CHAPTER TWENTY-THREE

Infants' understanding of the physical world

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Traditionally, researchers believed that infants understand very little about the physical world. With the advent of new methodologies, however, investigators came to realize that even young infants possess a surprising wealth of knowledge about physical events. These findings led researchers to orient their efforts in a new direction and to ask how infants attain their physical knowledge. The account my colleagues and I have proposed holds that infants are born with a specialized learning mechanism that guides their acquisition of physical knowledge. I first present this model and then review some of the evidence supporting it, focusing in particular on findings from investigations of infants' knowledge about collision, occlusion, and support events. Finally, I examine alternative accounts of infants' approach to the physical world and discuss ways in which these different accounts can be reconciled.

Les chercheurs ont longtemps cru que les nourrissons n'avaient qu'une compréhension très limitée de l'univers physique. Cependant, la mise au point de nouvelles méthodologies a permis d'observer que, même tôt, les nourrissons disposaient de connaissances étonnamment riches sur les phénomènes physiques. Ce constat a réorienté les efforts dans une direction consistant à se demander comment les nourrissons accèdent à de telles connaissances. Selon l'explication ici proposée, ces derniers naîtraient dotés d'un mécanisme spécialisé d'apprentissage qui guide leur acquisition. La présentation de ce modèle est suivie de l'examen de certains des éléments de preuve le validant, avec une insistance particulière sur les résultats de travaux mettant en évidence les connaissances des nourrissons sur les phénomènes de collision, de masquage (produit par un écran) et d'appui. Sont enfin présentées d'autres explications de l'accès des nourrissons à l'univers physique et discutées les façons de concilier les diverses explications existantes.

INTRODUCTION

As they look about them, infants routinely observe many different physical events: For example, they may see a parent pour juice into a cup, stack dishes on a table, or store groceries in a cupboard, or they may see a sibling drop a ball, hit a tower of blocks, or send a toy car crashing into a wall. How well do infants understand such events? Traditionally, investigators assumed that infants understand very little about the physical world (e.g. Piaget, 1952, 1954). This conclusion was based primarily on analyses of infants' performance in object-manipulation tasks. For example, young infants were said to be unaware that an object continues to exist when hidden because they consistently failed tasks that required them to search for a toy hidden behind or under a cover (e.g. Piaget, 1952, 1954).

In time, however, researchers came to realize that young infants might perform poorly in object-manipulation tasks, not because they lacked the necessary physical knowledge, but because they had difficulty planning and executing complex action sequences. This concern led investigators to seek alternative methods for assessing infants' physical knowledge, methods that did not depend on the performance of complex actions.

During the 1980s, several new methods were developed that focused on infants' visual attention to events. These methods were inspired by the well-documented finding that infants tend to look longer at novel than at familiar stimuli (e.g. Fagan, 1970, 1971, 1972, 1973; Fantz, 1964; Friedman, 1972). One such method is the *habituation-dishabituation* method (e.g. Kellman & Spelke, 1983; Kotovsky & Baillargeon, 1994; Leslie & Keeble, 1987; Oakes, 1994; Spelke, Kestenbaum, Simons, & Wein, 1995a; Woodward, Phillips, & Spelke, 1993). In a typical experiment, infants are first habituated to an event (i.e. they are shown the event repeatedly until their looking time declines to a pre-selected criterion level). Next, infants are presented with one or two test events. Dishabituation or increased looking at one or both events (with appropriate controls) is taken to indicate that infants' physical knowledge leads them to perceive the event(s) as novel or unexpected relative to the habituation event presented earlier.

Another visual-attention method that is commonly used in investigations of infants' physical knowledge is the *violation-of-expectation* method (e.g. Arterberry, 1993; Baillargeon, 1986; Baillargeon, Spelke, & Wasserman, 1985; Needham & Baillargeon, 1997; Spelke, Breinlinger, Macomber, & Jacobson, 1992; Wilcox, Nadel, & Rosser, 1996). In a typical experiment, infants are presented with a possible and an impossible test event. The possible event is consistent with the knowledge or expectation being examined in the experiment; the impossible event, in contrast, violates this expectation. Longer looking at the impossible than at the possible event (with appropriate controls) is taken to indicate that infants' physical knowledge leads them to view the impossible event as more novel or unexpected than the possible event. Prior to the test trials, infants often


