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The acquisition of physical knowledge in infancy

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INTRODUCTION

What role does causality play in the development of infants' physical reasoning? The answer to this question naturally depends on *how* we define causality. On the one hand, we might characterize causal reasoning at a very general level in terms of the construction of conceptual descriptions that capture regularities in the displacements of objects and their interactions with other objects. On the other hand, we might take causality to mean something far more specific associated with the formation of sequences in which one event is understood to bring about another event through the transmission of force or some other generative process.

In this chapter we focus primarily on the first of the two definitions listed above. There is now considerable evidence that, in learning about physical events, infants construct increasingly elaborate descriptions that enable them to arrive at increasingly accurate predictions about the events. How does this construction process take place? Over the past few years, we have begun to build a model of the development of infants' physical reasoning. This model is based on the assumption that infants are born, not with substantive beliefs about objects, as Leslie (1988; Chapter 5 of this volume) and Spelke and her colleagues (Spelke 1991; Spelke *et al.* 1992; Chapter 3 of this volume) have proposed, but with a highly constrained mechanism that guides infants' acquisition of knowledge about objects. The model is derived from findings concerning the development of infants' intuitions about different phenomena (for example support, collision, unveiling, arrested-motion, occlusion, and containment phenomena). Comparison of these findings points to a developmental pattern that recurs across ages and phenomena. We assume that this pattern reflects, at least indirectly, the nature and properties of infants' innate learning mechanism.

In what follows, we describe the developmental pattern identified in the model and review some of the evidence supporting it (readers are referred to Baillargeon (in press *a*, *b*, *c*) for further discussion of the model). Finally, we contrast the present approach with that adopted by Spelke and her colleagues (Spelke 1991; Spelke *et al.* 1992; Chapter 3 of this volume) and by Leslie (1988; Chapter 5 of this volume). In this context, we return to the second, more specific, definition of causality mentioned earlier and ask whether this definition, with its focus on notions of force or generative transmission, can shed further light on the findings discussed in this chapter.

INITIAL CONCEPTS AND VARIABLES

Current evidence suggests that, when learning about a physical phenomenon, infants first form a preliminary all-or-nothing 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 phenomenon and incorporate this accrued knowledge into their reasoning, resulting in increasingly accurate interpretations and predictions over time.

To illustrate the distinction between initial concepts and variables, we shall summarize experiments on the development of young infants' reasoning about support, collision, and unveiling phenomena.

Reasoning about support phenomena

Evidence from our laboratory

Adults possess sophisticated intuitions about support relations between objects. These intuitions enable them to place objects safely on tables and shelves, stack objects in cupboards and trunks, carry armfuls of groceries and dishes, improvise makeshift shelters and ladders, and balance ornaments at the top of Christmas trees and wedding cakes.

At what age do infants begin to develop an understanding of support phenomena? To address this question, we conducted a series of experiments in which infants aged from 3 to 6.5 months were presented with simple support problems involving a box and a platform.

Initial concept: contact between the box and platform In our first experiment (Needham and Baillargeon 1993*a*) we 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 Fig. 4.1. 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

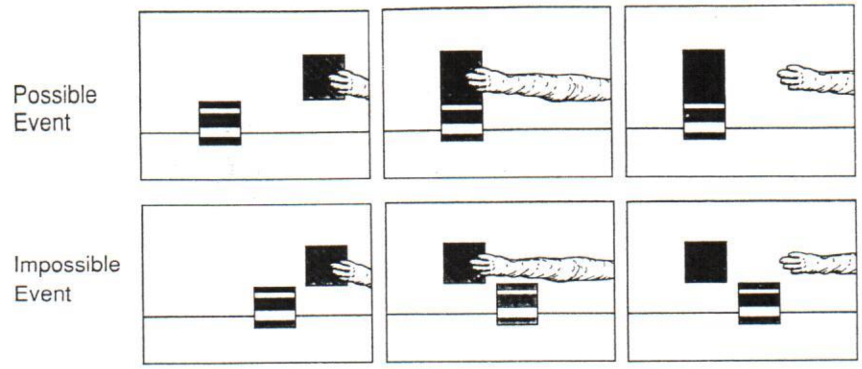

Fig. 4.1. Schematic drawing of the test events used by Needham and Baillargeon (1993*a*).

platform. In the impossible event, the hand deposited the box beyond the platform and then retreated, leaving the box suspended in mid-air 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. Together, these results indicated that the infants expected the box to fall when it was released beyond the platform 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 and Baillargeon, 1993*b*). 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 (Fig. 4.2). 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 stayed 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 (Fig. 4.2).

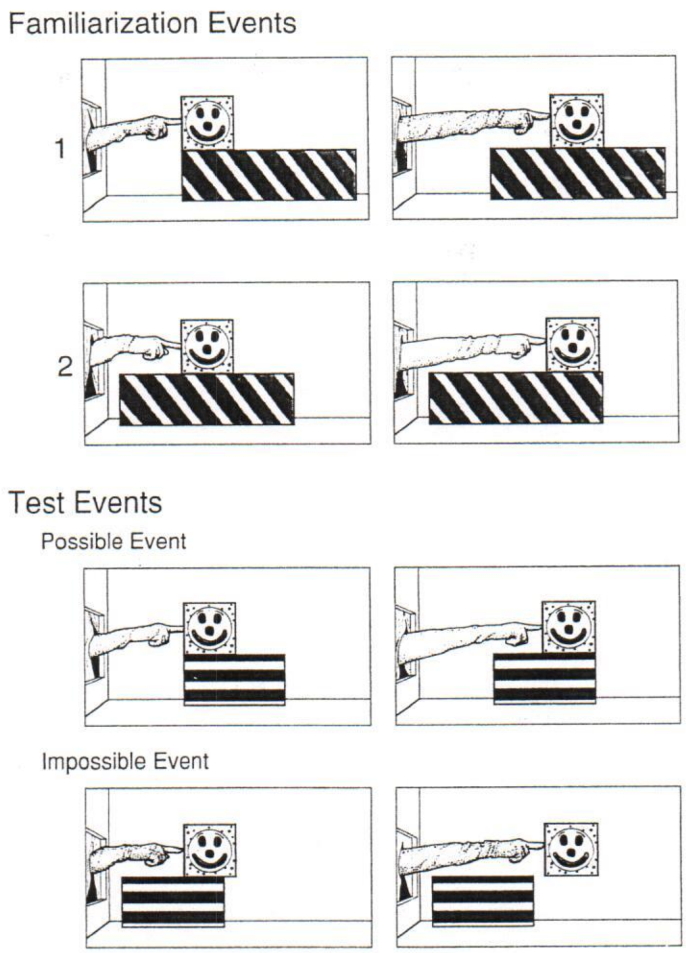

Fig. 4.2. Schematic drawing of the events used by Needham and Baillargeon (1993*b*, experiment 1).

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 that 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.

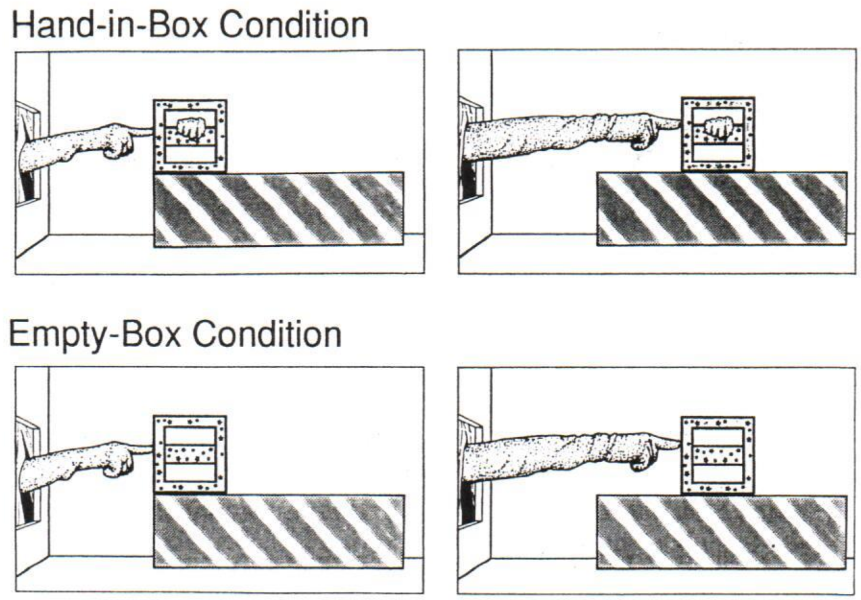

Fig. 4.3. Schematic drawing of the events used by Needham and Baillargeon (1993*b*, experiment 2).

