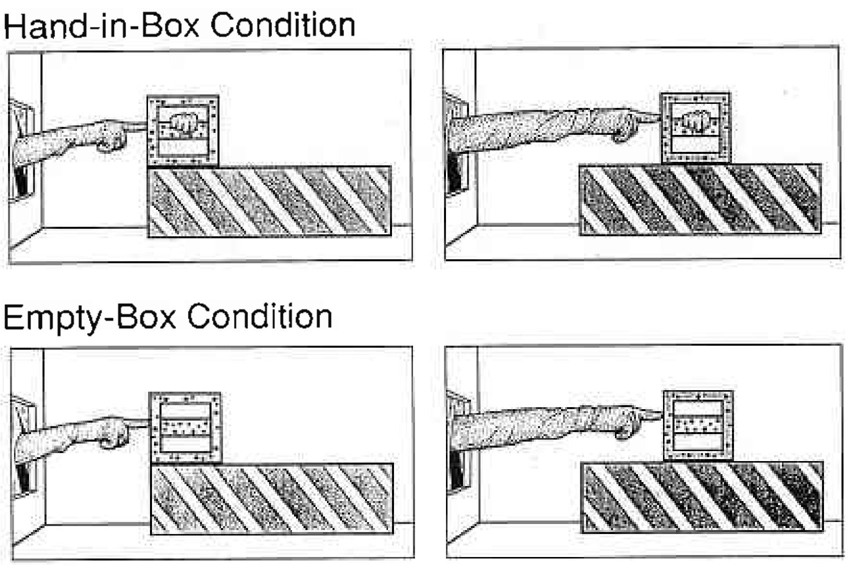

Fig. 5. *Schematic drawing of the test events used in Needham and Baillargeon (1995, Exp. 2).*

Specifically, they assumed that the box did not fall when pushed off the platform because it was held at the back by a second, hidden hand.

Discrete variable: Type of contact between the box and platform. The results of our initial experiments indicated that by 3 months of age, infants understand that a box must be in contact with a platform in order to be stable. Our next experiment (Baillargeon, Raschke, & Needham, 1995) asked whether infants also appreciate what type of contact is needed between a box and a platform for the box to be stable (see Figure 6). Subjects were 4.5-month-old infants. In the possible event, a gloved hand placed a small square box against the side of a large, open platform on top of a smaller, closed platform. The impossible event was identical to the possible event except that the closed platform was much shorter so that the box lay well above it.

Different results were obtained with the female and the male infants. The female infants looked reliably longer at the impossible than at the possible event, suggesting that they (a) realized that the box was inadequately supported when it contacted only the side of the open platform, and hence (b) expected the box to fall in the impossible event and were surprised that it did not. A control condition in which the hand retained its grasp on the box provided evidence for this interpretation.

In contrast to the female infants, the male infants in the experimental

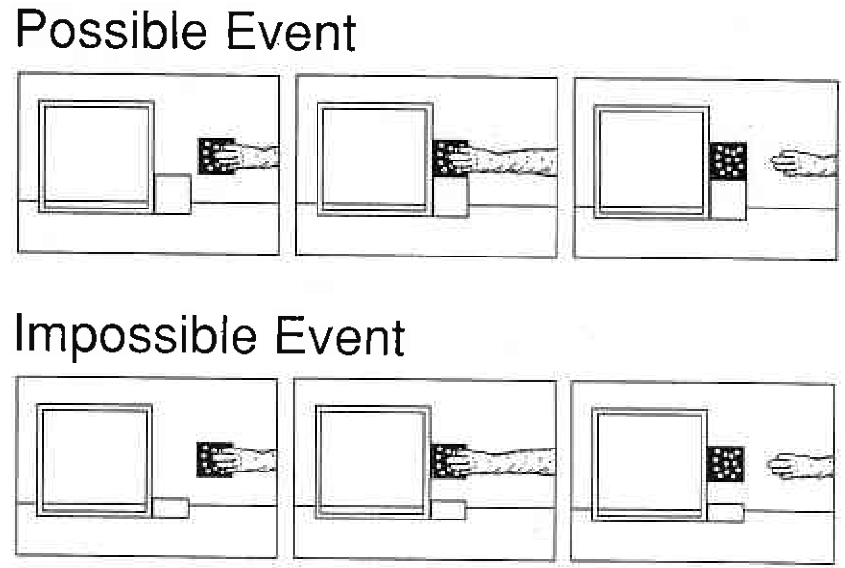

Fig. 6. *Schematic drawing of the test events used in Baillargeon et al. (1995).*

condition tended to look equally at the impossible and the possible events, suggesting that they believed that the box was adequately supported in both events. Because female infants mature slightly faster than male infants (e.g., Haywood, 1986; Held, in press), sex differences such as the one described here are not uncommon in infancy research (e.g., Baillargeon & DeVos, 1991; Kotovsky & Baillargeon, 1995a). Given this evidence, it is likely that when tested with the same experimental procedure, slightly younger female infants (i.e., infants aged 3.5 months) would perform like the 4.5-month-old male infants, and slightly older male infants (i.e., infants aged 5.5 months) would perform like the 4.5-month-old female infants. An experiment is under way to confirm this last prediction.

Continuous variable: Amount of contact between the box and platform. The results of the last experiment indicated that by 4.5 months of age infants have begun to realize that a box can be stable when placed on but not against a platform. Our next experiment examined whether infants are aware that, in judging the box's stability, one must consider not only the type but also the amount of contact between the box and the platform (Baillargeon, Needham, & DeVos, 1992). Subjects were 6.5-month-old infants. The infants were assigned to either a 15% or a 70% condition. The infants in the 15% condition watched test events in which a gloved hand pushed a box from left to right along the top of a platform (see Figure

7). In the possible event, the box was pushed until its leading edge reached the end of the platform. In the impossible event, the box was pushed until only the left 15% of its bottom surface remained on the platform. The infants in the 70% condition saw similar test events except that the box was pushed until the left 70%, rather than the left 15%, of its bottom surface remained on the platform. Prior to the test events, the infants in the two conditions watched familiarization events involving a longer platform (see Figure 7).

The results indicated that the infants in the 15% condition looked reliably longer at the impossible than at the possible event, whereas the infants in the 70% condition tended to look equally at the events they were shown. These results suggested that the infants (a) realized that the box was adequately supported when 70%, but not 15%, of its bottom surface lay on the platform, and hence (b) expected the box to fall in the impossible event and were surprised that it did not. This interpretation was confirmed by the results of a control condition identical to the 15% condition except that the hand grasped the box, thereby ensuring its support.

In a subsequent experiment, 5.5-month-old infants were tested using

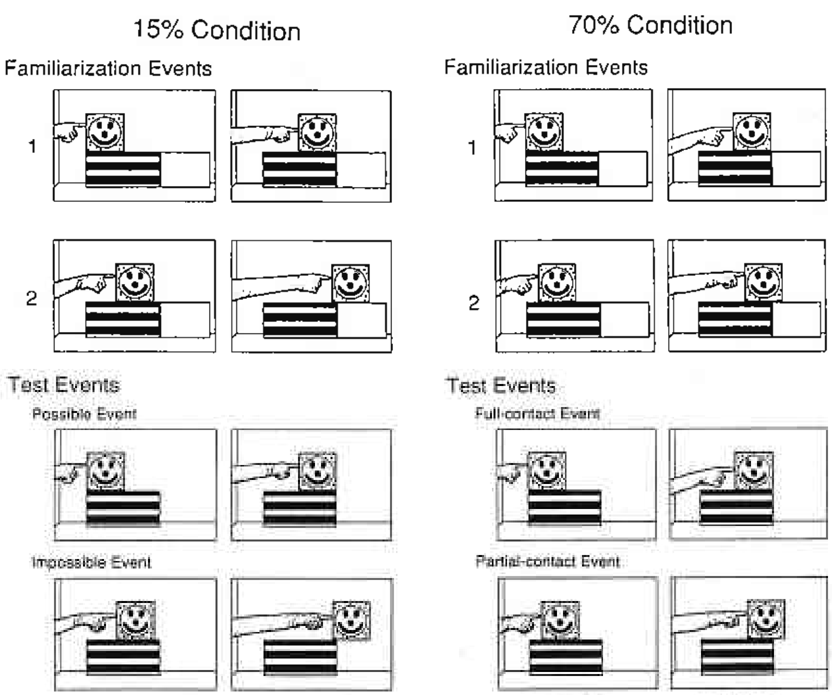

Fig. 7. Schematic drawing of the test events used in Baillargeon et al. (1992).

the 15% condition procedure (Baillargeon et al., 1992). Unlike the 6.5-month-old infants, these younger infants tended to look equally at the impossible and the possible events, as though they judged that the box was adequately supported even when only its left corner remained on the platform. This negative result was replicated in a later experiment using a similar procedure (Needham & Baillargeon, 1995).

Conclusions. The results reported in this section suggest that, in reasoning about support problems involving a box and a platform, infants progress through the following developmental sequence: By 3 months of age, if not before, infants expect the box to fall if it loses contact with the platform and to remain stable otherwise. At this stage, *any* contact between the box and the platform is deemed sufficient to ensure the box's stability. At least two developments take place between 3 and 6.5 months of age. First, infants become aware that the type of contact between the box and the platform must be taken into account when reasoning about the box's stability. Infants initially assume that the box will remain stable if placed either on or against the platform. By 4.5 to (presumably) 5.5 months of age, however, infants come to distinguish between the two types of contact and recognize that only the former ensures support. The second development is that infants begin to appreciate that the amount of contact between the box and the platform affects the box's stability. Initially, infants believe that the box will be stable even if only a small portion (e.g., the left 15%) of its bottom surface rests on the platform. By 6.5 months of age, however, infants expect the box to fall unless a significant portion (e.g., 70%) of its bottom surface is supported.

One way of describing this developmental sequence is that when learning about the support relation between two objects, infants first form an initial concept centered on a contact/no-contact distinction. In time, this initial concept is slowly elaborated. Infants incorporate first a discrete variable (type of contact between the objects) and later, a continuous variable (amount of contact between the objects) into their initial concept, leading to increasingly successful predictions over time.[2]

2. Knowledge About Collision Phenomena

Initial concept: Impact between the moving and stationary object. Our research on infants' reasoning about collision phenomena has focused on simple problems involving a moving and a stationary object.

[2]Spelke and her colleagues have also investigated young infants' intuitions about support phenomena, with largely negative results (e.g., Spelke et al., 1992; Spelke, Jacobson, Keller, & Sebba, 1994; Spelke, Simmons, Breinlinger, & Jacobson, 1994). See Needham and Baillargeon (1993) and Baillargeon et al. (in press) for possible explanations of these results.

Our first experiment (Kotovsky & Baillargeon, 1995c) asked whether 2.5-month-old infants expect a stationary object to be displaced when hit by a moving object. The infants in the experiment sat in front of an inclined ramp; to the right of the ramp was a track (see Figure 8). The infants were first habituated to a cylinder that rolled down the ramp; small stoppers prevented the cylinder from rolling past the end of the ramp onto the track. Following habituation, a wheeled toy bug was placed on the track. In the possible event, the bug was placed 10 cm from the ramp. In this event, the bug was not hit by the cylinder and remained stationary after the cylinder rolled down the ramp. In the impossible event, the bug was placed directly at the bottom of the ramp. In this event, the bug was hit by the cylinder but again remained stationary. Adult subjects typically expected the bug to be displaced when hit by the cylinder; the experiment thus tested whether 2.5-month-old infants would possess the same expectation.

A second group of 2.5-month-old infants was tested in a control condition identical to the experimental condition with one exception. In each test event, the right wall of the apparatus was adjusted so that it stood against the front end of the bug, preventing its displacement.[3]

The infants in the experimental condition looked reliably longer at the impossible than at the possible event, whereas the infants in the control condition tended to look equally at the two test events they were shown. Together, these results pointed to two conclusions. One was that the infants in the experimental condition expected the bug to be displaced when hit and hence were surprised in the impossible event that it remained stationary. The second conclusion was that the infants in the control condition realized that the bug remained stationary when hit because its displacement was prevented by the wall.

These conclusions were supported by the results of another experiment with 2.5-month-old infants (Kotovsky & Baillargeon, 1995c). The infants saw habituation events similar to those used in the previous experiment, except that a tall, thin barrier was added. On alternate trials, this barrier stood across the ramp, where it blocked the cylinder's path, or behind the ramp, out of the cylinder's path (see Figure 9). Following habituation, the bug was placed at the bottom of the ramp. In the possible event, the barrier stood behind the ramp; the cylinder rolled down the ramp and hit the bug, causing it to roll down the track. In the impossible event, the barrier stood

[3]To equate more narrowly the test events shown to the infants in the experimental and the control conditions, the right wall of the apparatus was also moved in the experimental test events: In each event, the wall was positioned 10 cm from the front end of the bug. The infants were also shown the two wall positions on alternate habituation trials (see Figure 8). Analysis of the habituation data revealed no reliable preference for either wall position.

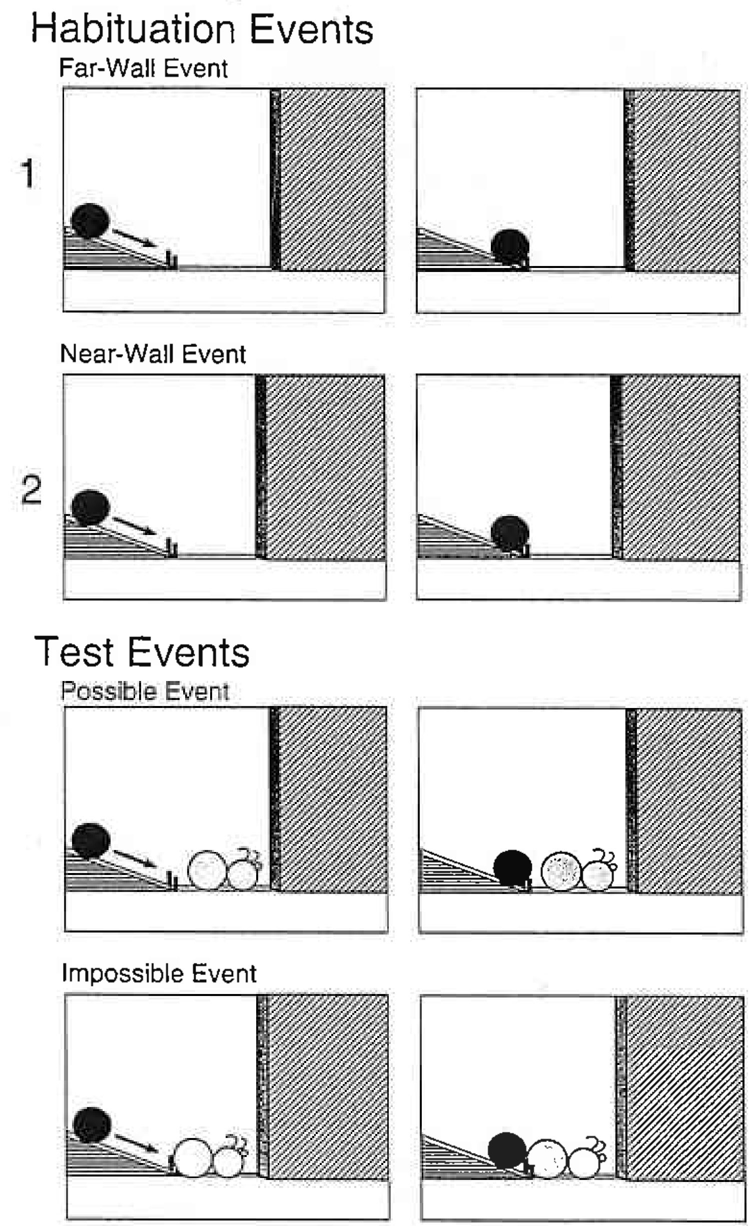

Fig. 8. Schematic drawing of the test events used in Kotovsky and Baillargeon (1995c, Exp. 1).