Habituation: Causal Event

Test: Causal Event Reversed

Habituation: Non-causal Event

Test: Non-causal Event Reversed

FIG. 23.1 Schematic drawing (based on the authors' description) of the test events used in Leslie and Keeble (1987).

receive familiarization or habituation trials designed to acquaint them with various aspects of the test events. However, these trials play a different role in the violation-of-expectation than in the habituation-dishabituation method: They are intended simply to introduce infants to the test situation, not to provide them with an essential basis of comparison for evaluating the novelty of the test events.

Multiple tests of infants' physical knowledge conducted with these new visual-attention methods revealed that, contrary to traditional claims, even young infants possess a surprising wealth of knowledge about the physical world (for recent reviews, see Baillargeon, 1995; Leslie, 1995; Mandler, in press; Needham, Baillargeon, & Kaufman, 1997; Oakes & Cohen, 1995; Spelke, 1994). To illustrate this claim, I will describe two experiments: a habituation-dishabituation experiment conducted by Leslie and Keeble (1987), and a violation-of-expectation experiment conducted by Spelke et al. (1992).

The experiment conducted by Leslie and Keeble (1987) examined whether 6-month-old infants distinguish between causal and non-causal events (see Fig. 23.1). The infants were habituated to one of two filmed events: (a) a causal event in which a red brick approached and contacted a green brick, which immediately moved off; or (b) a noncausal event in which the two bricks' motions were separated by a 0.5sec delay. Following habituation, the infants watched the

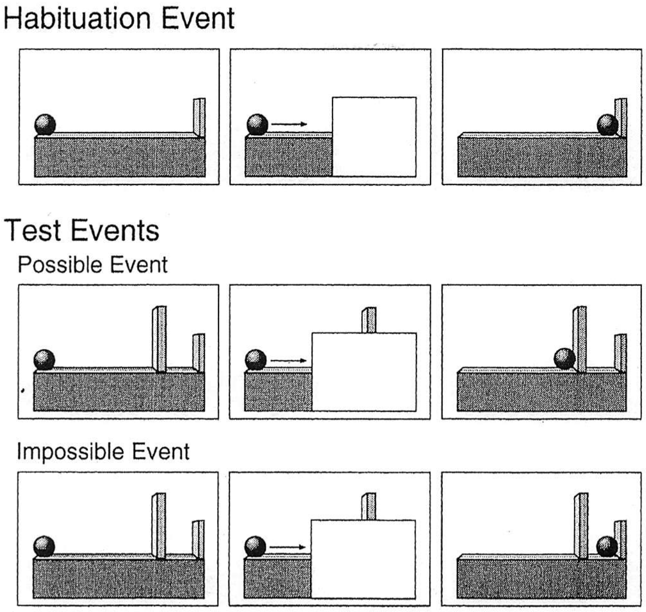

FIG. 23.2 Schematic drawing (based on the authors' description) of the test events used in Spelke et al. (1992). From "Physical reasoning in infancy" (p. 183), by R. Baillargeon, 1995, in M. S. Gazzaniga (Ed.-in-chief), *The cognitive neurosciences* (pp. 181–204). Cambridge, MA: MIT Press. Copyright 1995 by Massachusetts Institute of Technology. Reprinted with permission.

same event in reverse. The authors reasoned that, whereas only spatiotemporal direction was reversed in the noncausal event, both spatiotemporal and causal direction was reversed in the causal event; therefore, if the infants were sensitive to causality, they should dishabituate more to the causal than to the noncausal test event. The infants looked reliably longer when the causal as opposed to the noncausal event was reversed. These and control results suggested that, by 6 months of age, infants are already sensitive to the causal properties of events.