This interpretation was supported by the results of another experiment with 3-month-old infants (Needham and Baillargeon 1993*b*). The infants in this experiment saw the same familiarization and test events as the infants in the experimental condition in the first experiment. However, prior to seeing these events the infants received an additional trial that was similar to the familiarization trials except that the front of the box was removed, creating a large opening (Fig. 4.3). For half 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, not because they were intrigued to see the box suspended in mid-air, but 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;

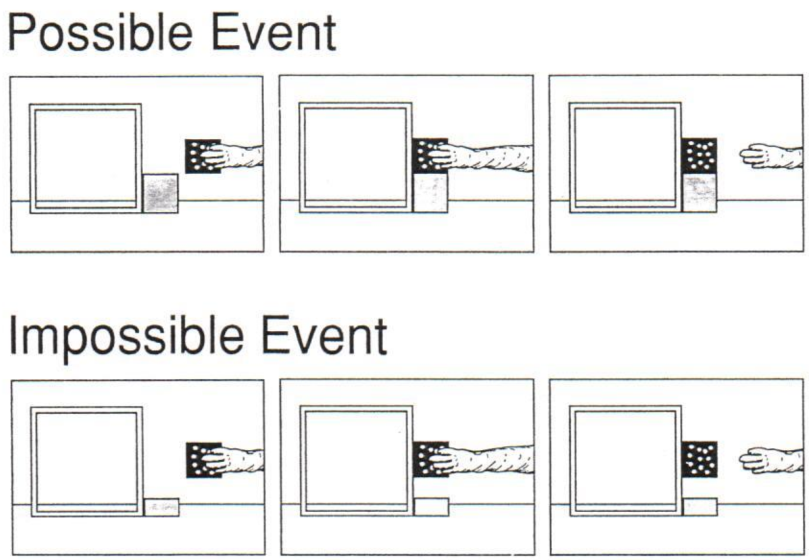

Fig. 4.4. Schematic drawing of the test events used by R. Baillargeon, H. Raschke, and A. Needham (in preparation).

specifically, they realized 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. In our next experiment (R. Baillargeon, H. Raschke, and A. Needham, in preparation) we asked whether infants also appreciate what *type of contact* is needed between a box and a platform for the box to be stable. In the experiment, 4.5-month-old infants saw the possible and impossible events depicted in Fig. 4.4. 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 with the possible event except that the closed platform was much thinner so that the box lay well above it.

The results indicated that 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 with the female infants, the male infants in the experimental 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 (Haywood 1986; Held, in press), sex differences such as the one described here are not uncommon in infancy research (Baillargeon and DeVos 1991; L. Kotovsky and R. Baillargeon, in preparation). 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, not only the type but also the amount of contact between the box and the platform must be considered (Baillargeon *et al.* 1992). Subjects were 6.5-month-old infants. The infants were assigned to either the 15 per cent or the 70 per cent condition. The infants in the 15 per cent condition watched test events in which a gloved hand pushed a box from left to right along the top of a platform (Fig. 4.5). 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 per cent of its bottom surface remained on the platform. The infants in the 70 per cent condition saw similar test events except that the box was pushed until the left 70 per cent, rather than the left 15 per cent, 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 (Fig. 4.5).

The results indicated that the infants in the 15 per cent condition looked reliably longer at the impossible than at the possible event, whereas the infants in the 70 per cent condition tended to look equally at the events that they were shown. These results suggested that the infants (a) realized that the box was adequately supported when 70 per cent, but not 15 per cent, 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 with the 15 per cent condition except that the hand grasped the box, thereby ensuring its support.

In a subsequent experiment, 5.5-month-old infants were tested using the 15 per cent 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

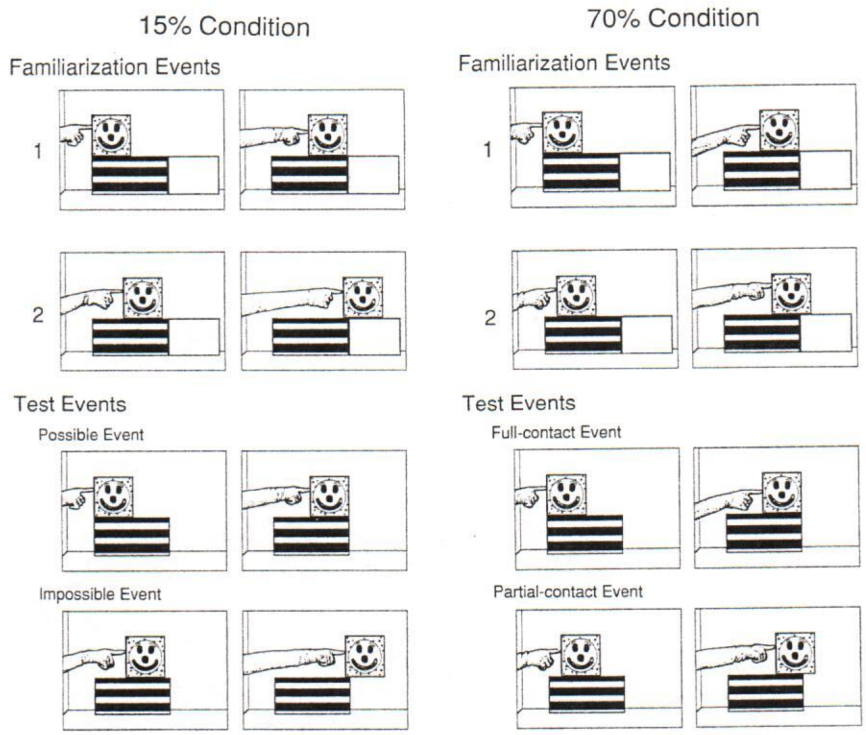

Fig. 4.5. Schematic drawing of the events used by Baillargeon *et al.* (1992).

was adequately supported even when only its left corner remained on the platform. This negative result was replicated in a later experiment (Needham and Baillargeon 1993*b*).

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 per cent) 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 per cent) 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 centred on a distinction between contact and no contact. In time, this initial concept is slowly elaborated. Infants identify first a discrete (type of contact between the objects) and later a continuous (amount of contact between the objects) variable and incorporate them into their initial concept, leading to increasingly successful predictions over time.

Evidence from Spelke's laboratory

The evidence reviewed in the preceding section indicates that young infants possess intuitions about support phenomena. This evidence contrasts with reports from Spelke's laboratory (Spelke *et al.* 1992; E. S. Spelke, K. Jacobson, M. Keller, and D. Sebba, submitted; E. S. Spelke, A. Simmons, K. Breinlinger, and K. Jacobson, submitted) that young infants either lack such intuitions, or possess intuitions that are best characterized as exceedingly fragile and limited. These reports involve six different experiments, most of which yielded negative results. In what follows, we describe these various experiments and consider alternative explanations for their findings.

Experiments with a falling object that stops in mid-air In the first experiment we discuss (Spelke *et al.* 1992, experiment 4), 4-month-old infants were habituated to an event in which a hand released a ball in mid-air and the ball then fell some distance until it disappeared behind a screen. After a few seconds, the screen was removed to reveal the ball resting on a horizontal surface above the floor of the apparatus. Following habituation, the horizontal surface was removed, and the infants saw a possible and an impossible test event. In the possible event, the ball was revealed on the apparatus floor when the screen was removed. In the impossible event, the ball was revealed in the same position that it had occupied in the habituation event; however, because the horizontal surface was no longer present, the ball now appeared to be floating in mid-air. The infants tended to look equally at the impossible and the possible events, suggesting that they were not surprised to see the ball suspended in mid-air when the screen was removed.

How can we account for these negative results? One possibility is suggested by a comparison of the impossible event used by Spelke *et al.* (1992, experiment 4) with that shown in the first support experiment described above (Needham and Baillargeon 1993*a*). In the impossible event devised by Spelke *et al.*, a hand released a ball which then fell behind a screen; after a few seconds the screen was removed to reveal the ball floating in mid-air. In the impossible event used by Needham and Baillargeon (1993*a*), a hand released a box which remained suspended in mid-air (Fig. 4.1). Thus a subtle difference between the violations shown in the two experiments was that the latter involved a dynamic event in which an object lost its support and yet failed to fall, whereas the former involved a static display in which an object was revealed already suspended in mid-air.

Evidence for the importance of this distinction was provided by an additional experiment conducted by Needham and Baillargeon (1993*a*) using the same box and platform as before (Fig. 4.1). The infants in this experiment saw a possible and an impossible static test display. In the possible display, the box rested on the platform, as in the possible event shown in the initial experiment. In the impossible display, the box stood suspended in mid-air to the left of the platform, as in the impossible event used in the initial experiment. The results indicated that the infants tended to look equally at the two displays as though they were not surprised in the impossible display to see the box suspended above the apparatus floor with no visible source of support.