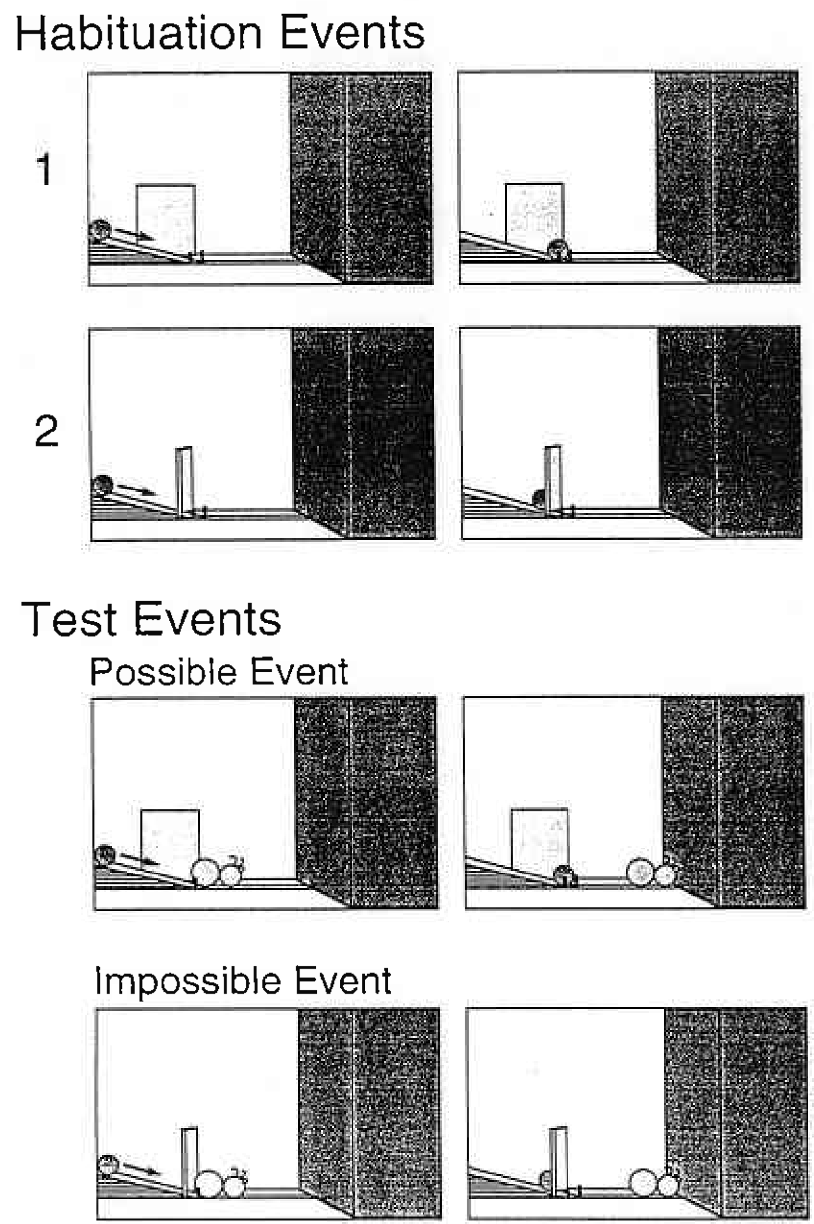

Fig. 9. Schematic drawing of the test events used in Kotovsky and Baillargeon (1995c, Exp. 2).

across the ramp so that the cylinder now hit the barrier rather than the bug; nevertheless, the bug again rolled down the track, as in the possible event.

The infants tended to look equally at the two habituation events, but looked reliably longer at the impossible than at the possible test event. Together, these results suggested that the infants were surprised to see the bug move when the cylinder hit the barrier rather than the bug. An experiment is in progress to provide further support for this interpretation.

Continuous variable: Size of the moving object. The results of our initial experiments indicated that by 2.5 months of age, infants expect a stationary object to be displaced when hit by a moving object. Our next experiments asked whether infants realize that how far a stationary object is displaced, when hit by a moving object, depends on the moving object's size (or, more precisely, mass; however, because our data are insufficient to judge whether infants considered the moving object's size or mass, I will refer only to its size). Subjects in the experiments were 11- (Kotovsky & Baillargeon, 1994) and 6.5- (Kotovsky & Baillargeon, 1995a) month-old infants. Because similar findings were obtained with the two age groups, only the experiment with the younger infants is described.

The apparatus and stimuli in this experiment (Kotovsky & Baillargeon, 1995a) were similar to those used in the previous experiments, except that the track was much longer (see Figure 10). The infants in the midpoint condition were habituated to a blue, medium-size cylinder that rolled down the ramp and hit the bug, causing it to roll to the middle of the track. Two new cylinders (constructed of the same material as the habituation cylinder) were introduced in the test events: a yellow cylinder that was larger than the habituation cylinder, and an orange cylinder that was smaller than the habituation cylinder. Both cylinders caused the bug to travel farther than in the habituation event: The bug now stopped only when it reached the end of the track and hit the right wall of the apparatus.[4]

When asked how far the bug would roll when hit by any one cylinder, adult subjects were typically reluctant to hazard a guess: They were aware that the length of the bug's trajectory depended on a host of factors (e.g., the weight of the cylinder and bug, the smoothness of the ramp and track, and so on) about which they had no information. After observing that the

[4]Because observers could determine from available sound cues in each trial which cylinder was used and how far the bug rolled, special steps were taken to ensure that the primary observer remained blind to the condition to which the infant was assigned. Specifically, different primary observers were used to monitor the infant's looking times in the habituation and test trials. During the habituation phase of the experiment, one of the primary observers left the experimental room so that the sounds that accompanied the bug's displacement did not clue him or her as to the infant's test condition. The same approach was used in the other collision experiments described later in the chapter.

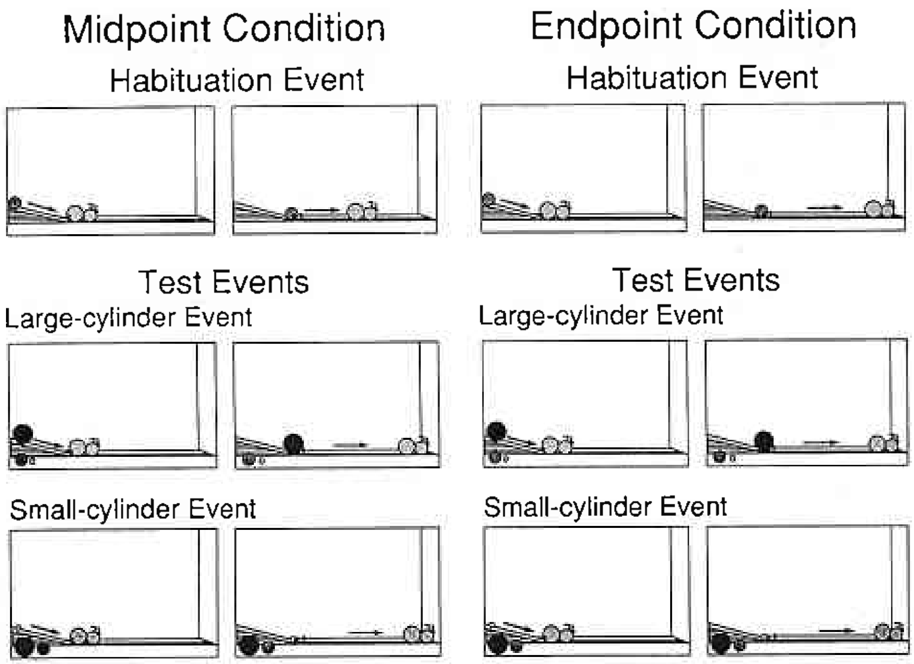

Fig. 10. Schematic drawing of the test events used in Kotovsky and Baillargeon (1995a, Exp. 1).

bug rolled to the middle of the track when hit by the medium cylinder, however, adult subjects readily predicted that the bug would roll farther with the larger and less far with the smaller cylinder and were surprised when this last prediction was violated. The experiment thus tested whether 6.5-month-old infants, like adults, (a) would understand that the size of the cylinder affected the length of the bug's displacement, and (b) would be able to use the information conveyed in the habituation event to calibrate their predictions about the test events.

A second group of infants (endpoint condition) was tested in a condition identical to the midpoint condition except that they were given a different calibration point in the habituation event. As shown in Figure 10, the medium cylinder now caused the bug to roll to the end of the track, just as in the test events.

After seeing that the bug rolled to the end of the track when hit by the medium cylinder, adult subjects (a) expected the bug to do the same with the large cylinder, and (b) were not surprised to see the bug do the same with the small cylinder (subjects simply concluded that the track was too short to show effects of cylinder size). The experiment thus tested whether 6.5-month-old infants, like adults, would perceive both of the endpoint condition test events as possible.

The results indicated that 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. Together, these results indicated that the infants (a) were aware that the size of the cylinder should affect the length of the bug's trajectory, and (b) used the habituation event to calibrate their predictions about the test events. After watching the bug travel to the middle of the track when hit by the medium cylinder, the infants were surprised to see the bug travel farther with the smaller but not the larger cylinder. In contrast, after watching the bug travel 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 small or the large cylinder.

In a subsequent experiment, 5.5-month-old infants were tested with the procedure used in the midpoint condition (Kotovsky & Baillargeon, 1995a). The performance of the female infants was identical to that of the 6.5-month-old infants, suggesting that they were surprised to see the bug roll to the end of the track with the small but not the large cylinder. This interpretation was supported by an additional experiment in which 5.5-month-old female infants were shown the endpoint condition events. Like the 6.5-month-old infants, these infants looked equally at the small- and the large-cylinder events.

In contrast to the female infants, the male infants who were shown the midpoint condition events tended to look equally at the small- and the large-cylinder events. These negative results suggested that the infants were not surprised, after seeing the medium cylinder cause the bug to roll to the middle of the track, to see the small cylinder cause the bug to roll to the end of the track. At least two interpretations could be advanced for this negative finding. One was that the male infants were still unaware that the size of the cylinder could be used to reason about the length of the bug's displacement. The other interpretation was that the male infants had difficulty remembering how far the bug traveled in the habituation event and hence lacked the necessary information to calibrate their predictions about the small and the large cylinders.

To examine this second interpretation, two groups of 5.5-month-old male infants were tested in a simple memory experiment (Kotovsky & Baillargeon, 1995a). The infants in the midpoint condition, as before, were habituated to the medium cylinder rolling down the ramp and hitting the bug, causing it to roll to the middle of the track (see Figure 11). Following habituation, the infants saw two test events. One (familiar test event) was identical to the habituation event. In the other event (novel test event), the

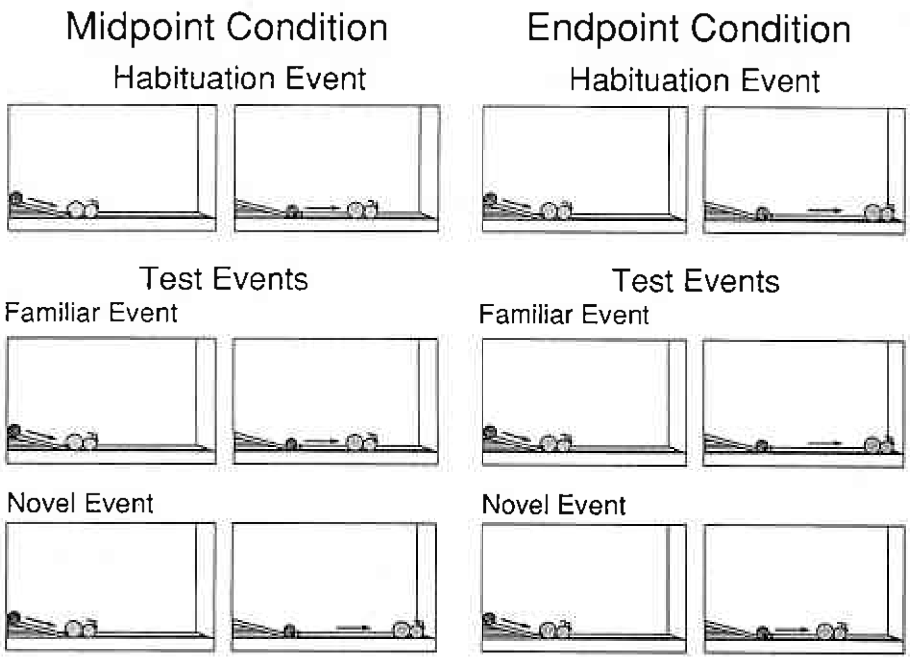

Fig. 11. *Schematic drawing of the test events used in Kotovsky and Baillargeon (1995a, Exp. 3).*

medium cylinder now caused the bug to roll to the end of the track. The infants in the endpoint condition saw similar habituation and test events, except that the bug rolled to the end of the track in the habituation event so that which test event was familiar and which novel was reversed.

The results revealed a significant overall preference for the novel over the familiar test event, indicating that the infants had no difficulty recalling how far the bug rolled in the habituation event. Such a finding, combined with the negative finding obtained in the last experiment, suggests the following conclusion: After observing that the medium cylinder causes the bug to roll to the middle of the track, 5.5-month-old male infants expect the bug to do so again when hit by the *same* cylinder, but have no expectation as to how far the bug should roll when hit by cylinders of different sizes. Infants seem unaware that they possess information they can use to reason about the novel cylinders.

Conclusions. Together, the results of the collision experiments reported here point to the following developmental sequence: By 2.5 months of age, infants expect a stationary object to be displaced when hit by a moving object; however, they are not yet aware that the size of the moving

object can be used to predict how far the stationary object will be displaced. If shown that a medium cylinder causes a bug to roll to the middle of a track, for example, infants have no expectation that the bug should travel farther when hit by a larger cylinder and less far when hit by a smaller cylinder. By 5.5 to 6.5 months of age, however, infants recognize not only that a stationary object should be displaced when hit by a moving object, but they also appreciate that how far the stationary object is displaced depends on the size of the moving object.

One interpretation of these findings is that when learning about collision events between a moving and a stationary object, infants first form an initial concept centered on an impact/no-impact distinction. With further experience, infants begin to identify variables that influence this initial concept. By 5.5 to 6.5 months of age, infants realize that the size of the moving object can be used to predict how far the stationary object will be displaced.