The experiment conducted by Spelke et al. (1992) tested whether 2.5-month-old infants realize that objects exist continuously in time and move along continuous, unobstructed paths (see Fig. 23.2). The infants sat in front of a wide platform; at the right end of the platform was a tall, thin box. The infants were habituated to the following event: First, a screen was lowered in front of the right half of the platform; next, a ball rolled from left to right along the platform and disappeared behind the screen; after a pause, the screen was raised to reveal the ball resting against the box at the end of the platform. Following habituation, the infants saw a possible and an impossible test event similar to the habituation event except that a second box was placed on the platform; this box was taller than the end box and protruded above the screen. At the end of the test events, the screen was removed to reveal the ball resting against either the tall box (possible event) or the end box (impossible event). The infants looked reliably longer at the impossible than at the possible event, suggesting that they (a) understood that the ball continued to exist, and pursued its trajectory, after it moved behind the screen; (b) realized that the ball could not roll through the space occupied by the tall box; and hence (c) expected the ball to stop against the tall box and were surprised when it did not. These and control results suggested that, by 2.5 months of age, infants already conceive of objects as permanent entities that exist and move continuously in time and space.

The discovery that even young infants possess sophisticated intuitions about objects led researchers to focus their efforts in a new direction and to ask not only *what* infants know about the physical world, but also *how* they attain this knowledge. Largely as a result of this new developmental focus, several accounts have been proposed in recent years that attempt to explain infants' rapid mastery of the physical world (e.g. Baillargeon, 1995; Karmiloff-Smith, 1992; Leslie, 1995; Mandler, in press; Spelke, 1994; Thelen & Smith, 1994). In the next section, I describe the account that my colleagues and I have developed over the past few years (e.g. Baillargeon, 1994, 1995; Baillargeon, Kotovsky, & Needham, 1995). Next, I describe a few alternative accounts of infants' approach to the physical world, and discuss ways in which these different accounts can be reconciled.

INFANTS' LEARNING MECHANISM

According to our model, infants are born with a specialized learning mechanism that guides their acquisition of physical knowledge (e.g. Baillargeon, 1994, 1995; Baillargeon et al., 1995). This mechanism is thought to be responsible for at least two closely intertwined learning processes. One is the formation of broad *event and object categories. Event* categories correspond to distinct ways in which objects behave or interact. We believe that infants' early event categories include: collision events (events in which an object approaches and hits another object); arrested-motion events (events in which an object approaches and hits a broad surface such as a wall or floor); occlusion events (events in which an object becomes occluded by another, closer, object or surface); and support events (events in which an object becomes supported by another object or surface). *Object* categories refer to the distinct types of objects that exist in the world. We suspect that infants' early object categories include: animate objects (objects such as people who possess certain facial features, can express emotions, respond contingently, are capable of a wide range of self-motions, and so on); inanimate, self-moving objects (objects such as cars that lack many of the properties of animate objects but are capable of at least limited self-motion); and inanimate, inert objects (objects such as cups that move only when acted on). From an early age, infants take into account the type of object involved in an event when interpreting the outcome of the event. To illustrate, infants respond somewhat differently to collision events involving self-moving and inert objects (e.g. Kotovsky & Baillargeon, in prep., in press a,b; Leslie, 1982, 1984a,b; Leslie & Keeble, 1987; Oakes, 1994; Oakes & Cohen, 1995; Spelke, Phillips, & Woodward, 1995b; Woodward et al., 1993). Ongoing experiments in our laboratory are exploring infants' expectations about the behavior of self-moving objects (e.g. Kaufman, 1997). Due to lack of space, however, the remainder of this chapter will focus exclusively on research conducted with inert objects.

The second process that is controlled by infants' learning mechanism is the identification, for each event category, of an *initial concept* and *variables*. We believe that, when learning about a new event category, infants first form a preliminary, all-or-none concept that captures only the essence of the event. With further experience, this initial concept is progressively elaborated. Infants slowly identify variables that are relevant to the event and incorporate this additional knowledge into their reasoning, resulting in increasingly accurate predictions and interpretations over time.

What is the nature of the learning mechanism that directs infants' formation of event categories and identification of initial concepts and variables? To answer this question, we have been pursuing a dual research strategy. A first strategy has been to investigate distinct event categories (e.g. collision, occlusion, and support events) and trace their respective developmental courses. We believe that specifying and comparing the sequences of variables that emerge for different event categories can yield fundamental insights about the nature of infants' learning mechanism. A second strategy has been to conduct experiments in which we attempt to "teach" infants variables they have not yet identified, by presenting them with pertinent observations. We hope that by discovering precisely what observations, and how many observations, infants require for learning, we can better understand how their learning mechanism processes and stores new information and integrates it with prior information to yield new knowledge. I now describe some of the findings we have obtained in pursuing these two strategies.