What should be made of the fact that the infants in both the experiment of Spelke *et al.* (1992, experiment 4) and the above experiment failed to respond to the impossible static displays that they were shown? At least two hypotheses come to mind. One is that, unlike dynamic events in which objects are observed to lose their supports, static displays involving suspended objects fail to engage infants' reasoning about support. It could be that infants initially reason about support relations only in situations where they can identify two clear participants: an object and a support (e.g. a hand and a platform). In such situations, infants would readily demonstrate an expectation that the object should fall when inadequately supported (Needham and Baillargeon 1993*a*, *b*; R. Baillargeon, H. Raschke, and A. Needham, submitted). In contrast, situations in which an object floats in mid-air without a visible support (and infants have been given no hint of a hidden support) would fail to engage or bring forth infants' intuitions about support, leading to unsuccessful performances.

A second (and perhaps not unrelated) hypothesis is associated with the nature of the data available to infants concerning support phenomena. From birth, infants no doubt experience countless situations whose outcome is consistent with the notion that objects fall when they lose contact with their supports. Thus infants may notice that their dummies fall when they open their mouths, and that toys fall when they open their hands. Similarly, infants may observe that objects typically fall when released (or are swept off tables) by their parents and siblings. In addition to these situations, however, infants may also experience situations involving stable and yet apparently unsupported objects: shades on floor-lamps, ceiling fans, lamps suspended in front of a wall, hanging plants, or even doorknobs could all seem to be free-floating in space when viewed in such a way that their supports are not visible. It could be that, by 4 or even 3 months of age (Needham and Baillargeon 1993*b*), infants have formed definite expectations about the first type of situation: they expect objects to fall when they lose their supports. At the same time, infants might possess no expectations about the second type of situation, as though the latter did not yet fall within the purview of support phenomena.

Whatever the explanation for young infants' consistent lack of response to static displays involving apparently unsupported objects, there is evidence that, by 6 months of age, infants already show reliable surprise at such displays. In another experiment, Spelke *et al.* (E. S. Spelke, A. Simmons, K. Breinlinger, and K. Jacobson, submitted, experiment 1) tested 6-month-old infants with the same procedure that they had used with their 4-month-old subjects (Spelke *et al.* 1992, experiment 4). The results indicated that these older infants looked reliably longer at the impossible than at the possible event. This positive finding was later confirmed in an experiment (E. S. Spelke, K. Jacobson, M. Keller, and D. Sebba, submitted, experiment 2) conducted with a similar procedure except that the screen was absent; thus the infants saw the ball fall in full view to the horizontal surface (habituation event), the apparatus floor (possible event), or a point in mid-air corresponding to the position of the horizontal surface in the habituation event. The infants again showed a reliable preference for the impossible over the possible event, suggesting that they were surprised to see the ball suspended in mid-air with no apparent support. Additional results (E. S. Spelke, K. Jacobson, M. Keller, and D. Sebba, submitted; E. S. Spelke, A. Simmons, K. Breinlinger, submitted) provided further evidence for this interpretation.

Experiments with an object released in mid-air In the preceding subsection, we discussed two experiments conducted by Spelke and her colleagues (E. S. Spelke, K. Jacobson, M. Keller, and D. Sebba, submitted, experiment 2, 1993*b*, experiment 1) with 6-month-old infants that yielded positive results. In contrast with these two experiments, three additional experiments carried out by Spelke *et al.* (E. S. Spelke, K. Jacobson, M. Keller, and D. Sebba, submitted) with 6-month-old infants produced negative findings. Surprisingly, the method of these three experiments was very similar to that of the two successful experiments described above. For example, in one experiment (E. S. Spelke, K. Jacobson, M. Keller, and D. Sebba, submitted, experiment 4) the infants were habituated to an event in which a hand lowered a ball to a horizontal surface above an apparatus floor and then released the ball. Following habituation, the surface was removed and the hand released the ball after lowering it either to the apparatus floor (possible event) or to a point in mid-air corresponding to the surface's position in the habituation event (impossible event). Another experiment (E. S. Spelke, K. Jacobson, M. Keller, and D. Sebba, submitted, experiment 7) was similar to the last except that the hand moved the ball forward in depth instead of lowering it from above. Finally, a third experiment (E. S. Spelke, K. Jacobson, M. Keller, and D. Sebba, submitted, experiment 6) again examined infants' responses to test events in which a ball was released after being lowered to a surface (possible event) or to a point in mid-air (impossible event); however, no habituation event was shown in this experiment.

How can we account for the discrepancy between the positive and negative results obtained by Spelke *et al.* (E. S. Spelke, K. Jacobson, M. Keller, and D. Sebba, submitted; E. S. Spelke, A. Simmons, K. Breinlinger, and K. Jacobson, submitted) in these five, superficially very similar, experiments? The most probable explanation is related to infants' ability to detect that the hand had released the ball. In the two experiments that yielded positive results (E. S. Spelke, K. Jacobson, M. Keller, and D. Sebba, submitted, experiment 2; E. S. Spelke, A. Simmons, K. Breinlinger, and K. Jacobson, submitted, experiment 1), the hand dropped the ball, making it very easy for the infants to notice that the hand no longer held the ball. However, in all three of the experiments that produced negative results, the hand moved the ball to its final position and then released it, presumably by opening its fingers (there is no mention in the papers that the hand moved away from the ball). It may be that this form of release was too subtle for 6-month-old infants. Yonas and his colleagues (Yonas and Granrud 1984; Yonas *et al.* 1987) have demonstrated 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. In the experiments under discussion, an important cue as to whether the hand was holding or had released the ball may have been pictorial in nature: the occlusion or non-occlusion of the ball by the hand's fingers (the figures in Spelke *et al.* (E. S. Spelke, K. Jacobson, M. Keller and D. Sebba, submitted; E. S. Spelke, A. Simmons, K. Breinlinger, and K. Jacobson, submitted) suggest that the hand held the ball from the back, with only the fingers visible). Lacking the ability to interpret this occlusion cue, the 6-month-old infants in the experiments would have been unable to determine whether the hand was holding or had released the ball, and hence would have failed to detect the violations that they were shown (for further situations in which infants fail to show surprise at impossible events because of limited depth perception, see Baillargeon (in press *a*)).

Experiment with an object rolling across a gap Spelke *et al.* (E. S. Spelke, A. Simmons, K. Breinlinger, and K. Jacobson, submitted, experiment 3) reported one further experiment with 6-month-old infants that had negative findings. The infants were habituated to an event in which a ball rolled from left to right along the upper of two horizontal surfaces and disappeared behind a screen that hid the right end portion of the two surfaces. After a few seconds, the screen was removed to reveal the ball resting on the upper surface against the right wall of the apparatus. Following habituation, a gap considerably wider than the ball was created in the upper surface, behind the screen, and the infants saw a possible and an impossible test event. The possible event was similar to the habituation event except that the ball rolled along the lower of the two surfaces. The impossible event was identical to the habituation event: the ball rolled along the upper surface and disappeared behind the screen; when the screen was removed, the ball was revealed on the same surface to the right of the gap. The infants did not show a reliable preference for the impossible over the possible event, suggesting that they were not surprised, when the screen was removed, to see the ball resting past the gap in the apparatus's upper surface.

To what should these negative findings be attributed? One possibility is that the infants lacked the physical knowledge necessary to interpret the test events correctly; their knowledge of displacement, as opposed to support, phenomena might have been too limited for them to appreciate the conditions under which a moving object can 'jump' across a gap (e.g. a golf ball that rolls across a hole instead of falling into it). A second possibility is that the infants possessed the knowledge required to detect the violation shown in the impossible event, but failed to demonstrate this knowledge because they did not attend to the gap's presence (for examples of attentional failures in infants' physical reasoning, see Baillargeon (in press *a*)). Yet a third possibility, and the one we believe is most likely, is related to the design of the experiment. Recall that the impossible event was perceptually more similar than the possible event to the habituation event: the ball rolled along the upper surface in the habituation and the impossible events, and along the lower surface in the possible event.

The type of cross-design used in this experiment is frequently used (Baillargeon *et al.* 1985; Baillargeon 1987; Spelke 1991; Spelke *et al.* 1992), no doubt because it presents obvious advantages: if an impossible event is perceptually more similar than a possible event to a habituation event, then a higher response to the impossible event cannot be interpreted as a superficial novelty response. Nevertheless, data from our laboratory have led us to suspect that such a design may not be appropriate for infants aged 6 months and older. In a series of experiments on arrested-motion phenomena, infants aged 5.5, 4.5, and 3.5 months were habituated to a screen that rotated through a 180° arc (Baillargeon *et al.* 1985; Baillargeon 1987). Following habituation, a box was placed behind the screen, and the infants saw a possible and an impossible test event (Fig. 4.6). In the possible event, the screen rotated until it reached the box (112° arc); in the impossible event, the screen rotated through a full 180° arc, as though the box were no longer behind it. The results indicated that the 5.5- and

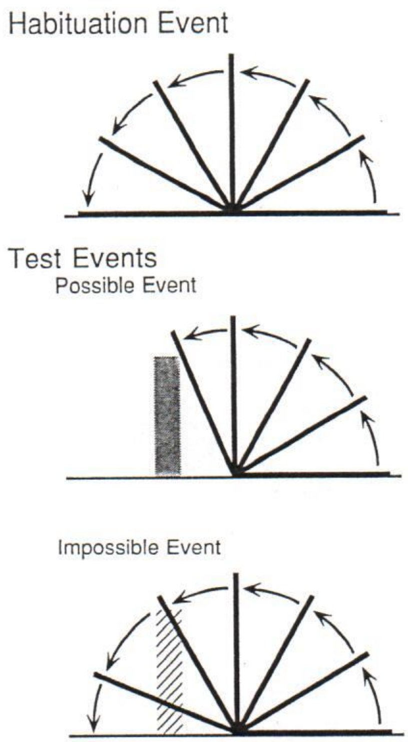

Fig. 4.6. Schematic drawing of the events used by Baillargeon (1987).