3. Knowledge About Unveiling Phenomena

Initial concept: Presence of a protuberance in a cloth cover. Our experiments on unveiling phenomena have involved problems in which a cloth cover is removed to reveal an object. Our first experiment examined whether 9.5-month-old infants realize that the presence (absence) of a protuberance in a cover signals the presence (absence) of an object beneath the cover (Baillargeon & DeVos, 1995a). At the start of the possible event, the infants saw two covers made of a soft, fluid fabric; the left cover lay flat on the floor of the apparatus, and the right cover showed a marked protuberance (see Figure 12). Next, two screens were pushed in front of the covers, hiding them from view. A hand then reached behind the right screen and reappeared first with the cover and then with a toy bear of the same

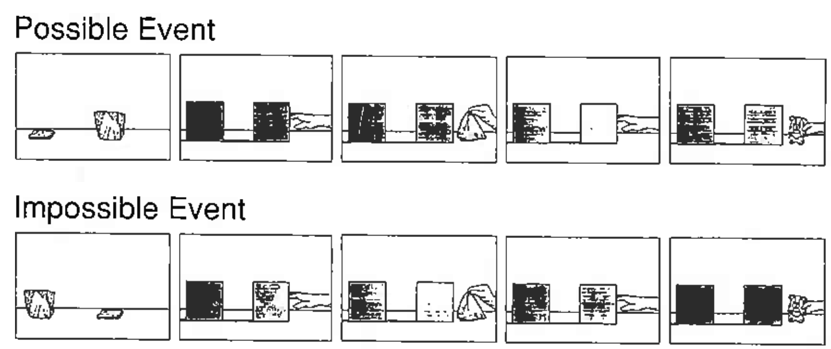

Fig. 12. *Schematic drawing of the test events used in Baillargeon and DeVos (1995a, Exp. 1).*

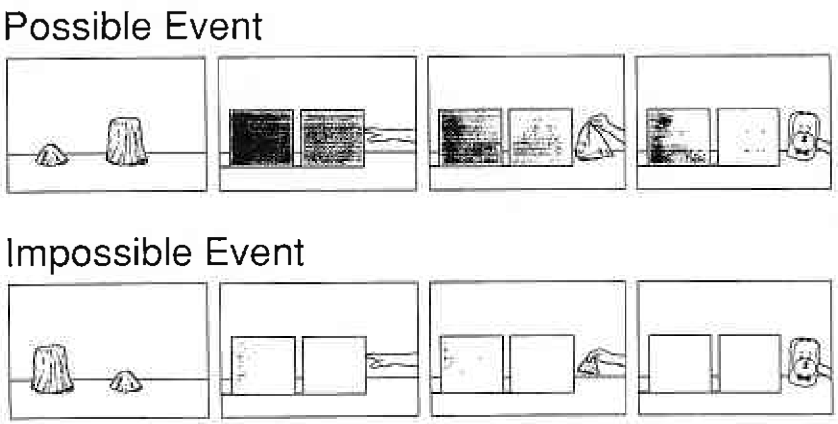

Fig. 13. *Schematic drawing of the test events used in Baillargeon and DeVos (1995a, Exp. 2).*

height as the protuberance shown earlier; the hand waved the bear gently to the side of the screen until the computer signaled that the trial had ended.[5] The impossible event was identical except that the location of the two covers at the start of the event was reversed, so that it should have been impossible for the hand to retrieve the bear.

The infants looked reliably longer at the impossible than at the possible event, suggesting that they understood that the bear could have been hidden under the cover with a protuberance but not the flat cover. This interpretation was supported by the results of a second condition in which the hand reached behind the left as opposed to the right screen, so that the location of the two covers in the impossible and the possible events was reversed.

Continuous variable: Size of the protuberance. The results of our first experiment indicated that by 9 months of age, infants can use the existence of a protuberance in a cloth cover to infer the existence of an object beneath the cover. Our next experiment (Baillargeon & DeVos, 1995a) investigated whether infants could also use the size of the protuberance to infer the size of the object under the cover (see Figure 13). At the start of the possible event, the infants saw two covers made of a soft fabric: On the left was a small cover with a small protuberance; on the right was a large cover with a large protuberance (the small protuberance was 10.5 cm high, and the large protuberance, 22 cm high; the difference between the two was thus easily detectable). Next, screens were pushed in front of the covers, and a gloved hand reached behind the right screen twice in succession, reappearing first

[5]In this experiment and all succeeding unveiling experiments, the possible and impossible events were presented only once per trial.

with the cover and then with a large toy dog 22 cm in height. The impossible event was identical to the possible event except that the location of the two covers at the start of the event was reversed, so that the hand now appeared to retrieve the large dog from under the cover with the small protuberance.

Unlike the infants in the last experiment, the infants in this experiment tended to look equally at the impossible and the possible events, suggesting that they believed that the large dog could have been hidden under the cover with either the small or the large protuberance. The same result was obtained in a subsequent experiment that made use of a slightly different procedure (Baillargeon & DeVos, 1995a). How should these negative findings be explained? At least two hypotheses could be proposed. One was that the infants were not yet aware that the size of the protuberance in each cover could be used to infer the size of the object hidden beneath the cover. The other explanation was that the infants recognized the significance of each protuberance's size, but had difficulty remembering this information after the cover was hidden from view.

The results of another experiment provided evidence for the first of these two interpretations. The infants in this experiment (Baillargeon & DeVos, 1995b) were given a reminder of the size of the protuberance in the cover behind the screen (see Figure 14). Subjects were 9.5- and 12.5-month-old infants. At the start of the possible event, the infants saw the cover with the small protuberance; to the right of this cover was a second, identical cover. After a brief pause, the first cover was hidden by the screen; the second cover remained visible to the right of the screen. Next, the hand reached behind the screen's right edge and removed first the cover and then a small toy dog 10.5 cm in height. The hand held the small dog next to the visible cover, allowing the infants to directly compare their sizes. The impossible event was identical to the possible event, except that the hand retrieved the large toy dog (22 cm in height) from behind the screen.

The 12.5-month-old infants looked reliably longer at the impossible

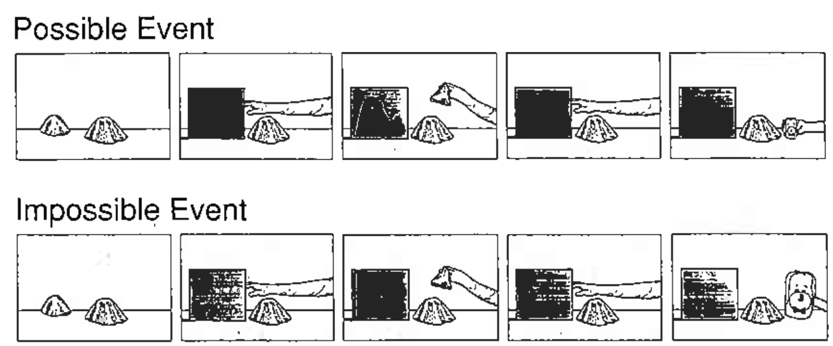

Fig. 14. *Schematic drawing of the test events used in Baillargeon and DeVos (1995b, Exp. 2).*

than at the possible event, suggesting that they realized that the small but not the large dog could have been hidden under the cover behind the screen. This interpretation was supported by the results of a control condition in which the infants simply saw each dog held next to the visible cover (as in the rightmost panels in Figure 14); no reliable preference was found for the large- over the small-dog display.

In contrast to the 12.5-month-old infants, the 9.5-month-old infants tended to look equally at the impossible and the possible events. Thus, despite the fact that the infants had available a reminder—an exact copy—of the cover behind the screen, they still failed to show surprise at the large dog's retrieval. It could be objected that infants less than 12.5 months of age might be unable, when reasoning about hidden objects, to take advantage of reminders such as the visible cover. As well be seen in a later section (section III. B. 3), however, even young infants can use visual reminders to make predictions about hidden objects.

Conclusions. The results summarized here suggest the following developmental sequence: By 9 months of age, infants realize that the existence of a protuberance in a cloth cover signals the existence of an object beneath the cover; they are surprised to see an object retrieved from under a flat cover but not from under a cover with a protuberance. However, infants are not yet aware that the size of the protuberance can be used to infer the size of the hidden object. When shown a cover with a small protuberance, they are not surprised to see either a small or a large object retrieved from under the cover. Furthermore, providing a reminder of the protuberance's size has no effect on infants' performance. Under the same conditions, however, 12.5-month-old infants show reliable surprise at the large object's retrieval.

One interpretation of these findings is that when learning about unveiling phenomena infants first form an initial concept centered on a protuberance/no-protuberance distinction. Later on, infants identify a continuous variable that affects this concept: They begin to appreciate that the size of the protuberance in a cover can be used to predict the size of the object hidden under the cover.

4. Further Developments

In the preceding sections, it has been argued that infants' knowledge about physical phenomena develops in a regular pattern, with infants first identifying all-or-none concepts and later adding discrete and continuous variables to these concepts.

This sketchy description may suggest a rather static view of development in which accomplishments, once attained, are retained in their initial forms. Such a characterization is unlikely to be valid, however. Additional

data suggest that development involves not only the identification but also the progressive revision of variables over time.

Revising a support variable. To illustrate, I return to the finding (see earlier section III. A. 1) that by 6.5 months of age infants consider how much contact exists between a box and a platform when judging the box's stability (Baillargeon et al., 1992). In subsequent experiments (Baillargeon & Raschke, 1995), we asked *how* infants assess the amount of contact needed between a box and a platform for the box to be stable. Do infants judge, for example, that any box will be stable as long as 50% or more of its bottom surface is in contact with the platform? Or do infants take into account the box's shape (or, more precisely, mass distribution) in determining how much contact is needed to ensure the box's stability?

To decide between these two hypotheses, 12.5-month-old infants were shown a possible and an impossible static display involving an asymmetrical, L-shaped box and a platform (see Figure 15). In each test display, exactly 50% of the box's bottom surface was in contact with the platform. In the possible display, the vertical, heavier portion of the box lay on the platform; in the impossible display, the horizontal, lighter portion of the box rested on the platform. In both displays, a gloved hand pointed at the box to call the infants' attention to it.

Different looking patterns were obtained with the older and younger infants in the sample. The infants aged 12.5 to 13 months looked reliably longer at the impossible than at the possible display, suggesting that they (a) recognized that the box was adequately supported when its vertical but not its horizontal portion rested on the platform, and hence (b) were surprised in the impossible display that the box did not fall. A control condition in which the hand grasped the box confirmed this interpretation.

The infants aged 12 to 12.5 months, in contrast to the older infants, tended to look equally at the impossible and the possible displays, suggesting that they believed that the box was adequately supported in each display. An alternative interpretation for this negative finding, however, was that the static procedure used in the experiment was ill-suited to test infants less than 12.5 months of age.[6]

[6]Our use of a static procedure in these experiments was dictated by pilot data obtained with 9.5- and 12.5-month-old infants tested in the 15% condition described earlier (see section III. A. 1). Unlike the 6.5-month-old infants in our initial experiment (Baillargeon et al., 1992), these older infants tended to look equally at the impossible and the possible test events. We eventually came to the conclusion that the infants were not surprised by the impossible event because they were able to generate an explanation for how it was produced (e.g., a metallic noise originating behind the box could be heard whenever it moved). This interpretation placed us in the unenviable position of inept magicians who fail to draw gasps of surprise from their audience because their tricks are too readily understood! We therefore set about improving our magic, so to speak, and eventually settled on the static procedure illustrated in Figure 15. See Baillargeon (1994) for a discussion of infants' ability to generate explanations for surprising events.

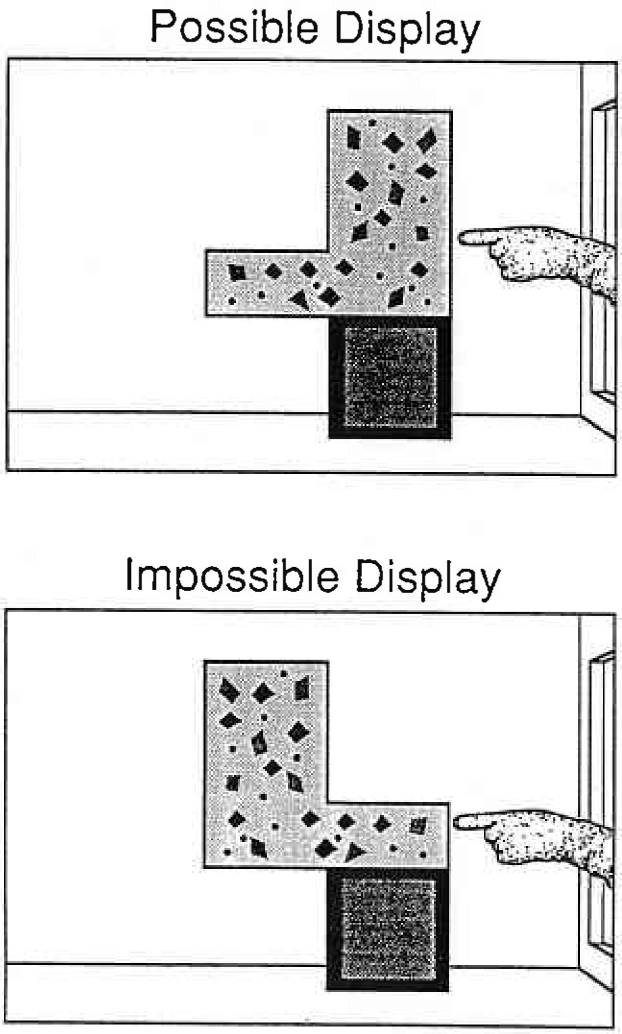

Fig. 15. Schematic drawing of the test events used in Baillargeon and Raschke (1995, Exp. 1).

To investigate this possibility, additional infants aged 12 to 12.5 months were tested in a follow-up experiment (Baillargeon & Raschke, 1995). Half of the infants were assigned to a 40% and half to a 50% condition. The infants in the 40% condition saw test displays involving a large, symmetrical box (equal in width and height to the L-shaped box used in the previous experiment) and a platform (see Figure 16). In the possible display, the box rested fully on the platform. In the impossible display, only 40% of

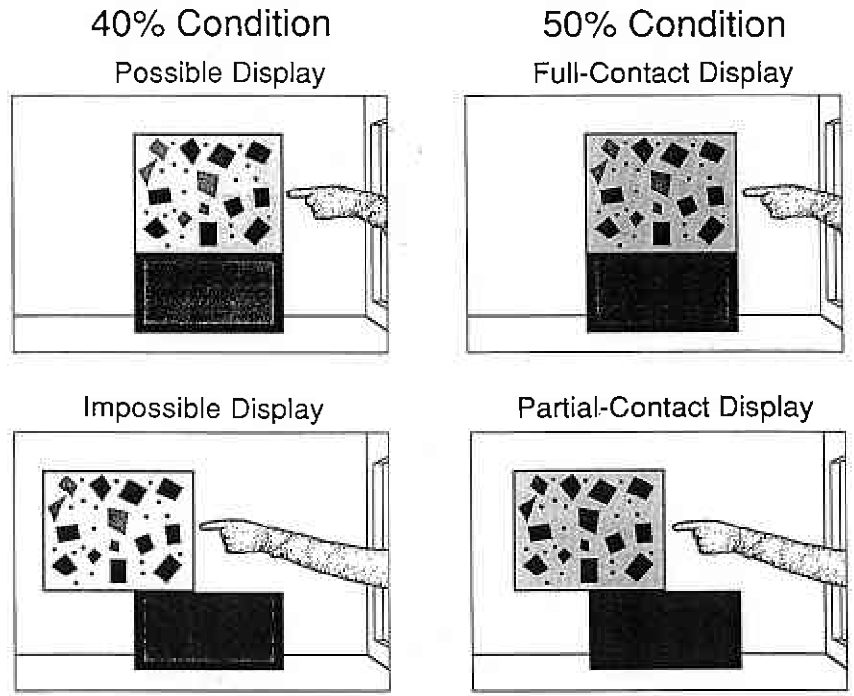

Fig. 16. Schematic drawing of the test events used in Baillargeon and Raschke (1995, Exp. 2).

the box's bottom surface lay on the platform. The infants in the 50% condition saw identical test events except that 50%, instead of 40%, of the box's bottom surface rested on the platform.

The results indicated that the infants in the 40% condition looked reliably longer at the impossible than at the possible display, whereas the infants in the 50% condition tended to look equally at the test displays they were shown. These results suggested that the infants (a) judged that the box was adequately supported when 50%, but not 40%, of its bottom surface lay on the platform, and hence (b) expected the box to fall in the impossible display and were surprised that it did not. This interpretation was confirmed in a control condition in which infants saw versions of the 40% condition test displays in which the hand fully grasped the box.