Knowledge about different event categories

Collision events. In our first series of experiments on the development of infants' reasoning about collision events (e.g. Kotovsky & Baillargeon, 1994, in press a, in prep.; see Baillargeon, 1995, and Baillargeon et al., 1995, for reviews), infants aged 2.5 to 11 months were presented with collision events involving a moving object (a cylinder rolling down a ramp) and a stationary object (a wheeled toy bug positioned on a track at the bottom of the ramp).

The results of these experiments (summarized in Fig. 23.3) indicate that, by 2.5 months of age, infants have formed an initial concept of collision centered on a simple *impact/no-impact* distinction: They expect a stationary object to be displaced when hit by a moving object, and to remain stationary otherwise. Thus, infants are surprised to see the bug remain stationary when hit by the cylinder, and to see the bug move when not hit.

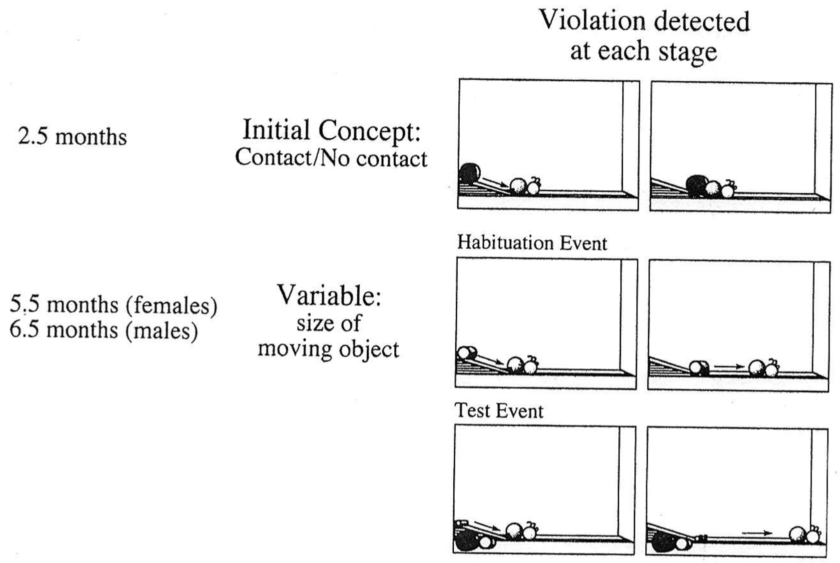

FIG. 23.3 Schematic description of the development of infants' knowledge about collision events: 2.5 to 6.5 months.

At about 5.5 to 6.5 months of age (females precede males by a few weeks in this development), infants add a variable to their initial concept: They begin to appreciate that in a collision between a moving and a stationary object, the *size*[1] of the moving object affects the length of the stationary object's displacement. After seeing a medium cylinder cause the bug to roll to the middle of the track, infants judge that the bug should roll farther when hit by a larger but not a smaller cylinder. Younger infants are not surprised to see the bug roll farther with either the larger or the smaller cylinder, even though (a) all three of the cylinders are simultaneously present in the apparatus, so that their sizes can be readily compared, and (b) infants have no difficulty remembering (as shown in other experiments) that the bug rolled to the middle of the track when hit by the medium cylinder. These results suggest that, prior to 5.5 to 6.5 months of age, infants do not understand the proportional relation between the size of the cylinder and the length of the bug's trajectory.

In a second series of experiments, 8-month-old infants were presented with collision events similar to those in our initial experiments except that the bug was replaced with a box (e.g. Kaufman & Kotovsky, 1997; Kotovsky & Baillargeon, in press b). The results of these experiments (summarized in Fig. 23.4) suggest that, at about 8 months of age, infants begin to distinguish

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[1] We refer to the moving object's size rather than mass because our data are insufficient to determine which variable guided the infants' responses (Kotovsky & Baillargeon, 1994, in press a).