4.5-month-old infants, and even some of those aged 3.5 months, looked reliably longer at the impossible than at the possible event, suggesting that they expected the screen to stop when it reached the box and were surprised that it did not in the impossible event. Control data obtained without a box behind the screen provided evidence for this interpretation.

In a subsequent unpublished experiment, we also tested 6.5-month-old infants using the same procedure. Much to our surprise, however, the data collected with these older infants were negative: the infants tended to look equally at the two test events. In our quest for an explanation of this puzzling finding, we were led to examine more closely the infants' responses to the first pair of test trials in which they were presented with the impossible and the possible events. Data analyses indicated that the infants looked reliably longer at whichever event they were shown first. This result led us to the hypothesis that the 6.5-month-old infants looked equally at the two test events because they were responding simultaneously to both the physical novelty of the impossible event and the perceptual novelty of the possible event. Recall that the screen moved through a full 180° rotation in the habituation and the impossible events, but underwent a shorter 112° rotation in the possible event. To examine this hypothesis, we tested an additional group of 6.5-month-old infants using the same procedure as before, except that the infants received a single habituation trial. The infants now showed a reliable preference for the impossible event, presumably because the single habituation trial was not sufficient to lead them to perceive the possible event as more novel than the impossible event.

Given our claim that cross-designs may be not be suitable for testing infants aged 6.5 months and older, readers may wonder how we explain the two positive results that Spelke *et al.* (E. S. Spelke, K. Jacobson, M. Keller, and D. Sebba, submitted, experiment 2; E. S. Spelke, A. Simmons, K. Breinlinger, and K. Jacobson, submitted, experiment 1) obtained with 6-month-old infants. Recall that, in both experiments (described above), a ball fell to a surface above the apparatus floor in the habituation event. In the test events, the surface was removed and the ball fell to the same position in mid-air (impossible event) or to a novel position on the apparatus floor (possible event). Our intuition is that the infants encoded the ball's position in the habituation event not in absolute terms (e.g. 'the ball is occupying *x* location in space'), but rather in relative terms (e.g. 'the ball is on the surface'). In the test events, the surface was removed so that both positions of the ball appeared relatively novel. Research with older children has also found that, when landmarks are available, subjects are more likely to encode and remember objects' locations in terms of the landmarks rather than in absolute terms (Acredolo 1978).

Knowledge about collision phenomena

Evidence from our laboratory

Initial concept: impact between a moving and a stationary object Our research on infants' reasoning about collision phenomena has focused on simple problems involving a moving and a stationary object. Our first experiment (L. Kotovsky and R. Baillargeon, in preparation) asked whether 2.5-month-old infants expect a stationary object to be displaced when it is hit by a moving object. The infants in the experiment sat in front of an inclined ramp, to the right of which was a track (Fig. 4.7). The infants were first habituated to a cylinder that rolled down the ramp; small stoppers prevented it from rolling past the ramp onto the track. Following habituation, a large 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

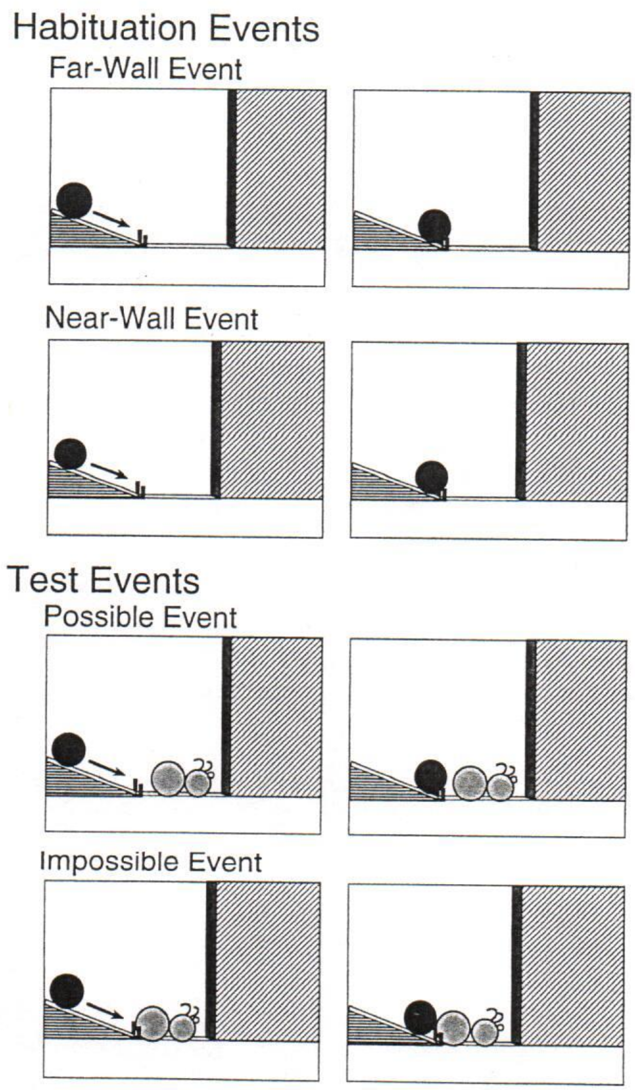

Fig. 4.7. Schematic drawing of the events used by L. Kotovsky and R. Baillargeon (in preparation, experiment 1).

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.*

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 that 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 that it remained stationary in the impossible event. 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.

A second experiment provided support for the findings of this initial experiment (L. Kotovsky and R. Baillargeon, in preparation). 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 (Fig. 4.8). 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 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. These results suggested that the infants preferred the impossible event, not because they were intrigued to see the barrier standing across as opposed to behind the ramp, but because they 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 realized that how far a stationary object is displaced, when hit by a moving object, depends on the moving object's

* To equate the test events shown to the infants in the experimental and the control conditions more closely, 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 Fig. 4.7). Analysis of the habituation data revealed no reliable preference for either wall position.

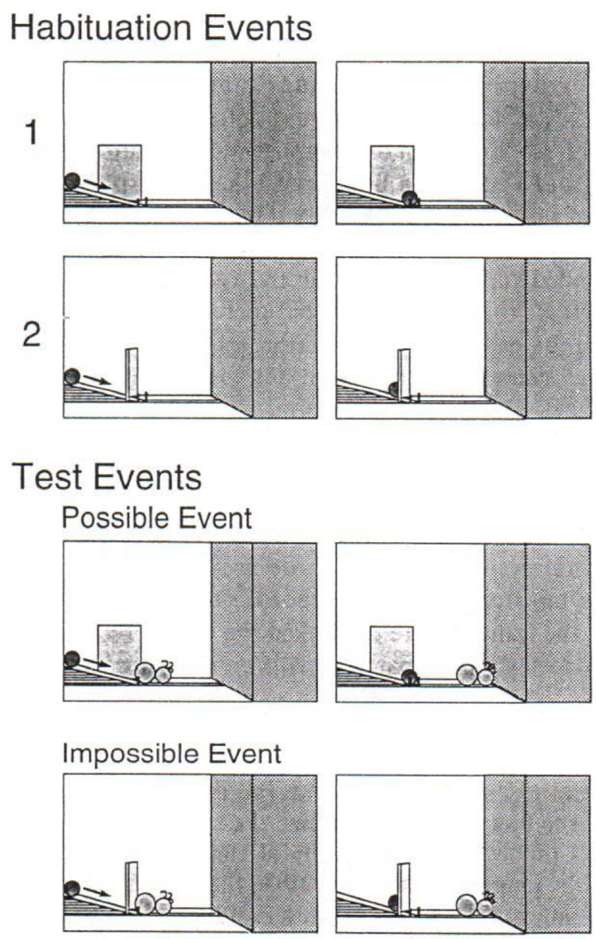

Fig. 4.8. Schematic drawing of the events used by L. Kotovsky and R. Baillargeon (in preparation, experiment 2).

size or, more precisely, mass (however, because our data are insufficient to judge whether infants based their predictions on the moving object's size or mass, we shall refer only to its size). Subjects in the experiments were 11-month-old infants (Kotovsky and Baillargeon, 1994) and 6.5-month-old infants (L. Kotovsky and R. Baillargeon, in preparation). However, because similar findings were obtained with the two age groups, only the experiment with the younger infants will be described.