The results of this last experiment provided clear evidence that the negative finding obtained with the infants aged 12 to 12.5 months in the L-shaped box experiment were not due to these younger infants' inability to reason about static displays. Rather, the results suggested that the infants treated the L-shaped box just as they did the symmetrical box in the 50%

condition and judged in each case that the box should be stable because at least half of its bottom surface rested on the platform.

This line of reasoning suggested that infants aged 12 to 12.5 months should expect the L-shaped box to fall when 40%, as opposed to 50%, of its bottom surface was supported. A final experiment was undertaken to evaluate this prediction (Baillargeon & Raschke, 1995). The displays were identical to the 40% condition displays in the last experiment, except that the symmetrical box was replaced by the L-shaped box used earlier (see Figure 17). The infants looked reliably longer at the impossible than at the possible display, suggesting that they now perceived the L-shaped box to be inadequately supported. A control condition in which the hand holds the box is under way to confirm this interpretation.

Together, the results of these experiments indicate that prior to 12.5 months of age, infants believe that a box, whether symmetrical or not, will be stable as long as 50% or more of its bottom surface is in contact with a platform. At about 12.5 months of age, however, infants begin to appreciate that, unlike a symmetrical box, an unsymmetrical box may be unstable even if 50% of its bottom surface rests on a platform.

The present data are not sufficient to determine exactly how infants aged 12.5 months and older judge what amount of contact an asymmetrical box needs to be supported. Do infants compare the proportion of the box on and off the platform and conclude that the box will be stable when the former is equal to or larger than the latter? Do infants look for the box's geometric center and assess whether or not it lies above the platform? Future research will no doubt help decide between these and other possibilities.

Despite their limitations, the present data make clear that an important change or revision occurs at the end of the first year of life in how infants evaluate the amount of contact an object resting on a platform requires to remain stable. From a simple rule that any object can be stable as long as half or more of its bottom surface lies on the platform, infants progress to a more complex stance in which the overall shape of the object is taken into account in deciding how much of its bottom surface must rest on the platform.

Revising a collision variable. Findings discussed in an earlier section indicated (section III. A. 2) that 6.5-month-old infants realize when observing a collision between a moving and a stationary object that the size of the moving object affects the length of the stationary object's displacement (Kotovsky & Baillargeon, 1995a). At least two revisions might take place with development. First, infants might become aware that the size of the moving object affects not only how far but also how fast the stationary object is displaced (see Kotovsky & Baillargeon, 1994, for a discussion of

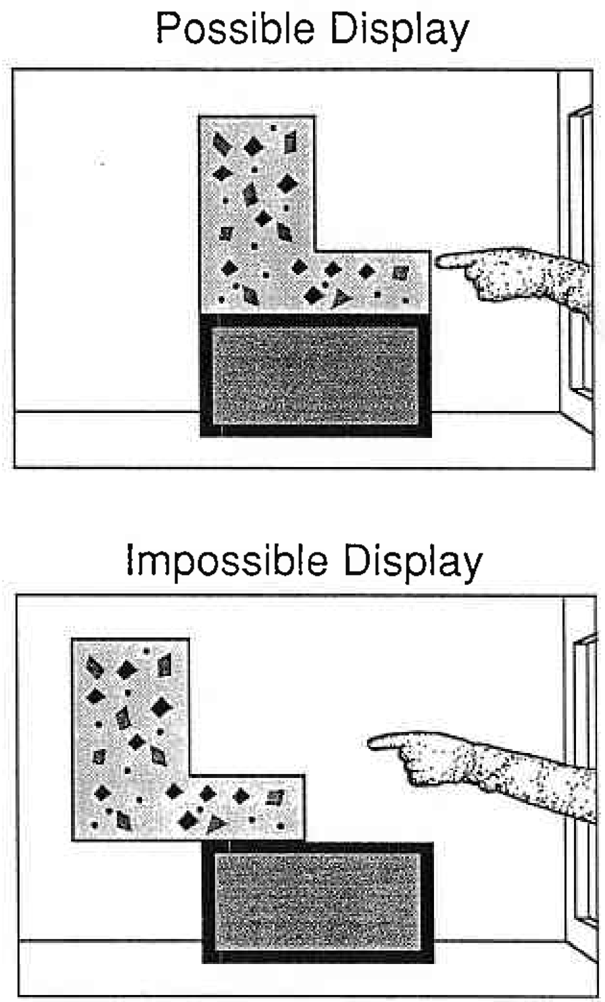

Fig. 17. Schematic drawing of the test events used in Baillargeon and Raschke (1995, Exp. 3).

this issue). Second, infants might come to realize that the mass, rather than the size, of the moving object affects the length and the speed of the stationary object's trajectory.

Whether such revisions occur is unknown at the present time (i.e., it is possible that infants appreciate from the start the multiple effects of the moving object's mass on the stationary object's displacement). Despite their speculative nature, such revisions are useful to contemplate because they help give a sense of how infants' knowledge about variables might be elaborated over time, through both the redefinition of variables (e.g., mass rather than size) and the identification of additional effects (e.g., speed as well as distance).

5. Mechanisms of Change

How can the various developmental sequences described earlier be explained? The present model assumes that these sequences reflect not the gradual unfolding of innate beliefs, but the application of highly constrained, innate learning mechanisms to available data (for a comparison of the present model to models that posit innate beliefs about objects, such as the models of Spelke [1991; Spelke, Phillips, & Woodward, in press] and Leslie [1988, in press], see Baillargeon, in press-a; Baillargeon et al., in press). In the present approach, the problem of explaining the age at which specific initial concepts and variables are understood is that of determining (a) what data—observations or manipulations—are necessary for learning, and (b) when these data become available to infants.

To illustrate, consider the developmental sequence revealed in the support experiments described in an earlier section (section III. A. 1). One might propose that 3-month-old infants have already learned that objects fall when released in mid-air (Needham & Baillargeon, 1995) because this expectation is consistent with countless observations (e.g., watching their caretakers drop peas in pots, toys in baskets, clothes in hampers) and manipulations (e.g., noticing that their pacifiers fall when they open their mouths) available virtually from birth.

Furthermore, one might speculate that infants do not begin to recognize until 4.5 months (Baillargeon et al., 1995) what type of contact is needed between objects and their supports because it is not until this age that infants have available pertinent data from which to abstract this variable. Researchers have found that unilateral, visually guided reaching emerges at about 4 months of age (e.g., Newell, Scully, McDonald, & Baillargeon, 1989; White, Castle, & Held, 1964). With this new-found ability, infants may have the opportunity to deliberately place objects against other objects and to observe the consequences of these actions. The sex difference revealed in our experiment, in this account, would be traceable to female infants engaging in these manipulations slightly ahead of the male infants.

In a similar vein, one could suggest that it is not until 6.5 months that infants begin to appreciate how much contact is needed between objects and their supports (Baillargeon et al., 1992) because, once again, it is not until this age that infants have data available from which to learn such a variable. Investigators have reported that the ability to sit without support emerges at about 6 months of age; infants then become able to sit in front of tables (e.g., on a parent's lap or in a high chair) with their upper limbs and hands

relieved from the encumbrance of postural maintenance and thus free to manipulate objects (e.g., Rochat & Bullinger, in press). For the first time, infants may have the opportunity to deposit objects on tables and to note that objects tend to fall unless a significant portion of their bottom surfaces is supported.

In the natural course of events, infants would be unlikely to learn about variables such as type or amount of contact from visual observation alone, because caretakers rarely deposit objects against vertical surfaces or on the edges of horizontal surfaces. There is no a priori reason, however, to assume that infants could not learn such variables if given appropriate observations. We return to this possibility in a later section.

B. Infants' Reasoning Strategies

Computational models of everyday physical reasoning (e.g., Forbus, 1984) commonly distinguish between two types of reasoning strategy, qualitative and quantitative. A strategy is said to be *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 A's size or distance from B). In contrast, a strategy is said to be *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).

Recent evidence suggests that after identifying a continuous variable as being relevant to a phenomenon, infants are able to reason about the variable, first, qualitatively and only after some time, quantitatively.

To illustrate the distinction between qualitative and quantitative strategies, I will report experiments on the development of infants' ability to reason about collision, unveiling, and arrested-motion phenomena.

1. Reasoning About Collision Phenomena

Findings reported in an earlier section (section III. A. 2) indicated that 6.5-month-old infants and 5.5-month-old female infants were surprised after observing that a medium-size cylinder caused a bug to roll to the middle of a track to see the bug roll farther when hit by a smaller but not a larger cylinder (Kotovsky & Baillargeon, 1995a). These and other findings indicated that the infants were aware that the size of the cylinder affected the length of the bug's trajectory.

In these experiments, each test event began with a pretrial in which the small, medium, and large cylinders lay side by side at the front of the apparatus. A gloved hand tapped on the cylinder to be used in the event (e.g., the small cylinder in the small-cylinder event). After the computer signaled that the infant had looked at the cylinder for 4 cumulative seconds, the hand grasped the cylinder and deposited it at the top of the ramp to begin the test event proper. The pretrial was included to enable the infants to directly compare the sizes of the cylinders.

In a subsequent experiment (Kotovsky & Baillargeon, 1995b), 6.5- and 7.5-month-old infants saw habituation and test events identical to those used in the midpoint condition in our initial experiments, with one exception: Only one cylinder was present in the apparatus in each event. During the pretrial preceding each test event, the gloved hand again tapped on the cylinder, but the other cylinders were absent so that the infants were no longer able to visually compare the cylinders' sizes. Under these conditions, the 6.5-month-old infants no longer showed surprise when the small cylinder caused the bug to roll to the end of the track; only the 7.5-month-old infants looked reliably longer at the impossible than at the possible event.[7]

Our interpretation of these results is that at 5.5 to 6.5 months of age infants are able to reason about the cylinder's size only qualitatively: They can predict the effect of modifications in the cylinder's size only when they are able to encode such modifications in relative terms (e.g., "this cylinder is smaller than the one next to it, which was used in the last trial"). When infants are forced to encode and compare the absolute sizes of the cylinders, because the cylinders are never shown side by side, they fail the task. By 7.5 months of age, however, infants have overcome this initial limitation and succeed in our task even when they must rely on their representation of the absolute size of each cylinder to do so.

2. Reasoning About Unveiling Phenomena

Results reported in an earlier section (section III. A. 3) indicated that 12.5-month-old infants were surprised to see a large but not a small toy dog retrieved from under a cover with a small protuberance (Baillargeon & DeVos, 1995b). These and control results indicated that the infants were aware that the size of the protuberance in the cover could be used to infer the size of the object hidden under the cover.

In our initial experiment, the infants were tested with a second, identical cover present to the right of the screen. Each dog, after it was

[7]To confirm that the 7.5-month-old infants did not simply prefer the small- over the large-cylinder event, an additional group of infants was tested using the endpoint condition procedure described earlier (Kotovsky & Baillargeon, 1995a; see section III. A. 2), except that, once again, only one cylinder was present in the apparatus in each event. Like the 6.5-month-old infants in the endpoint condition in our earlier experiment, the 7.5-month-old infants looked about equally at the small- and the large-cylinder events.

retrieved from behind the screen, was held next to the visible cover, allowing the infants to compare in a single glance the size of the dog to that of the cover (see Figure 14). In a subsequent experiment (Baillargeon & DeVos, 1995b), 12.5- and 13.5-month-old infants were tested with the same test events, except that only one cover was present: The infants were no longer provided with a second cover to remind them of the size of the cover behind the screen (see Figure 18). Under these conditions, only the 13.5-month-old infants looked reliably longer at the impossible than at the possible event, suggesting that they were surprised to see the large but not the small dog retrieved from under the cover behind the screen. This interpretation was supported by a control condition in which a cover with a large rather than a small protuberance stood behind the screen.

The results of this last experiment suggested that the 12.5-month-old infants could not succeed at our task without a reminder of the size of the cover behind the screen. In our next experiment, we examined whether infants would be successful if a second, identical cover was again included in the test events, but was placed to the left rather than to the right of the screen (see Figure 19). The infants still had in their visual fields an exact copy of the hidden cover; however, they were no longer able to compare in a single glance the size of each dog to that of the visible cover. The results were once again negative: The infants failed to show surprise at the large dog's retrieval.

Together, the results of these unveiling experiments suggest that at 12.5 months of age, infants are able to reason about the size of the protuberance in the cover only qualitatively: They can determine which dog could have been hidden under the cover only if they are able to compare, in a single glance, the size of the dog to that of a second, identical cover (e.g., "the dog is bigger than the cover"). When infants are forced to represent the absolute size of the protuberance in the cover, they fail the task. By 13.5 months of

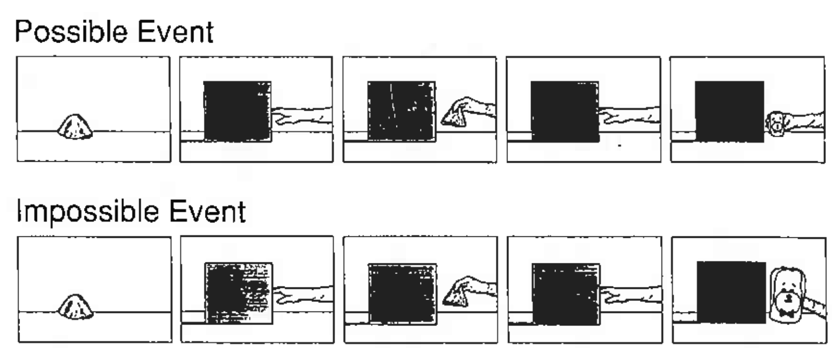

Fig. 18. Schematic drawing of the test events used in Baillargeon and DeVos (1995b, Exp. 1).

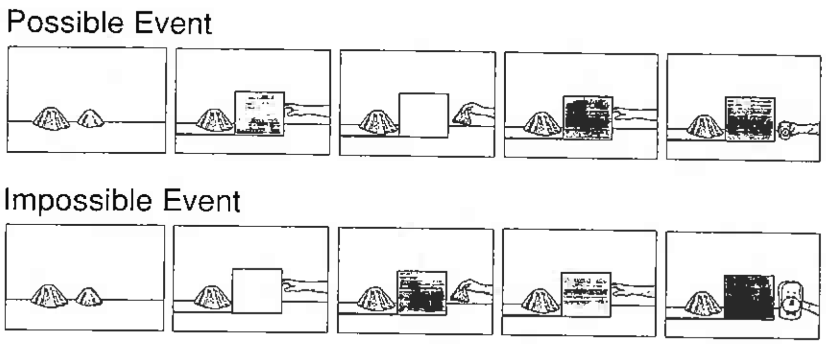

Fig. 19. *Schematic drawing of the test events used in Baillargeon and DeVos (1995b, Exp. 3).*

age, however, infants have already progressed beyond this initial limitation; they no longer have difficulty representing the absolute size of the protuberance and comparing it to that of each dog.

3. Reasoning about Arrested-Motion Phenomena

Our research on arrested-motion phenomena has focused on problems involving a large box placed in the path of a rotating screen. One experiment examined 4.5-month-old infants' ability to use the box's height and location to predict at what point the screen should reach the box and stop (Baillargeon, 1991). At the start of each habituation event (see Figure 20), the infants saw a screen that lay flat against the floor of the apparatus, toward them; the screen then rotated 180° about its distant edge until it lay flat against the apparatus floor, toward the back wall. Following habituation, a box was placed behind the screen; this box was progressively occluded as the screen rotated upward. In the possible event, the screen rotated until it reached the occluded box (112° arc). In the impossible event, the screen stopped only after it rotated through the top 80% of the space occupied by the box (157° arc)—to adults, it was an extreme and easily detectable violation.