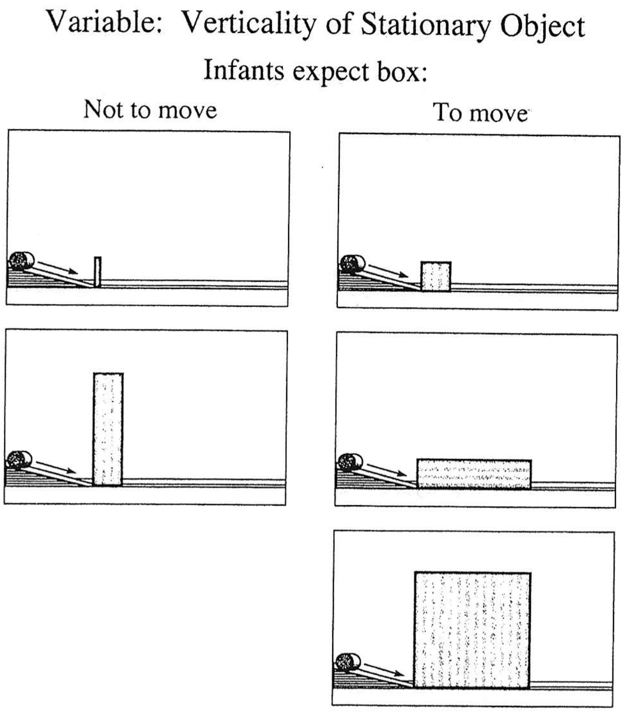

FIG. 23.4 Schematic description of the development of infants' knowledge about collision events: 8 months.

among stationary objects between those that are likely to be displaced when hit, and those that are not. The basis for this distinction appears to be *verticality*: Infants expect objects with a salient vertical dimension to be immovable, and objects lacking such a dimension to be movable. Thus, infants expect boxes that are taller than they are wide, irrespective of their absolute dimensions, to remain stationary when hit by the cylinder; all other boxes are expected to move, again irrespective of their absolute dimensions.

How can we explain the developmental sequence revealed by these experiments? According to our model, infants cannot identify a variable as relevant to an event category unless they have available *contrastive data* from which to abstract it. By contrastive data, we mean observations or manipulations indicating that an outcome occurs when some condition is met (positive data), and does not occur when the condition is not met (negative data). As an illustration, consider the finding that at about 8 months of age infants use verticality or its absence as a basis for predicting whether an object will remain stationary or move when hit. At about 7 to 8 months of age, infants begin to crawl and to pull themselves upright by holding on to surfaces that are often tall and thin:

the legs of tables and chairs, the vertical slats in cribs and banisters, and so on. On the basis of these manipulations, infants may conclude that objects with a salient vertical dimension, unlike other objects, typically remain stationary when acted on. Prior to this stage, infants would typically have been given only light objects to manipulate (e.g. cups, spoons, bowls, rattles, bottles, shoes, toy cars, blocks, keys, stuffed animals, and so on). Hence, infants' experiences with objects (as distinct from broad surfaces such as walls, floors, or tables) would all support the notion that objects typically move when acted on. Infants' observations of their caretakers' actions on objects would be consistent with the same conclusion: After all, infants must have few opportunities to observe their parents act on objects that remain stationary when pushed, pulled, or struck. When infants begin to navigate their environment, and to look for safe handholds to pull themselves upright, they must quickly learn to recognize, among the entire class of objects, a vertical subclass that can be relied on to remain stationary when acted on.

With further experience, infants presumably refine their ideas about verticality, and come to realize that only vertical objects that are rigidly anchored at the top or bottom are likely to provide useful handholds. At the same time, infants must also learn that nonvertical objects that are large or heavy are less likely to move when acted on than are small or light ones. As infants begin to explore their environment on their own, they encounter objects far heavier than those they have previously experienced. Many parents will fondly remember their crawling infants intently pulling heavy books from shelves or dragging heavy saucepans out of cupboards. Such experiences must lead infants to consider objects' size as well as verticality when predicting the outcome of collision events. Experiments are under way in our laboratory to test these speculations.