The apparatus and stimuli in this experiment (L. Kotovsky and R. Baillargeon, in preparation) were similar to those used in the previous experiments, except that the track was much longer (Fig. 4.9). The infants in the mid-point condition were habituated to a blue medium-size cylinder

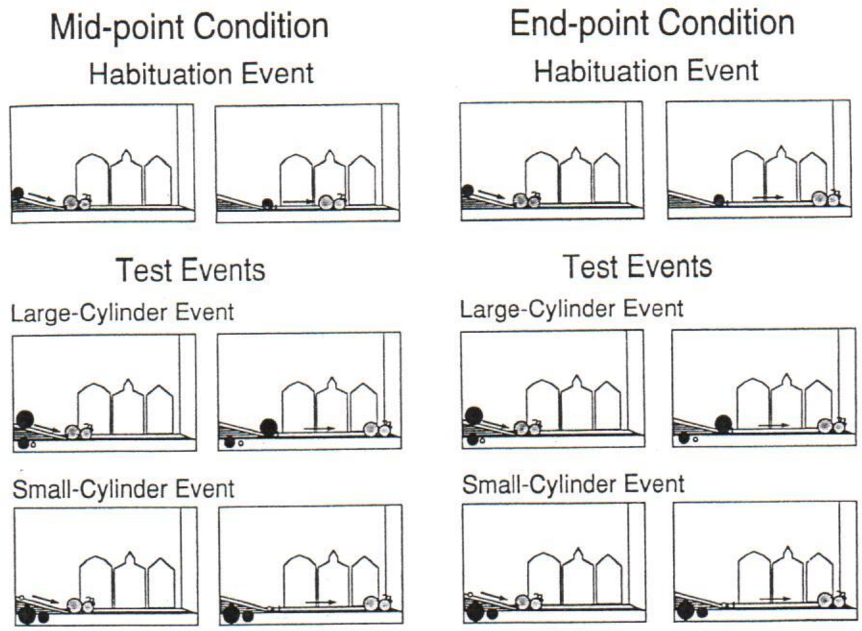

Fig. 4.9. Schematic drawing of the events used by L. Kotovsky and R. Baillargeon, (in preparation, experiment 1).

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.

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 (for example the weight of the cylinder and bug, the smoothness of the ramp and track, and so on) about which they had no information. However, after observing that the bug rolled to the middle of the track when hit by the medium cylinder, adult subjects readily predicted that it would roll farther with the larger cylinder 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 (end-point condition) were tested in a condition identical to the mid-point condition except that they were given a different calibration point in the habituation event. As shown in Fig. 4.9, 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 it to do the same with the large cylinder and (b) were not surprised to see it do the same with the small cylinder (subjects simply concluded that the track was too short to show the effects of cylinder size). The experiment thus tested whether 6.5-month-old infants, like adults, would perceive both the end-point condition test events as possible.

The results indicated that the infants in the mid-point condition looked reliably longer at the small cylinder event than at the large-cylinder event, whereas the infants in the end-point 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 it 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 it 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 mid-point condition (L. Kotovsky and R. Baillargeon, in preparation). 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 end-point condition events. Like the 6.5-month-old infants, they now looked equally at the small- and large-cylinder events.

In contrast with the female infants, the male infants who were shown the mid-point condition events tended to look equally at the small- and 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 it 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 was that the male infants had difficulty in remembering how far the bug had travelled in the habituation event and hence

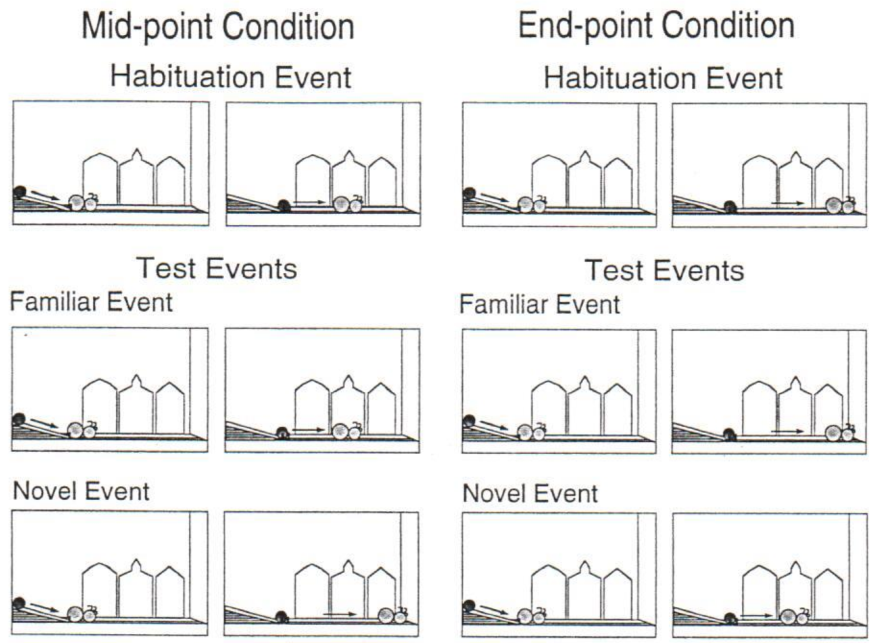

Fig. 4.10. Schematic drawing of the events used by L. Kotovsky and R. Baillargeon (in preparation, experiment 3).

lacked the necessary information to calibrate their predictions about the small and large cylinders.

To examine this second interpretation, two groups of 5.5-month-old male infants were tested in a simple memory experiment (L. Kotovsky and R. Baillargeon, in preparation). As before, the infants in the mid-point condition were habituated to the medium cylinder rolling down the ramp and hitting the bug, causing it to roll to the middle of the track (Fig. 4.10). 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 medium cylinder now caused the bug to roll to the end of the track. The infants in the end-point 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 was 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 had rolled in the habituation event. Data from a pilot experiment provided further support for this conclusion. The infants in this experiment saw the same habituation event as the infants in the mid-point condition above. During the test events, two novel medium cylinders were introduced, one yellow and the other orange; both caused the bug to roll to the end of the track. The infants' looking times indicated that they found both events surprising, suggesting that they (a) remembered that the blue medium cylinder in the habituation event caused the bug to roll to the middle of the track and (b) expected it to roll the same distance when hit by the yellow and orange medium cylinders, and were surprised that it did not.

Together, the findings obtained with the 5.5-month-old male infants suggest 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 it to do so again when hit by a cylinder of the same size, but have no expectation as to how far it should roll when hit by cylinders of different sizes. Infants seem unaware that they possess information that they can use to reason about the novel cylinders.

Conclusions Together, the results of the collision experiments reported above 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. For example, if shown that a medium cylinder causes a bug to roll to the middle of a track, infants have no expectation that it should travel farther when hit by a larger cylinder and less far when hit by a smaller cylinder. By 5.5–6.5 months of age, however, infants not only recognize that a stationary object should be displaced when hit by a moving object, but 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 centred on a distinction between impact and no impact. With further experience, infants begin to identify variables that influence this initial concept. By 5.5–6.5 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.

Evidence from other laboratories

Because collision events constitute prototypical causal sequences for adults, infants' responses to such events have long been of interest to researchers interested in the development of causal reasoning (Leslie and Keeble 1987; Oakes and Cohen 1990). These investigations have established that infants readily distinguish between collision events that adults perceive as causal and non-causal.

In one experiment, Oakes and Cohen (1990) habituated 6- and 10-month-old infants to one of three videotaped events: (a) a causal event in which a moving toy contacted a stationary toy, which immediately moved off; (b) a non-causal event in which a 1-second delay separated the motion of the first and the second toy; (c) another non-causal event in which a spatial gap of 2.5 cm separated the motion of the two toys. Following habituation, the infants were presented with the two events not shown in habituation. The results indicated that the 10-month-old infants who had been habituated to the causal event dishabituated to the two non-causal events, whereas those habituated to either of the non-causal events dishabituated only to the causal event. In contrast, the 6-month-old infants tended to look equally at the events. The authors concluded that, by 10 months of age, infants are already able to differentiate between causal and non-causal events.

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

How should the findings of Oakes and Cohen (1990) and Leslie and Keeble (1987) be integrated with the results of the collision experiments reported in the previous section? We might be tempted to conclude that the 6.5- and 11-month-old infants (Kotovsky and Baillargeon 1994; L. Kotovsky and R. Baillargeon, in preparation) in our experiments not only (a) expected the bug to move when hit by the cylinder and (b) realized that the size of the cylinder affected the length of the bug's displacement, but also (c) perceived the relation between the cylinder's and the bug's motion in causal terms. Such a causal relation might be defined in terms of abstract conceptual roles (i.e. 'agent', 'patient'), or in terms of a physical force transmitted from one object to the other, with a greater force resulting in a greater effect.