A second group of infants (two-box condition) saw the same test events as the infants in the first (one-box) condition, with one exception: A second, identical box was placed to the right of and in the same fronto-parallel plane as the box behind the screen (see Figure 20). The second box stood out of the screen's path and thus remained visible throughout the test events. In the possible event, the screen stopped when aligned with the top of the second box; in the impossible event, the screen rotated past the top of the visible box.

The infants in the two-box condition looked reliably longer at the

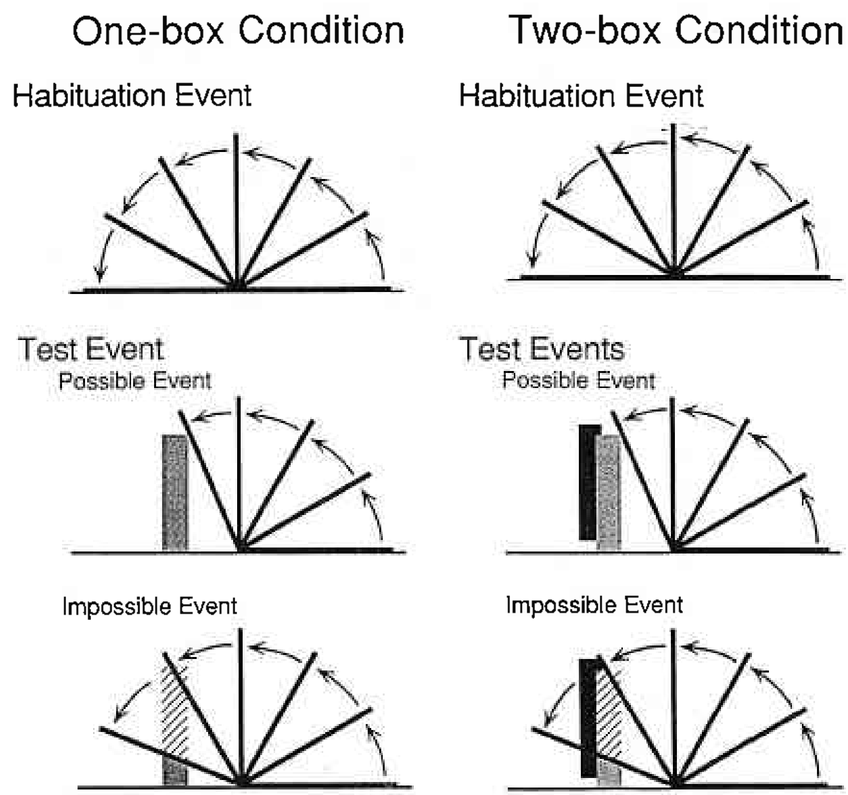

Fig. 20. *Schematic drawing of the test events used in Baillargeon (1991, Exp. 2).*

impossible than at the possible event, suggesting that they realized that the screen's 157° stopping point was inconsistent with the height and location of the occluded box. This interpretation was supported by a control condition in which the box behind the screen was removed; when only the box to the right of the screen was present, the infants tended to look equally at the events.

In contrast to the infants in the two-box condition, the infants in the one-box condition tended to look equally at the impossible and the possible events, as though they judged both the 112° and the 157° screen stopping points to be consistent with the box's height and location. Together, the results of the one- and two-box conditions indicated that the infants (a) were aware that the height and location of the box affected the screen's stopping point, but (b) could detect the 80% violation shown in the impossible event only when provided with a copy of the occluded box.

A subsequent experiment revealed that not only did 4.5-month-old infants require the presence of a second box to detect the 80% violation, but this box had to be placed in the same fronto-parallel plane as the occluded box (Baillargeon, 1991). When the second box was placed to the right but 10 cm in front of the box behind the screen, the infants no longer showed surprise at the screen's 157° stopping point (see Figure 21). In this experiment, the infants still had a reminder of the occluded box's height; however, they could no longer use a visual comparison strategy to solve the task. When the two boxes were in the same fronto-parallel plane, as in the first experiment, all that the infants needed to do to solve the task was to compare the height of the screen (at its stopping point) to that of the second

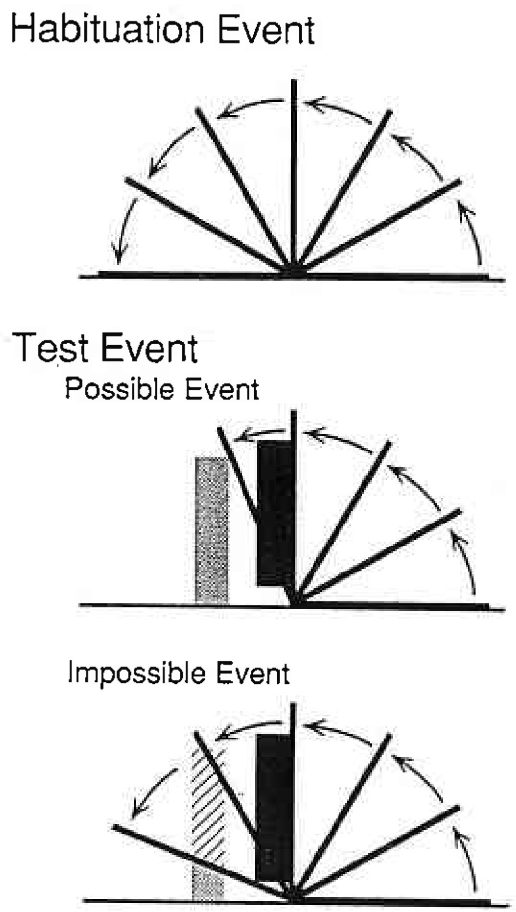

Fig. 21. Schematic drawing of the test events used in Baillargeon (1991, Exp. 4).

box. When the second box was in front of the occluded box, however, this alignment strategy was no longer valid, because the screen rotated past the top of the second box in both the possible and the impossible events.

The results of these experiments thus paralleled those obtained with 12.5-month-old infants in the unveiling experiments summarized in the last section (Baillargeon & Devos, 1995b). Recall that these infants were able to judge which dog could have been hidden under the cover behind the screen only when they could compare in a single glance the size of each dog to that of a second, identical cover. The infants failed the task when (a) no second cover was used, or (b) the location of the second cover did not allow direct visual comparison with each dog.

In a final experiment (Baillargeon, 1991), 6.5-month-old infants were tested in the one-box condition described earlier. Unlike the 4.5-month-old infants, these older infants looked reliably longer at the impossible than at the possible event, suggesting that they (a) represented the height and location of the occluded box; (b) used this information to estimate at what point the screen would reach the occluded box; and therefore (c) were surprised in the impossible event when the screen continued rotating past this point. A control condition carried out without the box supported this interpretation.

Together, the results of the experiments described earlier suggest that at 4.5 months of age, infants realize that when a box is placed in the path of a rotating screen, the box's height and location affect when the screen will stop. However, infants can reason only qualitatively about the screen's stopping point: They succeed at detecting violations only when they are able to visually compare the height of the screen to that of a second, identical box (e.g., "the screen is aligned with the top of the box"). When forced to reason about the absolute height and location of the box behind the screen, infants fail to detect even extreme violations. By 6.5 months of age, however, infants have progressed beyond this point; they can use their representation of the box's height and location to estimate at what point the screen will stop.

4. Further Developments

The results summarized in the preceding sections suggest that after identifying a continuous variable as being relevant to a physical phenomenon, infants typically succeed in using, first, qualitative and, only later, quantitative strategies to reason about the variable.

The preceding description might give rise to the expectation that development typically involves sequences in which each type of reasoning strategy is successively and fully mastered, in an all-or-none fashion. Additional results make clear, however, that such a characterization would be invalid. Just as variables appear to be revised and elaborated over time (see section III. A. 4), strategies too are perfected, becoming increasingly sophisticated and accurate over time.

Improvements in quantitative reasoning. We saw in the last section that 6.5-month-old infants are surprised, when a box is placed behind a rotating screen, to see the screen rotate through the top 80% of the space occupied by the box (Baillargeon, 1991). A subsequent experiment (Baillargeon, 1991) investigated whether infants this age would also detect a

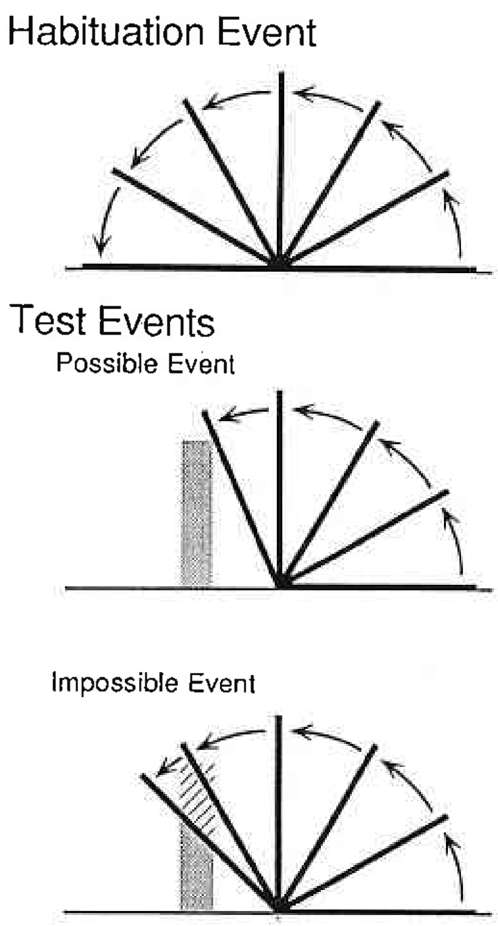

Fig. 22. Schematic drawing of the test events used in Baillargeon (1991, Exp. 1).

smaller, 50% violation (see Figure 22). Because the box used in these experiments was 25 cm high, the 50% violation, although smaller than the 80% violation, was still sizable (i.e., the screen rotated through the top 12.5 cm as opposed to the top 20 cm of the box).

In contrast to the infants presented with the 80% violation, however, the infants shown the 50% violation tended to look equally at the impossible and the possible events, as though they perceived both the 145° and the 112° screen stopping points to be consistent with the box's height and location. A pilot experiment conducted with 8.5-month-old infants, using a similar procedure, indicated that these infants, unlike the 6.5-month-old infants, had no difficulty detecting the 50% violation.

The results of these experiments suggest that after infants become able to reason quantitatively about a phenomenon, their ability to do so undergoes a rapid and dramatic development. Whereas 6.5-month-old infants are able to detect 80% but not 50% violations in a rotating screen task, 8.5-month-old infants readily detect both violations. At the present time, the source of these improvements is still unclear. Do infants become better at remembering the box's height and location? At using their representation of the box's height and location to predict the screen's stopping point? Or both? Future research will no doubt shed light on this issue.

Improvements in qualitative reasoning. The results reported earlier indicated that the 6.5-month-old infants tested with the rotating screen paradigm failed to detect the 50% violation (Baillargeon, 1991). In subsequent experiments (Baillargeon, 1991), both 6.5- and 4.5-month-old infants were found to readily detect such a violation, however, when a second, identical box was placed to the right and in the same fronto-parallel plane as the box behind the screen. (As was the case with the two-box experiments reported earlier, infants did not show surprise at the impossible screen rotation when the second box was placed to the right and slightly in front of the box behind the screen.)

A series of experiments (described in Baillargeon, 1993) was built on these positive findings and asked whether infants' ability to detect the 50% violation in the two-box condition was at all affected by the perceptual similarity of the occluded and the visible box. Adults would, of course, deem such similarity irrelevant: They would reason that as long as the two boxes were of the same height and were located the same distance from the screen, one box could be used to reason about the other. But would infants show the same capacity to overlook irrelevant differences in the boxes' appearances?

To find out, 6.5- and 4.5-month-old infants were again tested in the

50%, two-box condition described earlier. For all of the infants, the box visible to the right of the screen was a red box with white dots; the box behind the screen, however, varied between infants (see Figure 23): It was either (a) a red box with green dots (*high-similarity* condition); (b) a yellow box with green dots (*moderate-similarity* condition); or (c) a yellow box with a brightly colored clown face (*low-similarity* condition). (Clown boxes were used in all the preceding rotating screen experiments.)

The results indicated that the 6.5-month-old infants detected the 50% violation in the high- and moderate-similarity conditions, but not the low-similarity condition. In contrast, the 4.5-month-old infants detected the 50% violation only in the high-similarity condition. These results are intriguing because they suggest that just as infants' quantitative reasoning improves with development so does their qualitative reasoning: In scanning situations for objects that can be pressed into service as reference objects, infants may become increasingly adept at focusing on important similarities and dismissing irrelevant, superficial differences.

5. Mechanisms of Change

How should the developmental sequences described in the previous sections be explained? The model assumes that these sequences are unlikely to simply reflect the gradual maturation of infants' quantitative reasoning, because the same pattern recurs at different ages for different physical phenomena. To what other, phenomenon-specific changes should the sequences be attributed?

Cognitive overload. It might be argued that the qualitative/quantitative shifts described earlier stem primarily from a cognitive overload: When first learning to reason about a continuous variable, infants would fail whenever required to retrieve information about the variable from memory. On this view, the combined challenges of retrieving and processing the information about the variable would initially overwhelm infants, resulting in unsuccessful performances. With time, infants would become more adept at carrying the two tasks simultaneously, leading to positive outcomes.

Such an interpretation is consistent with the findings that infants perform better in the tasks described earlier when they can compare cylinders (collision experiments), protuberances and toys (unveiling experiments), and boxes (arrested-motion experiments) in a single glance. Nevertheless, there is some reason to suspect that this interpretation is incorrect, and that the sheer necessity of having to retrieve information from memory is not what constitutes infants' initial stumbling block in reasoning about continuous variables. The reason for this suspicion has to

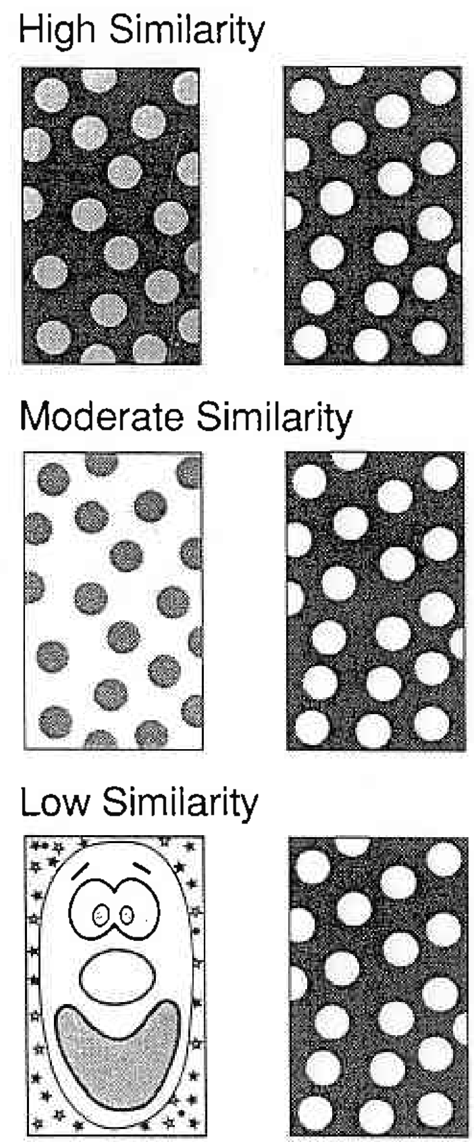

Fig. 23. Schematic drawing of the test events used in Baillargeon (1993).

do with infants' performance in the collision experiments reported earlier (Kotovsky & Baillargeon, 1995a, 1995b; see sections III A. 2 and III. B. 1). Recall that the 6.5-month-old infants in these experiments were surprised after watching a medium cylinder cause a bug to roll to the middle of a track to see the bug roll farther with a smaller cylinder. The infants showed surprise at the small-cylinder event, however, only when the experimental situation made it possible for them to directly compare the sizes of the two cylinders: The infants failed the task when forced to retrieve from memory the size of the medium cylinder.