Occlusion events. In our experiments on the development of infants' knowledge about occlusion events (e.g. Aguiar & Baillargeon, submitted a,b; Baillargeon & DeVos, 1991; Baillargeon & Graber, 1987), infants aged 2.5 to 5.5 months were tested with simple occlusion problems involving a screen and a toy such as a toy mouse. The infants were first habituated to the mouse moving back and forth behind the screen. Following habituation, a portion of the screen was removed, and infants judged whether the mouse should remain continuously hidden or should become temporarily visible when passing behind the screen.

The results of these experiments (summarized in Fig. 23.5) suggest that, by 2.5 months of age, infants have formed an initial concept of occlusion centered on a simple *behind/not-behind* distinction: They expect an object to be hidden when behind an occluder, and to be visible otherwise. This concept leads infants to be surprised when the mouse fails to appear between two separate screens (see Fig. 23.5). Presumably, infants (a) assume that the mouse exists continuously in time and moves continuously through space; (b) expect the mouse to

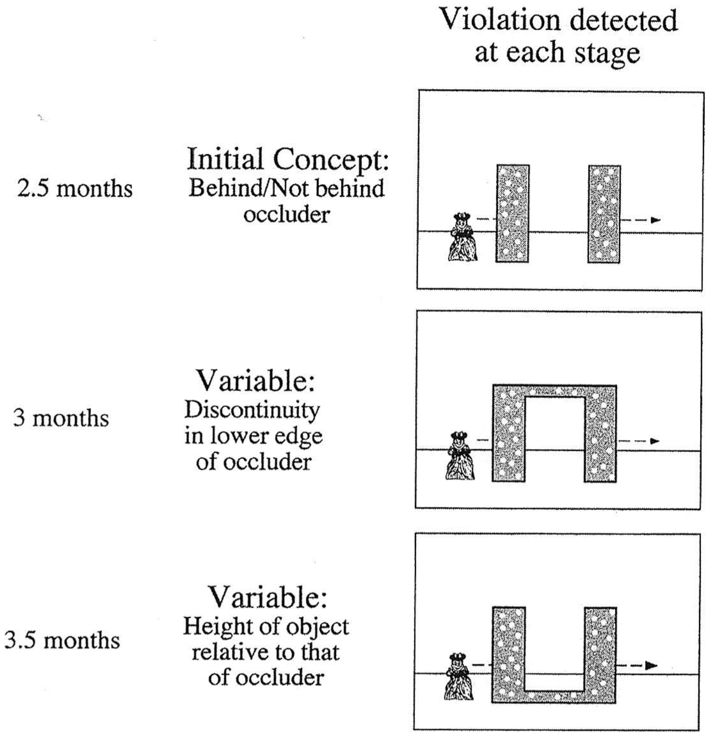

FIG. 23.5 Schematic description of the development of infants' knowledge about occlusion events: 2.5 to 3.5 months.

be hidden behind each screen and to be visible between them; and hence (c) are surprised when this last expectation is violated. However, infants' understanding of occlusion is still extremely primitive: When the two screens are connected by a narrow strip at the top or bottom, infants no longer show surprise when the mouse fails to appear between them. Infants apparently view the connected screens as forming a single object and, consistent with their simple behind/not-behind distinction, they expect the mouse to be hidden when passing behind it. Infants are not able to take into account additional variables to predict whether the mouse should remain hidden or become temporarily visible when passing behind the screen.

By 3 months of age, infants have already progressed beyond their initial concept of occlusion and identified a variable that enables them to better predict the outcome of occlusion events. When an object moves behind an occluder, infants now attend to the lower edge of the occluder; if this lower edge presents a discontinuity, infants expect the object to appear in the opening. As shown in Fig. 23.5, when faced with two screens that are connected at the top, 3-month-olds, unlike 2.5-month-olds, are surprised if the mouse fails to appear between the screens. Infants still show little or no surprise, however, when the mouse fails to appear between two screens that are connected at the bottom: Infants attend to lower but not upper occluder discontinuities.

By 3.5 months of age, infants have added a further variable to their knowledge of occlusion events. When an object moves behind an occluder that has a discontinuity along its upper edge, infants take into account the *height* of the object to predict whether it will remain fully hidden or become partly visible when passing behind the occluder. As shown in Fig. 23.5, when the two screens are connected at the bottom by a strip shorter than the mouse, infants are now surprised when the mouse fails to appear above the strip.