However, it is not entirely clear whether such a conclusion would be appropriate. A rather surprising aspect of the findings reported by Oakes and Cohen (1990) and Leslie and Keeble (1987) concerns their habituation

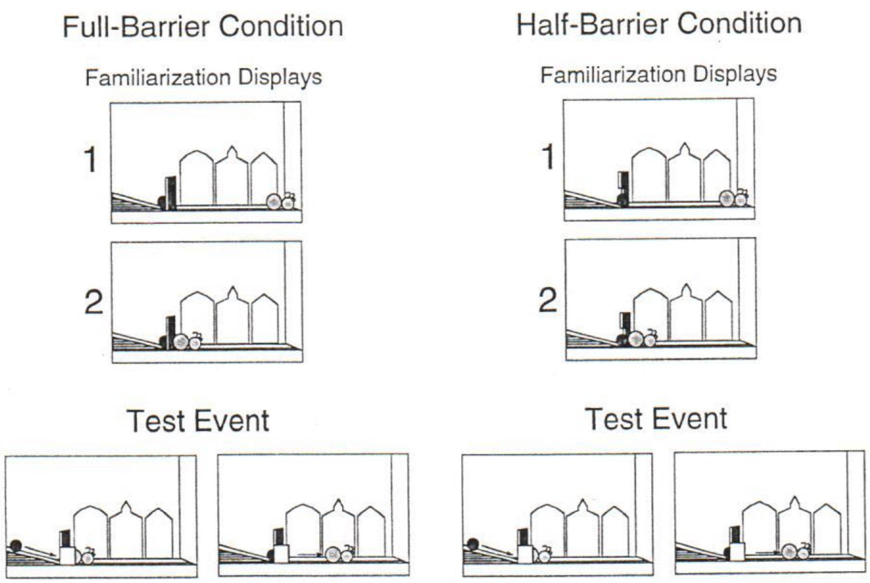

Fig. 4.11. Schematic drawing of the test events used by L. Kotovsky and R. Baillargeon (in preparation).

data. Both sets of authors reported that, in the habituation phases of their experiments, the infants tended to look equally at the causal and the non-causal collision events that they were shown. Thus, even though a spatial or a temporal gap separated the motion of the first and the second object in the non-causal events, the infants showed little or no surprise at the events. Such negative findings appear at odds with those obtained in the present experiments. Recall, for example, that even 2.5-month-old infants were found to look reliably longer when a spatial gap (created by a barrier) separated the motion of the cylinder and the bug than when no such gap existed and the cylinder hit the bug directly (L. Kotovsky and R. Baillargeon, in preparation).

Data from a further collision experiment might help bring this issue into sharper focus (L. Kotovsky and R. Baillargeon, in preparation). In this experiment, 7.5-month-old infants were assigned to a full- or a half-barrier condition. The infants in the full-barrier condition were first shown the two static familiarization displays depicted in Fig. 4.11. In the first display, the infants saw a tall thin barrier standing at the bottom of a ramp; a medium cylinder lay on the ramp, against the left side of the barrier. In the second familiarization display, a bug was added and stood against the right side of the barrier. It was hoped that examination of the two displays would lead the infants to realize that the barrier prevented contact between the cylinder and the bug. The infants in the half-barrier condition saw identical displays except that the lower half of the barrier was removed, so that contact between the cylinder and the bug was possible (the half-barrier was supported by a post located on the far side of the ramp). Following the two familiarization trials, a small screen was positioned at the bottom of, and parallel to, the ramp. The screen hid the rear portion of the bug as well as the lower portion of the barrier; with the screen in place, the full and the half barrier appeared identical. The infants in the two conditions watched, on four successive trials, a test event in which the medium cylinder rolled down the ramp and the bug rolled to the middle of the track.

Even though the infants in the full- and half-barrier conditions saw exactly the same test event, those in the full-barrier condition were found to look reliably longer than those in the half-barrier condition. These results suggested that the infants (a) remembered which barrier was present behind the screen, (b) understood that the cylinder could contact the bug when the half but not the full barrier was in place, and hence (c) were surprised in the full-barrier condition to see the bug move off after the cylinder rolled down the ramp. Data from a control condition in which the bug remained stationary with both the full and the half barriers confirmed this interpretation.

The design of this last experiment was similar in many ways to the habituation portions of the experiments conducted by Leslie and Keeble (1987) and Oakes and Cohen (1990). In each case, different groups of infants were shown collision events that adults might describe as causal (the first object causes the motion of the second object) or non-causal (the first object cannot be the cause of the motion of the second object because the motions of the two objects are separated by a temporal or a spatial gap). However, despite the similarity in their designs, the experiments yielded very different results.

We believe that such a discrepancy is important because it raises questions about the generality of the findings obtained by Leslie and Keeble (1987) and Oakes and Cohen (1990). The causal and non-causal events used by these authors involved filmed or videotaped events very different from the live events shown in the present experiments. Recall that in our events the infants saw an object that was set in motion by a hand roll down a ramp and loudly hit another object, which then rolled to a stop. Many of these features differed in the events shown by Leslie and Keeble and by Oakes and Cohen: the objects initiated their own movements, showed little or no deceleration, and so on.

These observations suggest the following speculations. It may be that, when shown stylized collisions, infants readily perceive non-causal events as arbitrary and make little attempt to understand them. However, when

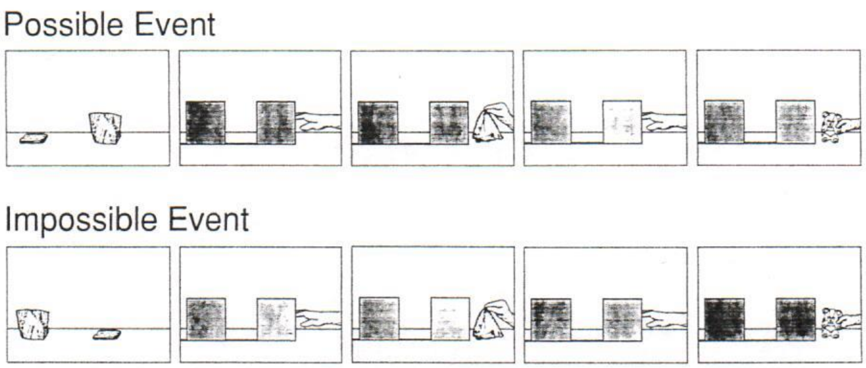

Fig. 4.12. Schematic drawing of the test events used by Baillargeon and DeVos (1993, experiment 1).

shown more natural collisions, infants may adopt a more inquisitive attitude toward non-causal events. Such an attitude might stem from two distinct sources. On the one hand, infants might dismiss the first object's motion as the cause of the second object's motion and scrutinize the event for an alternative cause. On the other hand, infants might still perceive the first object's motion as the cause of the second object's displacement, but be puzzled as to how this effect could have been accomplished. The interest of the second interpretation is that it would indicate that the conditions under which infants perceive events as causal or non-causal differ for different stimuli.

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 and DeVos 1993). 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 (Fig. 4.12). 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 height as the protuberance shown earlier; the hand waved the bear gently to the side of the screen until the computer signalled that the trial had ended. The impossible event was identical except that the location of the

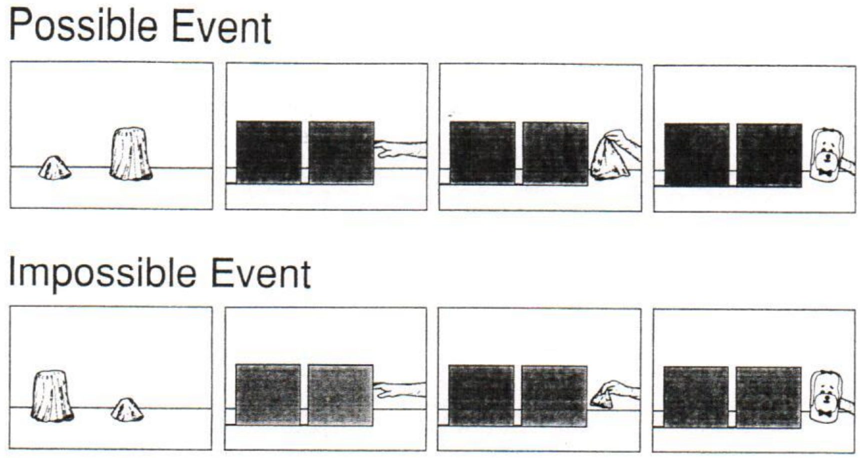

Fig. 4.13. Schematic drawing of the test events used by Baillargeon and DeVos (1993, experiment 2).

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 bear's position 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 and DeVos 1993) investigated whether infants could also use the size of the protuberance to infer the size of the object under the cover (Fig. 4.13). 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 and 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 thus the difference between the two was 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 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.