Until now, our discussions of these results has always focused on the sizes of the cylinders, but what of the distance traveled by the bug? To detect the violation embedded in the small-cylinder event, the infants not only had to realize that the cylinder was smaller than the habituation cylinder, they also had to recall how far the bug rolled when hit by the habituation cylinder. Success in the task thus did necessitate the retrieval of information from memory. It is likely, however, that the information retrieved was qualitative rather than quantitative in nature. That is, the infants most probably encoded and remembered the length of the bug's trajectory in the habituation event, not in absolute terms (e.g., "the bug traveled x distance from the ramp," where x stands for some absolute measure of the length of the bug's displacement), but in relative terms using as their point of reference the track itself (e.g., "the bug rolled to the middle or the end of the track"), their own spatial position (e.g., "the bug stopped in front of me or rolled past me"), or the brightly decorated back wall of the apparatus (e.g., "the bug stopped in front of this or that portion of the back wall"). This interpretation argues against the hypothesis that infants are initially restricted to qualitative reasoning after identifying a continuous variable because the need to retrieve relevant information from memory occasions a cognitive overload.

Quantitative memory. An alternative explanation for the qualitative/quantitative shifts reported earlier is that when first reasoning about a continuous variable, infants have difficulty encoding or retaining absolute information about the variable. As infants become practiced at reasoning about the variable, however, this ability would rapidly improve.

Is it plausible to posit phenomenon-specific shifts in the ability to encode and retain absolute information? Everyday observations suggest a positive answer. For example, one might expect that upon being introduced to the business of selling fish, shoes, or diamonds, adults would rapidly improve in their ability to encode and retain absolute information about their wares. There is every reason to expect that young children undergo similar developments, as the following anecdotes may illustrate. Recently, my 3-year-old daughter Colette and I noticed a small red car (a Honda Civic) parked on the street in front of our house. Colette then asked why our babysitter had parked her car in the street rather than in the driveway, as she usually did. I was taken aback by Colette's comment because our babysitter (who has been coming to our house every weekday for years and often drives Colette in her car) drives a red but much larger car (a Mercury Cougar). When questioned, Colette reiterated that the car was that of her babysitter, failing to acknowledge the considerable difference in the two cars' sizes. Later that week, I gave Colette a new bottle of white glue. Colette first commented that it was the same kind of glue she used in her preschool; after a long pause, during which she carefully examined the bottle, she added that this bottle was smaller than the one in her classroom.

The contrast between these two anecdotes is intriguing: On the one hand, Colette failed to detect the very large size difference between a Honda and a Mercury; on the other hand, Colette was able to recognize that her new bottle of glue was smaller than the one she used at school. Such a contrast is consistent with the suggestion that individuals are generally poor at encoding and retaining absolute information about objects when such information is deemed of little interest or significance. As this perception changes, improvements soon follow.

Note that according to the explanation proposed here, infants would not be fundamentally incapable of quantitative reasoning when first making predictions about a continuous variable: They would merely be extremely poor at it. This distinction is important because it suggests that one might be able to create conditions under which infants would succeed in our tasks, for example, by using violations even larger than the onese we used, and/or by thoroughly familiarizing infants with the test objects before asking them to reason about their sizes. Experiments are planned to investigate these possibilities.

C. Future Directions

The research described in the previous sections suggests that in learning about a physical phenomenon, infants first form an all-or-none concept that captures the essence of the phenomenon and then add to this initial concept discrete and continuous variables found to be relevant to the phenomenon. Furthermore, after identifying continuous variables, infants succeed in reasoning, first, qualitatively and, only later, quantitatively about the variables. To gain further insight into the nature and causes of these two developmental patterns, we have adopted a dual research strategy.

1. Additional Phenomena

One strategy is to examine the development of infants' understanding of additional physical phenomena to see how easily these developments can be captured in terms of the patterns described in the model. Research already in the literature provides encouraging hints for future investigations. For example, Sitskoorn and Smitsman (1991) presented 6- and 9-month-old infants with a possible and an impossible containment test event. In both events, a large box with an open top rested on the apparatus floor, and a block was lowered into the box. In the possible event, the block was narrower than the box and hence could be contained in it; in the impossible event, however, the block was wider than the box and hence should not have been contained in it. The authors found that the infants looked longer at the impossible than at the possible event only when they were able to compare in a single glance the width of the block to that of the box. When a screen prevented such a comparison, the infants failed the task, even though the block and the box were still visible above and below the screen. One way of characterizing these findings is that, at 6 months of age, infants (a) are aware that the width of an object relative to that of a container determines whether the one can fit into the other, but (b) can reason about this variable only qualitatively by a direct visual comparison of the two widths. Future experiments could ask: Do infants go through an initial stage in which they expect that any object can be contained in any open container, regardless of their respective dimensions? Furthermore, is it the case that infants older than 9 months of age succeed in reasoning not only qualitatively (no-screen condition) but also quantitatively (screen condition) about containment events?

Research by Spelke and her colleagues (Spelke et al., 1992) also suggests intriguing avenues for future research. In one experiment, 4-month-old infants were habituated to a passing-through event in which a hand dropped a medium-sized ball behind a screen; after a few seconds, the screen was removed to reveal the ball resting on the lower of two horizontal surfaces, beneath a gap in the upper surface that was wider than the ball. Following habituation, the infants saw a possible and an impossible passing-through test event identical to the habituation event except that two new balls were introduced. In the possible event, the ball was smaller than the habituation ball; in the impossible event, the ball was larger than both the habituation ball and the gap in the apparatus's upper surface. The infants looked reliably longer at the impossible than at the possible event. This result suggests that, by 4 months of age, infants (a) are aware that the width of an object relative to that of a gap affects whether the one can pass through the other, and (b) are able to reason at least qualitatively about this variable (because the ball stood immediately beneath the gap, their sizes could be visually compared). Further experiments could ask: Is there an initial stage in which infants expect any object to go through any surface that presents a gap, regardless of their respective dimensions? Furthermore, after infants become aware that these dimensions matter, do they succeed in reasoning,

first, qualitatively and, only later, quantitatively about passing-through events?

In addition to experiments suggested by the above findings, Andrea Aguiar and I have recently undertaken experiments on the development of infants' understanding of occlusion phenomena. These experiments, although preliminary, are noteworthy because they mark a return to earlier findings (Baillargeon & DeVos, 1991) described at the start of this chapter. Recall that these findings indicated that 3.5-month-old infants are aware that the height of an object affects whether it will be visible when passing behind a screen with a window. At the time this experiment was completed, we viewed its findings as an endpoint: Our interest in occlusion phenomena began and ended with the demonstration that even young infants possess a notion of object permanence. Inspired by the developmental patterns identified in our subsequent experiments, however, we have now returned, armed with entirely new questions, to the study of infants' understanding of occlusion phenomena. Thus, current experiments are exploring whether infants go through an initial stage—for example, at 2.5 months of age—in which they consider neither object nor occluder variables in reasoning about occlusion events, but rather simply expect any object to be invisible when passing behind any screen. The data collected so far support the existence of such an initial stage. Future experiments will examine at what ages infants begin to take into account various object and occluder variables in predicting the outcome of occlusion events.

2. Teaching Experiments

The second strategy we are pursuing, in the hope of shedding light on the nature and properties of infants' innate learning mechanisms, is to attempt to teach infants initial concepts and variables they have not yet acquired. In an earlier section (section III. A. 1), we saw that 6.5- but not 5.5-month-old infants are aware that the amount of contact between a symmetrical box and a platform affects whether the box will be stable (Baillargeon et al., 1992). We speculated that infants identify the variable "amount of contact" when they begin to generate, through their own manipulations, data from which to learn it (see section III A. 5). But what if the data were made available to infants in a different way, through exposure to a carefully constructed set of observations? Would infants less than 6.5 months of age be able to learn, on the basis of such observations, that the amount of contact between a box and a platform must be taken into account when predicting the box's stability?

The interest of such teaching experiments is that they will help us understand what kinds of observations, and how many observations, infants require to learn. Assume, in the example given earlier, that training trials involve watching a gloved hand deposit a box on a platform in such a way that the box is either fully or only partially supported, with the box remaining stable in the first but not the second case. Would such observations lead infants to identify the variable "amount of contact"? How many times would infants need to see the observations for learning to occur? Would it be necessary to show infants different boxes and platforms during training to ensure an appropriate generalization? If yes, how many distinct instances would be required? We believe that answers to these and related questions will provide important insights into the nature and properties of infants' innate learning mechanisms.

IV. PHENOMENON-GENERAL FACTORS IN INFANTS' PHYSICAL REASONING

In the introduction, we proposed that an account of infants' reasoning about a phenomenon must include not only phenomenon-specific factors having to do with infants' mastery of the phenomenon, but also more general factors that concern the sophistication of infants' perceptual and information-processing capacities. In what follows, we consider three factors that have been shown to affect infants' reasoning about physical events: (a) how well infants can perceive the events; (b) what information infants attend to and encode when shown the events; and (c) how long infants are able to retain the information they encode about the events.

A. Infants' Perceptual Abilities

It can hardly be disputed that infants are unlikely to reason correctly about events they perceive only imperfectly. As an illustration, consider an experiment that examined 4-month-old infants' ability to reason about a collision, out of sight, between a moving and a stationary object (Baillargeon & DeVos, 1991). The infants sat in front of a small screen; to the left of this screen was an inclined ramp (see Figure 24). The infants were habituated to the following event: The screen was raised (to show the infants that there was nothing behind it) and lowered, and a toy car rolled down the ramp, passed behind the screen, and exited the apparatus to the right. Following habituation, the infants saw test events identical to the habituation event except that a large toy mouse stood behind the screen; this mouse was revealed when the screen was raised. In the possible event, the mouse was placed in back of the car's tracks; in the impossible event, the mouse stood on top of the car's tracks, blocking its path. The female infants looked reliably longer at the impossible than at the possible

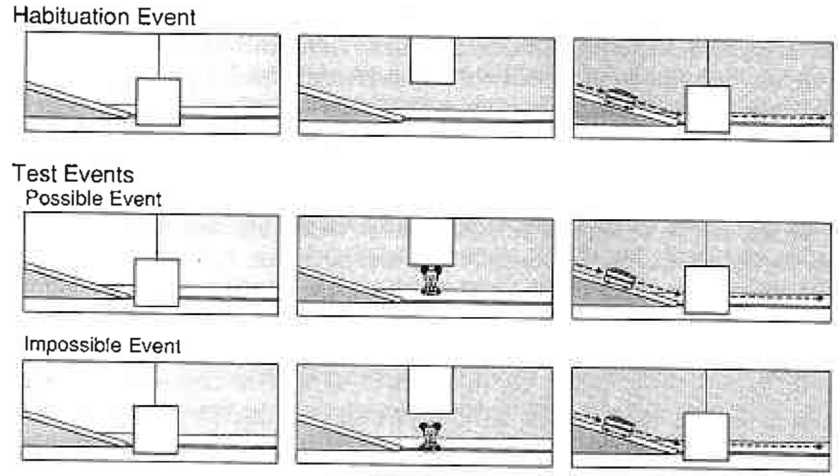

Fig. 24. Schematic drawing of the test events used in Baillargeon and DeVos (1991, Exp. 3).

event, suggesting that they were surprised to see the car roll past the screen when the mouse stood in its path. Control trials supported this interpretation. (Note that these findings do not tell us exactly what the female infants viewed as the most likely outcome of the collision between the car and the mouse – the car stopping against the mouse, or the car pushing the mouse some distance down the track.)

In contrast to the female infants, the male infants tended to look equally at the impossible and the possible events. Additional results indicated that 3.5-month-old female infants, like 4-month-old male infants, failed to show surprise at the impossible event. One explanation for these negative results is suggested by research on the development of depth perception. Experiments by Yonas and his colleagues (e.g., Yonas & Granrud, 1984; Yonas, Arterberry, & Granrud, 1987) have established that depth perception develops according to a regular sequence: Kinetic cues are used by infants at birth, binocular cues at about 4 months, and pictorial cues at about 7 months. Further research by Held and his colleagues (e.g., Gwiazda, Bauer, & Held, 1989a, 1989b; Held, in press) has shown that male infants lag behind female infants by 2 to 3 weeks in the development of binocular depth perception. Given this evidence, it is likely that the 4-month-old male infants and the 3.5-month-old female infants in our experiment failed to detect the violation embedded in the impossible event, not because they lacked the physical knowledge necessary to do so, but because they were unable to detect where the mouse stood relative to the car's path.

In a recent experiment, Cohen and Oakes (1992) tested 6- and 10-month-old infants using computer-generated, animated events similar to those in the experiment described above. Interestingly, these authors found that the 10- but not the 6-month-old infants preferred the impossible over the possible event. Because, as noted before, infants do not begin to use pictorial cues until 7 months of age, the negative findings obtained with the younger infants could easily be due to the fact that they lacked the perceptual skills necessary to correctly interpret the animated events they were shown (for a related discussion of experiments on support phenomena, see Baillargeon et al., in press).

B. Infants' Attentional Biases

Over the past few years, my colleagues and I have carried out several experiments in which infants failed to perform successfully, despite the fact that they possessed the physical knowledge, reasoning abilities, and perceptual skills necessary to do so. Although we were initially frustrated by these unexpected failures, we have come to see them in a much more positive light as reflections of the information infants do and do not spontaneously attend to when observing physical events.

When watching an event (e.g., a traffic accident), adults encode some but not all facets of the event (e.g., Irwin, 1991, 1992). As might be expected, infants are similar to adults in this respect: When shown possible or impossible events, infants attend to only some aspects of the events. In the case of impossible events, the information infants attend to is sometimes sufficient to detect the violations involved in the events; at other times, however, it is not. What is being proposed, then, is that infants sometimes fail to show surprise at impossible events simply because they are not attending to the relevant aspects of the events.

To date, we know little about the nature of the information infants spontaneously attend to when faced with physical events or about how this information changes with age, knowledge, or experience. What is clear, however, is that what information infants encode is highly context-sensitive: By manipulating the context in which an event is presented, we can often lead infants to attend to information that was ignored in the original context, thus ensuing a successful interpretation of the event.

To illustrate the effect of infants' attentional biases on their physical reasoning, I will describe the results of experiments that examined infants' reasoning about arrested-motion and occlusion phenomena.