How can we account for the developmental sequence just described? The most likely explanation, we believe, is the same one that was advanced when discussing the development of infants' knowledge about collision events. As they look about them, infants experience countless occlusion events every day. These data (which no doubt steadily improve in quality as infants' visual tracking ability itself improves; see Aslin, 1981, and Banks, 1983) then feed into the infants' learning mechanism. The mechanism in turn produces a sequence of increasingly refined variables that enable infants to predict occlusion outcomes more and more accurately over time. As with collision events, we believe that the primary data infants use to identify occlusion variables are contrastive data: For example, infants identify height as an important variable after noting that, when an object passes behind a screen with an upper window, the object is likely to appear in the window if it is taller (positive data) but not shorter (negative data) than the window's lower edge.

Support events. In our experiments on the development of infants' knowledge about support events (e.g. Baillargeon, Needham, & DeVos, 1992; Needham & Baillargeon, 1993; see Baillargeon, 1995, and Baillargeon et al., 1995, for reviews), infants aged 3 to 12.5 months were presented with simple support problems involving a box and a platform; the box was released in one of several positions relative to the platform (e.g. off the platform, on top of it, against its side, and so on), and the infants judged whether the box should remain stable when released.

The results (summarized in Fig. 23.6) indicate that, by 3 months of age, infants have formed an initial concept centered on a *contact/no-contact* distinction: They expect an object to fall if it does not contact another object when released, and to be stable if it does. As shown in Fig. 23.6, infants expect the box to fall when released off the platform, but not against its side. Ongoing experiments in our laboratory suggest that infants also show little surprise when the box is released under the top of an open platform and fails to fall. In this initial stage, infants apparently view *any* contact between the box and the platform as sufficient to ensure the box's stability.

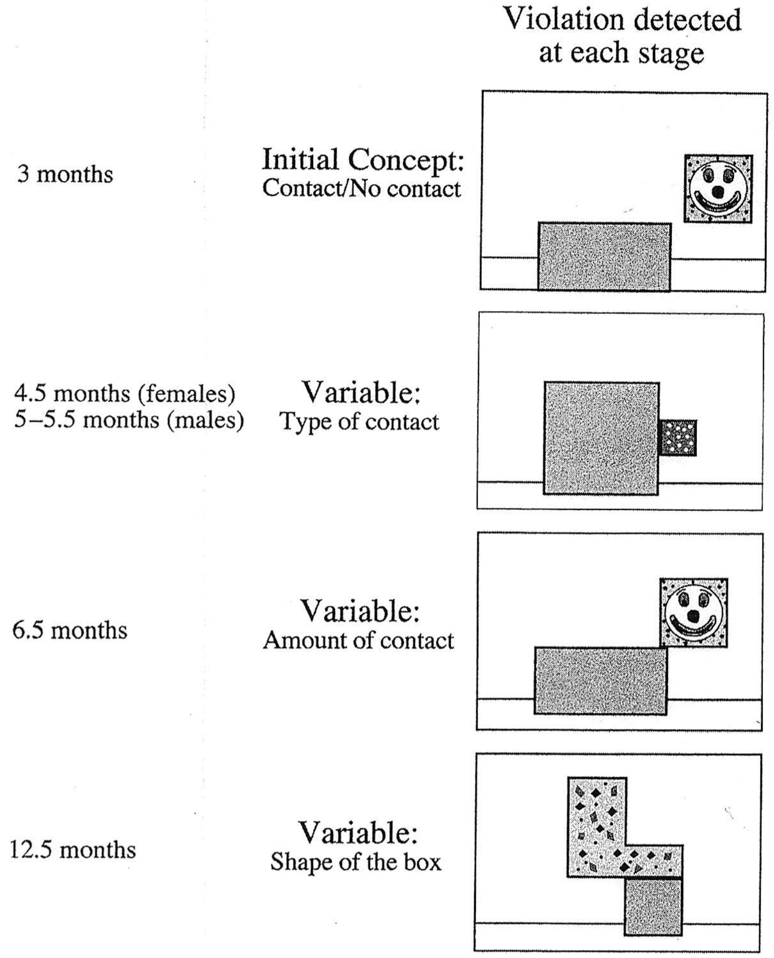

FIG. 23.6 Schematic description of the development of infants' knowledge about support events: 3 to 12.5 months.