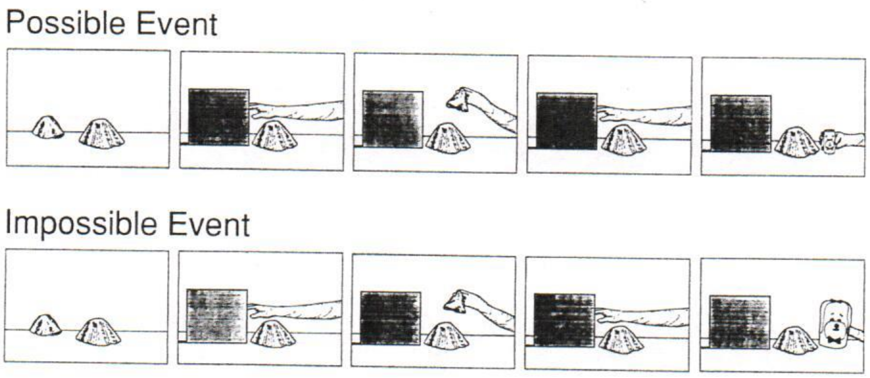

Fig. 4.14. Schematic drawing of the test events used by R. Baillargeon and J. DeVos (in preparation).

Unlike the infants in the last experiment, the infants in this experiment tended to look equally at the impossible and at 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 in which a slightly different procedure was used (Baillargeon and DeVos, 1993). 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 the 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 (R. Baillargeon and J. DeVos, in preparation), who were aged 9.5 and 12.5 months, were reminded of the size of the protuberance in the cover behind the screen (Fig. 4.14). 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 compare their sizes directly. The impossible event was identical with 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 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 Fig. 4.14); no reliable preference was found for the large-dog over the small-dog display.

In contrast with 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 retrieval of the large dog. It might be argued that infants less than 12.5 months of age are simply unable, when reasoning about hidden objects, to take advantage of reminders such as the visible cover. However, evidence from other experiments (Baillargeon 1991) indicates that even young infants can make use of visual reminders to make predictions concerning hidden objects.

Conclusions

The results summarized above 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. However, under the same conditions 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 centred on a distinction between a protuberance and no protuberance. 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.

Other phenomena

In the preceding sections, we have examined the development of infants' intuitions about three distinct phenomena: support, collision, and unveling phenomena. In each case, we have argued that infants' knowledge develops in a regular sequence beginning with the identification of a core event, followed in time by the addition of discrete and continuous variables (for a discussion of how variables are revised in time, see Baillargeon (in press *a*)).

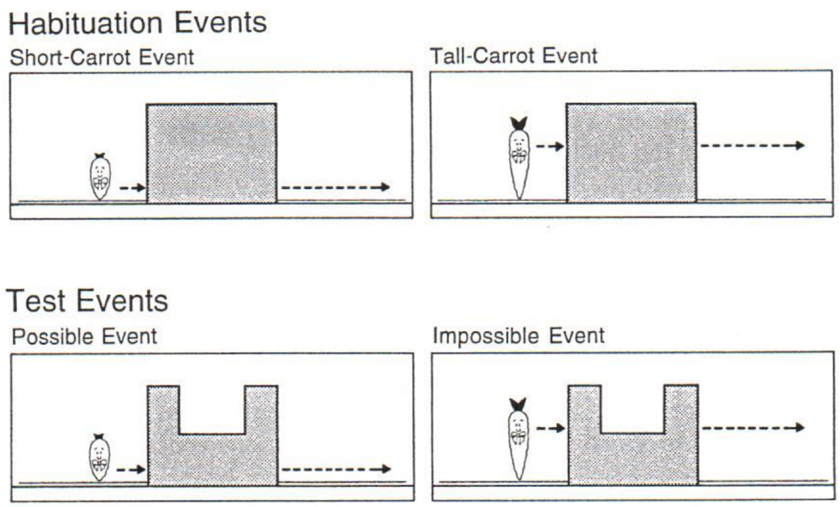

Fig. 4.15. Schematic drawing of the events used by Baillargeon and DeVos (1991).

Would other physical phenomena lend themselves to similar developmental descriptions? Research already in the literature provides encouraging hints for future investigations.

Occlusion phenomena

In an earlier experiment we examined whether 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 (Baillargeon and DeVos 1991). The infants were habituated to a toy carrot that slid back and forth along a horizontal track whose centre 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 Fig. 4.15). On alternate trials, the infants saw a short or a tall carrot slide along the track. Following habituation, the mid-section 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) realized that the height of each carrot determined whether it should be visible in the screen window and hence (b) were surprised that the tall carrot failed to appear in the window in the impossible event.

In a subsequent experiment, 3-month-old infants were tested using the same procedure (Baillargeon and DeVos 1991). However, unlike the 3.5-month-old infants, these younger infants tended to look equally at the impossible and the possible test events. Together, these results might be taken to suggest that, by 3.5 months of age, infants have already identified one variable that affects the outcome of occlusion events: they realize that whether an object is fully or partially visible when passing behind an occluder depends on the height of the object relative to that of the occluder. However, younger infants may not have identified this variable.

These data give rise to intriguing questions regarding the development of infants' intuitions about occlusion phenomena. Do infants go through an initial stage in which they expect any object to be invisible when passing behind any occluder? Do infants then go on to identify both object variables (e.g. height and width of the object) and occluder variables (e.g. presence and location of windows) that are relevant to occlusion events? In collaboration with Andrea Aguiar, we have recently begun experiments that address these questions. Although preliminary, our results suggest that the answers to the questions are likely to be positive.

Containment phenomena

In one experiment, Sitskoorn and Smitsman (1991) presented 6-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; however, in the impossible event, 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, suggesting that they were aware that the width of the block relative to that of the box determined whether one could fit into the other.

Future experiments could ask the following questions. Do infants go through an initial stage in which they expect that any object can be inserted into any open container, regardless of their respective dimensions? Also, at what age do infants become aware that the height, width, and compressibility of an object affect whether it will fit inside a given container? In collaboration with Andrea Aguiar, we have recently undertaken experiments that bear on this question. The data collected so far suggest that, at 5.5 months of age, infants are still unaware that the size of an object can be used to predict whether it can be contained in another;

unlike the infants tested by Sitskoorn and Smitsman (1991), our younger subjects failed to be surprised when shown a large ball being lowered into a much smaller container.

Passing-through phenomena

In a recent experiment, Spelke *et al.* (1992) habituated 4-month-old infants to an 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 test event that were 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 upper surface of the apparatus. The infants looked reliably longer at the impossible than at the possible event, suggesting that, by 4 months of age, infants are aware that the width of an object relative to that of a gap affects whether one can pass through the other (for another example of an arrested-motion phenomenon in which 4.5-month-old infants appear aware of a size variable, see Baillargeon (1991)).

Further experiments could ask the following questions. Is there an initial stage in which infants expect any object to pass through any surface that presents a gap, regardless of their respective dimensions? At what age do infants become aware that these dimensions matter?

Mechanisms of change

In the preceding section, we have described striking parallels in the development of infants' knowledge of support, collision, and unveiling pehnomena. We have also hinted, on the basis of various findings, that similar patterns may be found in the study of other phenomena such as occlusion, containment, and passing-through phenomena.

How can these various developmental sequences be explained? We believe that they reflect, not the gradual unfolding or progressive enrichment of innate beliefs about objects, but rather the application of a highly constrained innate learning mechanism to available data. 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 this, consider the developmental sequence revealed in the support experiments described above (pp. 86–7). One might propose that 3-month-old infants have already learned that objects fall when released in mid-air (Needham and Baillargeon 1993*b*) because this expectation is consistent with countless observations (e.g. watching their carers drop peas in pots, toys in baskets, clothes in hampers) and manipulations (e.g. noticing that their dummies fall when they open their mouths) available virtually from birth.

Furthermore, one might speculate that infants do not begin to recognize what type of contact is needed between objects and their supports until 4.5 months (R. Baillargeon, H. Raschke, and A. Needham, in preparation) 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 (White *et al.* 1964; Newell *et al.* 1989). With this new-found ability, infants may have the opportunity deliberately to place objects against other objects, and to observe the consequences of these actions. According to this account, the sex difference revealed in our experiment would be traceable to female infants' engaging in these manipulations slightly ahead of 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 available data 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 (Rochat and Bullinger, in press). For the first time, infants may have the opportunity to deposit objects on tables and to note that they 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 carers rarely deposit objects against vertical surfaces or on the edges of horizontal surfaces. However, there is no a priori reason to assume that infants could not learn such variables if given appropriate observations. We have recently undertaken a new research programme to investigate this possibility. This programme involves experiments that attempt to teach infants initial concepts and variables that they have not yet acquired.