1. Attending to Arrested-Motion Phenomena

We saw in an earlier section (section III. B. 3) that 4.5- and 6.5-month-old infants are able, under some conditions, to predict at what point a rotating

screen should encounter a box placed in its path. In earlier experiments, we asked a simpler question: Could infants aged 3.5 to 5.5 months predict that a rotating screen should stop when a box stands in its path (Baillargeon, 1987a; Baillargeon et al., 1985)? The infants were once again habituated to a screen that rotated back and forth through a 180° arc. Following habituation, a box was placed behind the screen, and the infants saw the two test events depicted in Figure 25. In the possible event, the screen rotated until it reached the box and then returned to its original position against the floor of the apparatus. In the impossible event, the screen rotated through a full 180° arc before it reversed direction and returned to its original position, revealing the box standing intact in the same location

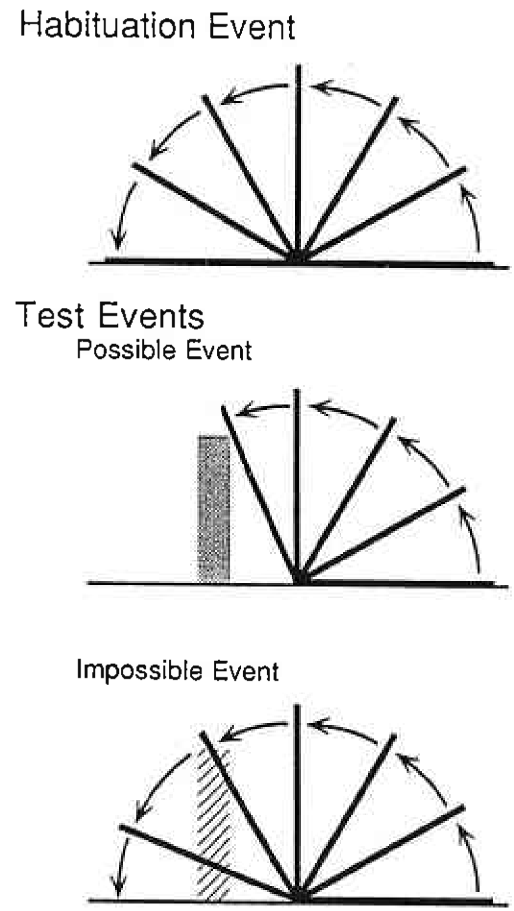

Fig. 25. Schematic drawing of the test events used in Baillargeon (1987a, Exp. 1).

as before. The results indicated that the 5.5-, and 4.5-, and even some of the 3.5-month-old infants looked reliably longer at the impossible than at the possible event, suggesting that they expected the screen to stop when the box stood in its path and were surprised in the impossible event that it did not. A control condition conducted without a box behind the screen supported this interpretation.

To adults, the impossible event used in these experiments is especially intriguing because it involves two violations. The first one occurs when the screen rotates backward through the space occupied by the box (first 180° rotation), and the second one occurs when the screen rotates forward to reveal the box standing intact behind it (second 180° rotation). In a recent experiment, we asked whether 6.5-month-old infants, like adults, were equally sensitive to both of these violations (Kotovsky, Mangione, & Baillargeon, 1995). The infants were assigned to the clown-first or the clown-last condition (see Figure 26). The infants in the clown-first condition saw a large toy clown standing behind a screen that lay flat against the apparatus floor, toward them. Next, the screen rotated upward, hiding the clown. In the possible event, the screen stopped against the clown; in the impossible event, the screen rotated through a full 180° arc, as though the clown were no longer behind it. The infants in the clown-last condition saw the same events as the infants in the clown-first condition, but in reverse. In

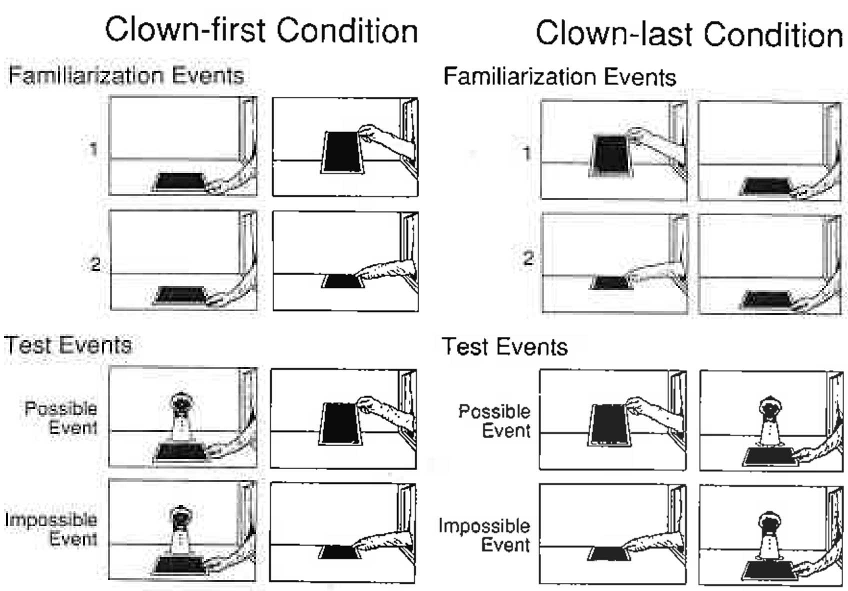

Fig. 26. Schematic drawing of the test events used in Kotovsky et al. (1995, Exp. 1).

the possible event, the screen first rested against the clown and was rotated forward to reveal it. In the impossible event, the screen first lay flat against the apparatus floor, toward the back wall, and was again rotated forward to reveal the clown behind it. At the start of the experiment, the infants in the two conditions saw familiarization events identical to the test events, except that the clown was absent. In both the familiarization and test events, the infants saw a single screen rotation per trial; events were not repeated within trials as they had been in our earlier rotating screen experiments.

The results indicated that the infants in the two conditions tended to look equally at the familiarization events they were shown. Different looking patterns were obtained with the test events, however; whereas the infants in the clown-first condition showed a reliable preference for the impossible over the possible event, the infants in the clown-last condition tended to look equally at the two events. Together, these results indicated that the infants readily detected the violation embedded in the clown-first but not the clown-last impossible event. In a subsequent experiment, 9.5-month-old infants were tested using the clown-last condition procedure; like the 6.5-month-old infants, these older infants failed to show surprise at the impossible event, suggesting that they too were unaware that the screen's position at the start of the event was inconsistent with the clown's presence. The negative results obtained with the 6.5- and 9.5-month-old infants were confirmed in a further experiment conducted with the same procedure except that the infants received no familiarization trials, only test trials (Kotovsky et al., 1995).

Why did the 6.5- and 9.5-month-old infants in these experiments fail to detect the violation shown in the clown-last impossible event? It seemed to us unlikely that the infants lacked the physical knowledge necessary to appreciate this violation: The results of the clown-first condition and of many related experiments (e.g., Baillargeon, 1986, 1991; Baillargeon & DeVos, 1991; Baillargeon et al., 1985, 1990; Spelke et al., 1992) indicated that even young infants recognize that (a) objects continue to exist when occluded, and (b) objects cannot move through the space occupied by other objects. A more plausible interpretation, we speculated, was that the infants in the clown-last condition did not attend to the orientation of the screen at the start of the event. Research on adult perception has demonstrated that information not attended to is typically not remembered (e.g., Irwin, 1991, 1992). If the infants did not attend to and did not remember the screen's orientation at the start of each event, they would have lacked the information necessary to determine whether this orientation was consistent with the clown's presence.

Could one create conditions under which infants would be more likely to attend to the screen's orientation at the start of each test event and hence to detect the violation shown in the clown-last impossible event? In a subsequent experiment, 6.5- and 9.5-month-old infants again watched the clown-last test events (Kotovsky et al., 1995). Prior to these events, however, the infants saw two static displays. In both displays, two screens stood side by side (see Figure 27): One lay flat against the apparatus floor, and the other rested against the (hidden) clown. The screens' location was reversed between displays. The results indicated that the infants now looked reliably longer at the impossible than at the possible event, suggesting that they realized that the clown could not have been hidden under the screen when it lay flat against the apparatus floor.

The results of the last experiment suggest that exposure to the static displays enhanced the infants' reasoning about the test events. How was this process accomplished? The present data are insufficient to offer a definite answer to this question. On the one hand, it may be that simultaneously seeing the two screens in the two different orientations highlighted these differences for the infants and thus made it more likely that they would attend to the screen's orientation at the start of each test event. On the other hand, seeing in each display a screen standing at an angle, without visible support, may have incited the infants to reflect on what could be propping up the screen and more generally to ponder whether objects were present behind that and the other flat screen. Future research will no doubt help determine which, if either, of these hypotheses is correct.

Together, the results of the experiments presented in this section suggest that young infants may fail to detect the violation embedded in an impossible arrested-motion event, not because they lack the necessary knowledge, reasoning strategies, or perceptual abilities, but because they do not attend to the significant aspects of the event. When the experimental context is modified to highlight this information, however, infants readily demonstrate their ability to attend to, remember, and use the information to correctly interpret the event.

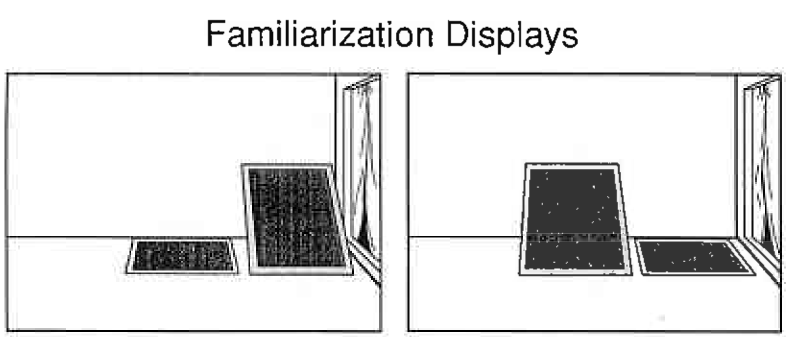

Fig. 27. Schematic drawing of the test events used in Kotovsky et al. (1995, Exp. 3).

2. Attending to Occlusion Phenomena

In the introduction, we reviewed an experiment whose findings indicated that by 3.5 months of age, infants appreciate that the height of an object can be used to predict whether it will be visible when passing behind a screen window (Baillargeon & DeVos, 1991). Recently, Arterberry (1993) asked at what age infants become aware that the width of an object affects how long it should be visible when passing behind a narrow window.

In her experiment, Arterberry (1993) habituated 8-, 10-, and 12-month-old infants to either a wide or a narrow rectangle moving back and forth along a horizontal track. Following habituation, a large screen with a small window was introduced; through this window, the infants could see the two rectangles undergoing the same motion as before. Because the window was very narrow and the two rectangles traveled at the same speed, no single view of either of the two rectangles through the window was sufficient to discriminate them; only temporal duration—that is, the amount of time that the rectangles were visible in the window—could be used to distinguish them and to recognize which had been seen during the habituation trials.

The 12-month-old infants looked reliably longer at the novel than at the familiar rectangle, suggesting that they (a) were aware that how long the rectangle took to pass behind the window was determined in part by the rectangle's width, and (b) they were able to judge whether the amount of time that the rectangle was visible in the window was consistent with the width of the rectangle seen during the habituation trials. The infants thus appeared to possess the knowledge, quantitative reasoning abilities, and perceptual skills necessary to succeed at the task.

In contrast to the 12-month-old infants, the 8- and 10-month-old infants tended to look equally at the novel and the familiar rectangles. Why did these younger infants fail to discriminate the two rectangles? One possibility was, of course, that the infants lacked the knowledge, reasoning strategies, or perceptual abilities required for a successful performance. This possibility is consistent with Arterberry's (1993) conclusion that the infants had difficulty processing the amount of time that the rectangle was in view in the window. Another possibility, however, was that the infants failed the task for attentional reasons: The infants might have ignored the width of the rectangle seen through the window, not because they were unable to reason about this width, but because other aspects of the task commanded greater attention. Recall that the infants did not see the rectangle move back and forth behind the screen until the test trials. Could it be that, upon seeing this occlusion event, the infants were so preoccupied with the existence and trajectory of the rectangle behind the screen that they gave little attention to the duration of its passage behind the window?

Data from a recent experiment provide some support for this hypothesis (Craton & Baillargeon, 1995). In this experiment, 9.5-month-old infants were assigned to an occlusion or a no-occlusion condition. The infants in the occlusion condition were first familiarized with an event in which a tall, rectangular object moved along a horizontal track whose right end was hidden by a large screen (see Figure 28). The object disappeared behind the screen as it moved from the left to the right end of the track and reappeared into view as it moved back to its original position at the left end of the track. Next, the infants saw a possible and an impossible test event that were identical to the familiarization event, with two exceptions. First, a small window was uncovered in the screen. Second, a thin, long screen was inserted between the left edge of the large screen and the left wall of the apparatus to hide the middle portion of the object. The only difference

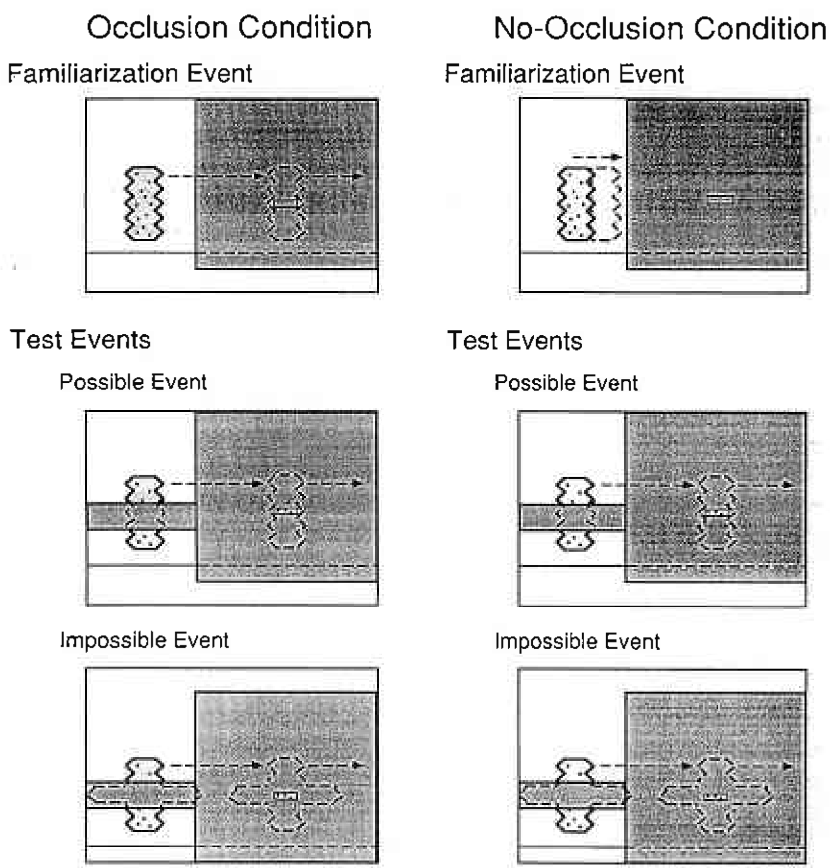

Fig. 28. Schematic drawing of the test events used in Craton and Baillargeon (1995).

between the two test events had to do with the object that moved along the track. In the possible event, the object was the same as in the familiarization event. In the impossible event, thin, long "arms" were attached to the object's middle section; the addition of these arms (which were hidden from the infants' view by the thin screen mentioned earlier) affected both how soon the object appeared in the screen window and how long the object took to traverse the window.

The infants in the no-occlusion condition watched the same test events as the infants in the occlusion condition, but they saw a different familiarization event. The object moved back and forth on a short trajectory to the left of the large screen and thus remained fully visible throughout the event.

The results indicated that the infants in the occlusion condition looked reliably longer at the impossible than at the possible event, whereas the infants in the no-occlusion condition did not. Our interpretation of these findings centers on infants' attention and the features likely to capture it. Specifically, we would argue that upon seeing an object pass behind a screen, young infants become immediately preoccupied with the task of representing the existence and/or path of the object behind the screen. Until this representation is complete, less salient aspects of the event receive little or no attention. By this view, familiarizing infants with the object's occlusion behind the screen would give them the opportunity to build a representation of the aspects of the event most salient to them, thus freeing them in subsequent trials to attend to other, less salient aspects of the event. Note that the present explanation would predict that the 3.5-month-old infants in our initial occlusion experiment (Baillargeon & DeVos, 1991) might have performed less successfully had they been habituated to an object moving in full view to the left of the screen, rather than behind the screen.

The results presented in this section suggest that infants may fail to detect the violation embedded in an impossible occlusion event, not because they lack the physical knowledge, reasoning skills, or perceptual abilities necessary to do so, but because their attention is captured by aspects of the event tangential to the violation. When infants are allowed to focus on those aspects of the event most salient to them before being asked to reason about the aspects relevant to the violation, however, infants readily demonstrate their ability to attend to, process, and correctly interpret these additional, initially less salient aspects.

C. Infants' Memory

It has been argued that to predict whether infants are able to correctly interpret an event depicting a certain phenomenon, one must take into account, in addition to factors having to do with infants' specific expertise with the phenomenon, a host of more general factors that include infants' perceptual and attentional abilities. In this final section, one more general factor is considered that appears to impact on infants' physical reasoning, namely, infants' memory abilities.

In the course of the chapter, several experiments were discussed in which young infants were found to have little difficulty remembering information about objects and using that information to predict the outcome of events involving the objects. For example, it was shown that 3.5-month-old infants could remember the height of a carrot after it disappeared behind a screen (Baillargeon & DeVos, 1991), that 4-month-old female infants could remember whether a box was located in or out of the path of a rolling car (Baillargeon & DeVos, 1991), that 5.5-month-old infants could remember whether a bear was placed under a cage or a clear cover (Baillargeon et al., 1990), and that 9.5-month-old infants could remember which of two screens hid a flat cover and which, a cover with a protuberance (Baillargeon & DeVos, 1995a). In all of these experiments, the infants were given information at the start of each event that they had to remember in order to correctly interpret the event (similar results obtained with 5.5-, 6.5-, 7.5-, and 8-month-old infants using a variety of experimental procedures are reported in Baillargeon, 1993).

In pursuing these experimental adventures, we have occasionally stumbled onto situations in which, in contrast to the experiments cited above, infants seemed to have difficulty remembering the information presented at the start of the events, leading to negative performances. Interestingly, the common element in these failure situations appears to be that infants were required to encode and remember the presence or absence of a feature: for example, whether a container had a bottom or not, or whether a cloth cover displayed a protuberance or not. I return to this observation after a consideration of the experimental evidence.

1. Remembering Information Concerning Containment Events

Do young infants appreciate that a bottomless object cannot function as a container? To address this question, 5.5- and 8.5-month-old infants were tested in the following experiment (Kolstad & Baillargeon, 1995b). The infants were habituated to the event depicted in Figure 29. At the start of the event, a gloved hand held a small container upright; the hand then rotated the container forward and backward so that the infants could see its opening and bottom. After returning the container to its upright position, the hand moved the container under a tap in the back wall of the apparatus. Salt then poured from the tap into the container; the infants could see a stream of salt enter the container, and none fall out of the bottom. Next,

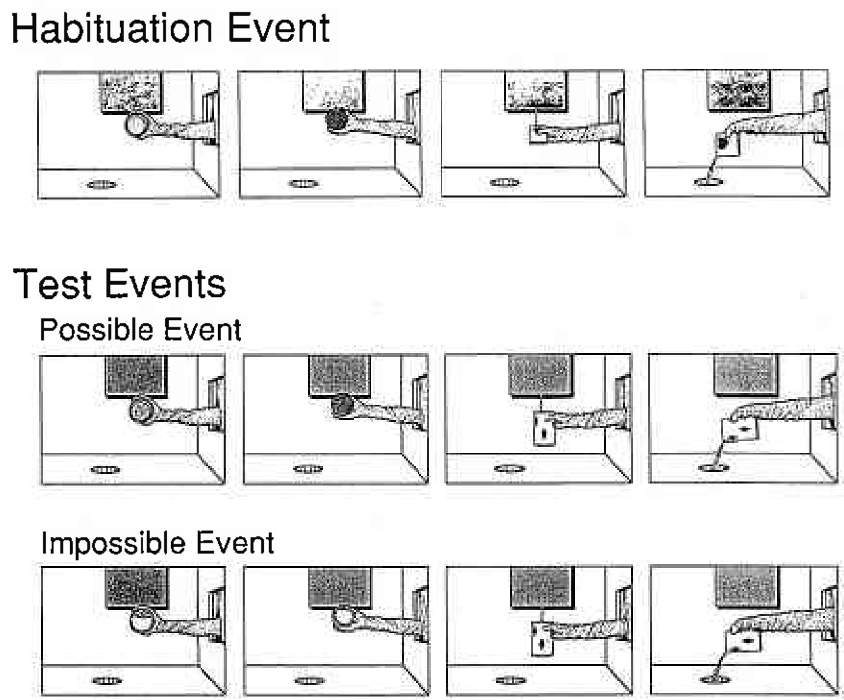

Fig. 29. Schematic drawing of the test events used in Kolstad and Baillargeon (1995b).

the hand moved the container to a hole in the floor of the apparatus and poured out the salt. Three different containers were used in the habituation trials; all three were brightly colored, cylindrical, and decorated with geometric shapes. One was yellow with red hearts, one blue with purple diamonds, and one pink with black spots. The three containers were shown on successive trials until the end of the habituation trials.

Following habituation, the infants saw test events identical to the habituation event except that novel objects were used. Both objects were yellow cylinders decorated with black diamonds. The only difference between the objects was that one possessed a bottom and thus could serve as a container (possible event), whereas the other lacked a bottom and hence should not have been able to contain the salt (impossible event).

The results indicated that both the 5.5- and the 8.5-month-old infants tended to look equally at the impossible and the possible events, as though they believed that either test object could function as a container. It eventually occurred to us, however, that the infants might have performed poorly in the experiment, not because they lacked the knowledge that objects require bottoms to contain, but because they became confused after the test objects were moved upright as to whether they were watching the object with or without a bottom. This line of reasoning led us to redo our experiment using a between- rather than a within-subjects procedure: Half of the infants saw the possible event and half the impossible event. With this procedure, confusion of the container and the tube test object could no longer occur because the infants saw only one of the two objects.

The results obtained with this between-subjects design were positive: The 5.5- and 8.5-month-old infants who saw the impossible event looked reliably longer overall than those who saw the possible event. These results suggested that by 5.5 months of age, infants are aware that a concave object cannot contain if it lacks a bottom. This interpretation was confirmed by the results of a control condition in which the habituation and test containers were manipulated in the same way, but no salt was used; the infants in this condition tended to look equally at the events they were shown, suggesting that the tube's bottomlessness in a no-containment context did not arouse infants' interest.

The results of these experiments suggest that young infants may fail to detect the violation embedded in an impossible containment event, not because they lack the necessary knowledge, reasoning strategies, or perceptual and attentional skills, but because of memory limitations. The infants in the present experiments seemed to have difficulty recalling in each trial which of two objects was being manipulated: the one with or the one without a bottom. Such a result is intriguing when compared with the many findings indicating that young infants readily update and keep track across trials of changes in objects' location, height, or compressibility (e.g., Baillargeon, 1987b).

2. Remembering Information Concerning Unveiling Phenomena

In an earlier section (section III. A. 3), we saw that by 9.5 months of age infants are able to use the presence of a protuberance in a cloth cover to infer the presence of an object beneath the cover (Baillargeon & DeVos, 1995a). In the initial experiment, the infants were presented with two covers side by side: a flat cover and a cover with a marked protuberance. Next, the covers were hidden by screens, and a hand reached behind the right or the left screen twice in succession, retrieving first the cover and then a toy bear. The results indicated that the infants looked reliably longer when the bear was retrieved from under the flat cover as opposed to the cover with a protuberance.

For reasons that are irrelevant here, it was decided in a subsequent experiment to test 9.5-month-old infants with a simpler version of our original procedure. In this experiment (Baillargeon & DeVos, 1995a), the

infants saw a single cover in each test event: the flat cover in the impossible event and the cover with a protuberance in the possible event (see Figure 30). After a few seconds, the cover was hidden by a screen, and the hand reached behind the screen to retrieve first the cover and then the bear. Much to our surprise, the results of this experiment proved negative: The infants tended to look equally at the two test events, as though they believed that the bear could have been hidden under either cover.

Why did the infants show surprise at the impossible event in the two- but not the one-cover experiment? One explanation had to do with the infants' attention: Seeing the two covers side by side might have helped the infants attend to and encode the differences between the covers, thus providing them with the information necessary to understand the events. An alternative explanation for the discrepancy between the results of the one- and the two-cover experiments centered on the infants' memory: The infants might have found it easier to remember the location of the two covers than to remember whether the (single) cover presented a protuberance or not.

To examine these hypotheses, we tested an additional group of 9.5-month-old infants (Baillargeon & DeVos, 1995a) using the one-cover procedure, with one exception: At the start of the experiment, the infants were given two familiarization displays modeled after those successfully used in the clown-last experiment described earlier (Kotovsky et al., 1995; see section IV. B. 1). In each display, the flat cover and the cover with a protuberance stood side by side; their locations (i.e., whether the flat cover was on the right or on the left) were reversed across displays. The results of this experiment were again negative, indicating that, unlike the 6.5- and 9.5-month-old infants in the clown-last experiment, the 9.5-month-old infants in the present experiment were not helped by the familiarization displays they were shown. These

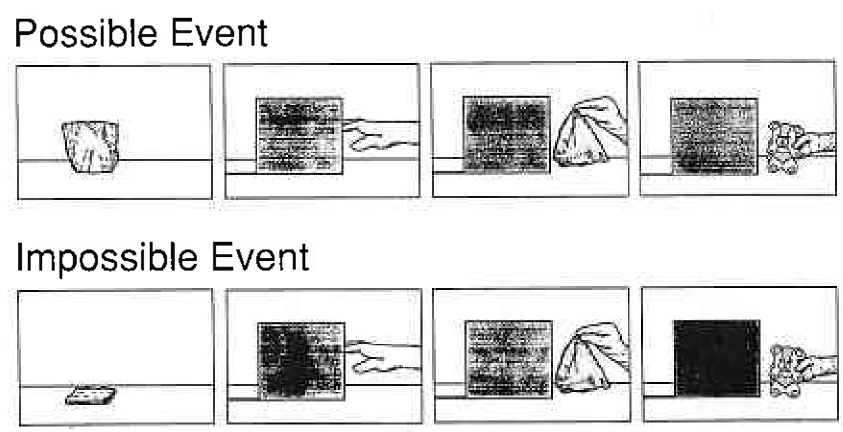

Fig. 30. Schematic drawing of the test events used in Baillargeon and DeVos (1995a, Exp. 4).

negative results led us to regard with more favor the hypothesis that infants have difficulty in the one-cover task remembering whether the cover hidden behind the screen is the cover with or without a protuberance. To investigate this hypothesis more directly, we have recently undertaken a between-subjects version of our one-cover experiment: Half of the infants see the flat cover, and half see the cover with a protuberance. This design has the obvious advantage of preventing confusion of the two covers because each group of infants sees only one. Although still preliminary, the results obtained to date provide encouraging hints that this method will succeed where our previous one-cover tasks failed.

The results of the experiments reported here are intriguing in that they appear to parallel those of the containment experiments mentioned in the previous section. Specifically, infants seem to have difficulty with tasks that require updating and remembering in each trial information about the presence or absence of a feature, be it the presence or absence of a bottom in a container or the presence or absence of a protuberance in a cloth cover. As noted earlier, such a memory limitation is especially interesting when one considers how successful infants are at updating and retaining location (e.g., Baillargeon, 1986; Baillargeon & DeVos, 1991; Baillargeon, DeVos, & Graber, 1989; Baillargeon & Graber, 1988; Baillargeon et al., 1990), height (e.g., Baillargeon & DeVos, 1991; Baillargeon & Graber, 1987), and even compressibility (Baillargeon, 1987b) information.

Further research is needed to determine exactly how the effect noted in the present experiments should be conceptualized (i.e., how the presence/absence of a feature might differ for infants from the presence of different features or of different, non-zero values of a feature). Research is also needed to ascertain why infants' memory for the presence/absence of a feature is less robust (more sensitive to proactive interference?) than memory for location or other information. In addition to giving us a better understanding of infants' memory capacities, this line of research may provide a useful, converging approach to the study of infants' initial concepts. Recall that in the discussion of unveiling phenomena (section III. A. 3), it was proposed that infants first form an initial concept centered on a protuberance/no-protuberance distinction. In this section, suggestive evidence was just reviewed that infants encode covers in terms of the presence or absence of a protuberance and are easily subject to confusion across trials. One could imagine future experiments that rely on confusion as evidence that infants' encóding of objects focuses on all-or-none distinctions involving the presence/absence of specific features.

D. Future Directions

In the preceding sections, it was argued that in order to explain infants' physical reasoning about any given phenomenon, one must consider not only phenomenon-specific factors such as infants' knowledge of the phenomenon, but also a host of phenomenon-general factors that concern infants' perceptual and information-processing abilities. Three such factors were considered in some detail: infants' perceptual, attentional, and memory abilities. There are very likely many more. Thus, one future direction for research is undoubtedly that of identifying the additional components that a full account of infants' physical reasoning will need to include.

A second direction for research will concern the mechanisms responsible for progress in these phenomenon-general factors. It is likely that infants' attentional biases, for example, change over time. One issue of particular interest is whether all attentional changes reflect general maturational or experiential developments or whether at least some changes arise from phenomenon-specific gains in expertise. Until now, a sharp distinction has been consistently drawn between phenomenon-specific and phenomenon-general factors. But it seems plausible that attentional changes might also stem from knowledge changes; one would not be surprised to discover that infants are more likely to attend to and encode certain information, if not when they have just begun to appreciate its significance, at least when they have become adept at processing its implications. Future research may thus lead to an eventual blurring of the distinction made here between phenomenon-specific and -general factors. Nevertheless, at the present time, such a distinction seems a useful starting point, as it enables us to organize and interpret a wealth of experimental findings.

V. CONCLUDING REMARKS

This chapter explored infants' remarkable ability to interpret the physical events they observe about them, and it described some of the many factors one must take into account to explain this ability.

One should not lose sight of the fact, however, that the type of physical reasoning investigated here represents only a small portion of infants' repertoire. In recent years, researchers have become increasingly conscious of this fact and, as a result, have begun to investigate additional aspects of infants' physical reasoning. A first aspect concerns infants' physical reasoning as revealed in object-manipulation tasks, rather than in the violation-of-expectation tasks used here. As was mentioned at the start of the chapter, Piaget (1954) was the first to note that young infants do not search for hidden objects. Piaget's interpretation of this finding was that young infants lack a notion of object permanence. This interpretation eventually came to be rejected because violation-of-expectation tasks demonstrated that young infants, like adults, represent the existence and properties of hidden objects. Such findings, although valuable, still leave open the question of why young infants fail to search for hidden objects.

More generally, the marked lag between infants' performance in manipulation and violation-of-expectation tasks gives rise to the question of how and when infants come to reveal in their actions the physical knowledge that they possess (e.g., Diamond, 1991).

A second facet of infants' physical reasoning that is attracting increasing attention concerns the distinction between animate and inanimate objects (e.g., Leslie, 1984, in press; Spelke et al., in press). All of the research reported here focused on infants' ability to reason about inanimate objects. Are young infants aware that animate objects sometimes behave as do inanimate objects, and sometimes not? How is infants' knowledge of the similarities and differences between animate and inanimate objects organized? Are the learning mechanisms posited to guide infants' acquisition of knowledge about inanimate objects also involved in the growth of infants' knowledge about animate objects? The challenge of answering such questions will no doubt occupy us well into the next century!

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Printed in the United States of America.

ISBN: 1-56750-126-5
ISSN: 0732-9598

ABLEX Publishing Corporation
355 Chestnut Street
Norwood, New Jersey 07648

ADVANCES IN INFANCY RESEARCH

VOLUME 9

1995

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