To illustrate, consider once again the finding that 6.5-month-old 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 above that infants identify the variable 'amount of contact' when they begin to generate, through their own manipulations, data from which to learn it. 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 aged less than 6.5 months 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? To examine these questions, we have recently begun an experiment in which 5.5-month-old infants are tested with events similar to those used in the 15 per cent condition in the experiment conducted by Baillargeon *et al.* (1992) (see Fig. 4.5). Prior to seeing these test events, however, the infants receive training trials in which they see a hand deposit a box on a platform and then withdraw a short distance, as in Needham and Baillargeon (1993*a*) (see Fig. 4.1). On alternate trials, the box is deposited in such a way that either 100 per cent or only 15 per cent of its bottom surface is in contact with the platform. In the first situation, the box remains stable when released; in the second, the box falls. Our hope is that, after seeing such training trials, infants will for the first time show surprise when, in the impossible test event, the finger pushes the box until only 15 per cent of its bottom surface rests on the platform.

In the course of conducting this and related experiments, we hope to determine precisely what type of observations, and how many, are necessary for infants to abstract the variable 'amount of contact'. The interest of such teaching experiments is that they will provide useful insights into the nature and properties of infants' innate learning mechanisms.

CONCLUDING REMARKS

The approach to infants' physical reasoning described in this chapter differs from that adopted by Spelke and her colleagues (Spelke 1991; Spelke *et al.* 1992; Chapter 3 of this volume) and Leslie (1988, Chapter 5 of this volume) in several respects. In these brief remarks, we shall focus on one major difference between these approaches, namely the nature and content of infants' innate endowment.

Spelke and her colleagues (Spelke 1991; Spelke *et al.* 1992) have argued that infants are born with certain core beliefs about objects, such as the belief that objects move along connected unobstructed paths. Non-core beliefs, such as the belief that objects require support to remain stable, would be acquired through observations and manipulations of objects. One prediction suggested by this distinction is that core principles would be demonstrated earlier than non-core beliefs, and would be revealed uniformly in all situations in which they are implicated. Non-core principles, in contrast, would yield more fragile piecemeal patterns, with performance varying widely across situations and infants.

The present approach differs from that of Spelke in that it assumes that infants are neither born with nor acquire general beliefs about objects. Rather, infants are thought to identify types of interactions between objects, and to learn in each case first initial concepts and variables. Thus infants are expected to learn separately about barrier phenomena, passing-through phenomena, containment phenomena, and unveiling phenomena, even though all such phenomena reflect the same fundamental principle that two objects cannot occupy the same space at the same time. The evidence, reviewed in this chapter, that infants learn about some of these phenomena long before others is of course consistent with this view; recall, for example, that infants have been shown to be aware that the size of an object affects whether it can pass through a given gap before they realize that the size of an object affects whether it can be inserted in a given container, or that the size of a protuberance in a cloth cover signals the size of the object hidden under the cover.

Of course, it is possible that in the course of development infants or children eventually come to integrate their knowledge of related phenomena into a single unified structure, but we believe that these developments are initially quite separate. Infants, we suspect, go about the world identifying basic ways in which objects behave or interact. These types of interactions are akin to conceptual roles, i.e. infants reason about objects and occluders, objects and gaps, objects and supports, objects and barriers, objects and containers, objects and soft fluid covers, and so on. A key research question, from this perspective, is that of determining how infants' innate learning mechanism leads them to identify, on the basis of available observations and manipulations, these distinct conceptual categories.

Let us now turn to the approach adopted by Leslie (1988, Chapter 5 of this volume). He has suggested that, from birth, infants' reasoning about physical objects is guided by a notion of agency that focuses on mechanical force relations between objects. A staightforward way of reconciling Leslie's perspective with our own would be to propose that one of the fundamental constraints on infants' innate learning mechanism is an intuitive notion of force. From this viewpoint, infants' identification of and learning about different types of physical phenomena would be tantamount to their learning about how force relations are expressed or implemented in different physical contexts. Thus infants' learning about displacement, collision, or arrested-motion phenomena would be described in terms of objects bearing, transmitting, or resisting forces.

At the start of the chapter, we distinguished between two definitions of causality. We suggested that causal reasoning could be characterized at a general level in terms of the construction of conceptual descriptions that capture regularities in objects' displacements and interactions with other objects. However, causality could also be taken to mean something more specific associated with the formation of sequences in which events are linked through force relations. In describing our research in the preceding section of this chapter, we opted implicitly for the first of these definitions: infants' reasoning was discussed in terms of the identification of increasingly sophisticated regularities in the ways in which objects behave and interact. If we were to adopt Leslie's assumption that an intuitive notion of force lies at the core of infants' representations of objects' displacements and interactions, we would be shifting towards the second definition.

At the present time, we are still uncertain whether the data available to us warrant such a shift. Much of Leslie's research with infants has focused on collision events (see discussion of Leslie and Keeble (1987) on pp. 100–4). Such events naturally lend themselves to discussions of force relations. But what of other events such as support or unveiling events? Should we assume that infants represent such events in terms of objects passively exerting or resisting forces? And what of events such as occlusion events, where force descriptions seem inapplicable?

No doubt future research will help us to determine which, if any, of the three approaches discussed here most closely captures the development of infants' physical reasoning. Given the merits of each approach, however, it is plausible that our final model of physical reasoning in infancy will represent a combination of all three approaches. How might such a model be characterized? One possibility is that infants will be thought to be born with an innate learning mechanism that guides their identification of and learning about distinct physical phenomena—distinct conceptual ways in which objects behave and interact. Among the constraints on this learning mechanism will be a few core intuitive notions. One such notion may be related to a definition of an object—a definition less involved than but nevertheless akin to some of the core beliefs posited by Spelke to be innate (for example a tendency to view connected surfaces or surfaces that move together as wholes). Another such notion might be the force notion proposed by Leslie. However, such a notion would no longer operate as the central or key element in infants' physical representations; rather, it would operate as one of several constraints on these representations. In this broad perspective, infants' causal reasoning would thus come to encompass both definitions of causal reasoning mentioned earlier.

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Part III

Causal understanding in naïve psychology

Foreword to Part III

Readers heartened by agreement may wish to linger over this section; they will find, despite keen differences in style, greater consensus than in other sections. For instance, all three chapters agree on the starting point of naïve psychology: infants distinguish categorically between objects whose motions are internally and externally caused.

Alan Leslie divides the concept of agency into three hierarchically ordered subtheories, each of which activates the other, and deals with agency on an increasingly internal level. The first, dealing with outward mechanical properties, pivots on the concept of force and stresses that agents (unlike physical objects) have internal and renewable sources of force. The second notes that agents are not merely internally motivated self-propelled systems; they also perceive the environment, pursue goals, and interact with one another. The final component moves inside the agent and treats agents' beliefs about the world, representing their propositional relations to information with a meta-representational data structure that is specific to this subsystem.

In this neat set of interlocking subtheories, Leslie captures the three principal levels of an organism: physical, motivational, and cognitive. The reader will find a truly profound agreement between parts of his system and that of Gelman, Durgin, and Kaufman, as well as little disharmony with that of Premack and Premack. Moreover, in the case of the latter two, each fills out the part underplayed by the other. For example, Leslie gives a full account of the mechanical level showing the explanatory merit of his concept of force, while Premack and Premack dwell on the motivational level, showing the explanatory merit of the concepts of value and power.

Rochel Gelman, Frank Durgin, and Lisa Kaufman argue that infants use causal principles in distinguishing animate from inanimate objects. These 'first' principles concern 'requisite energy sources' and the 'stuff' of which an object is made. The cause of animate motion, they argue, comes from internally controlled release of stored chemical energy, whereas the cause of inanimate motion is external force and involves a transfer of energy from one object to another. It is this knowledge, they contend, and not perceptual information that enables the infant to distinguish animate from inanimate. Parts of Gelman's 'first principles' and the first two of Leslie's 'subtheories' are siblings if not twins in different attire.

Gelman and her colleagues discount a hypothesis by Steward (1984), according to which infants identify animate objects by their failure to move according to Newtonian principles. That hypothesis may sink without assistance, however, for it not only defines a major ontological category on negative grounds, but also presupposes (unrealistically) an exquisite mastery of Newtonian principles by the infant. When calling into question the informativeness of spatio-temporal analysis, why fix on deviations from Newton? There are livelier alternatives. Action at a distance and goal directedness are also spatiotemporal analyses.

The ontological category of Gelman and her associates is that of animacy, which presupposes the distinction between alive and not alive and thus has one foot in pyschology and the other in biology. It is a more complex category than that of either agency or intentional, which does not presuppose the distinction and has both feet in psychology.

An intentional object, in the model proposed by David Premack and Ann James Premack, is one that is both self-propelled and goal-directed. Although, in their view, infants lack both a general concept of goal and a well-formed motivational theory, they can recognize three kinds of goal-seeking. Infants interpret goal-directed action as intentional, i.e. internally caused.

Value is the fundamental property that infants attribute to the interaction between intentional objects. Recognition of power—that some intentional objects can control the movement of others—leads the infant to distinguish between free and forced co-movement, interpreting the former as group and the latter as possession. The older infant 'explains' the properties that it attributes in terms of states of mind. Thus Premack and Premack join Spelke in assigning 'theory' to the infant, but include the most basic of human dispositions, the disposition to explain.

D.P.
A.J.P.

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