By about 4.5 to 5.5 months of age (females precede males by a few weeks in this development),[2] infants have progressed beyond their initial concept of support: They now realize that the *type of contact* between an object and its support must be taken into account when judging the object's stability. Infants

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[2] The reader may find puzzling the sex differences noted here and earlier in our discussion of the development of infants' knowledge about collision events. We believe that these two sex differences, which are both found in infants aged 4 to 6 months, reflect the slower development of male infants' binocular depth perception. Research by Held, Gwiazda, and their colleagues (e.g. Bauer, Shimojo, Gwiazda, & Held, 1986; Gwiazda, Bauer, & Held, 1989a,b) indicates that, compared to female infants, male infants show slower development of stereopsis during the third through sixth

now expect the box to remain stable when released on but not against or under the platform. Nevertheless, as shown in Fig. 23.6, infants' understanding of support is still very limited: They believe that any amount of contact between the box and the platform can lead to stability.

At about 6.5 months of age, infants overcome this limitation: They begin to appreciate that the *amount of contact* between an object and its support affects the object's stability. Infants now expect the box to fall when a small portion (e.g. the left 15%), but not a large portion (e.g. the left 70%), of its bottom surface rests on the platform (see Fig. 23.6).

Another important development in infants' understanding of support events takes place at about 12.5 months of age. Prior to this stage, infants treat symmetrical and asymmetrical (e.g. L-shaped) objects alike: They expect any object to be stable as long as half or more of its bottom surface lies on a support. At about 12.5 months, however, infants begin to take into account an object's *shape or proportional distribution*[3] when judging its stability. When shown an L-box that has 50% of its bottom surface supported on a platform (see Fig. 23.6), infants attend to the entire box, not just its bottom surface, and they expect the box to be stable only if the proportion of the box that lies on the platform is greater than that off the platform.

How can we explain the developmental sequence just described? As was the case with collision and occlusion events, our model assumes that each successive support variable is identified by infants' learning mechanism through the analysis of pertinent contrastive data. To illustrate, consider the finding that it is not until about 6.5 months of age that infants begin to appreciate how much contact is needed between objects and their supports. Prior to this age, infants must often see their caretakers deposit objects on horizontal surfaces. In most cases, objects will be released with sufficient overlap with their supporting surfaces to remain stable—only in rare accidental cases will infants see an object fall after being deposited on a surface. Because infants cannot learn in the absence of contrastive data, they will not be able to abstract the variable "amount of contact" from seeing only positive instances of the variable (objects remaining stable when in sufficient contact with their supports). The identification of the variable will thus typically be delayed until infants are able to generate the necessary data for themselves. Researchers have pointed out that when infants attain the ability to sit at about 6 months of age, their upper limbs and hands are relieved from the encumbrance of postural maintenance and thus become free to manipulate objects (e.g. Rochat, 1992). For the first time, infants may have the opportunity to deposit objects on horizontal surfaces and to gather contrastive

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months of life. It seems plausible that infants with a less mature depth perception—be they males or younger females—would be slower at gathering data about objects' spatial arrangements and displacements than infants with a more mature depth perception.

[3] We refer to the object's shape or proportional distribution rather than mass or weight distribution because our data are insufficient to determine which variable guided the infants' responses (see Baillargeon, 1995).

data indicating that objects remain stable when half or more of their bottom surface is supported, and fall otherwise.

According to the model, it is necessary that infants generate contrastive data for the variable "amount of contact" only because in the natural course of events caretakers are unlikely to generate such data for them. Hence, one prediction of the model is that infants might identify this or other variables sooner if they were presented with appropriate contrastive observations. The "teaching" experiments described in the next section were designed to explore this possibility.

Teaching infants new physical variables

As mentioned earlier, our second research strategy to shed light on the nature and operation of infants' learning mechanism has been to teach infants variables they have not yet identified. Our rationale is that by specifying how many observations, and what precise observations, infants require for learning, we can better understand how their learning mechanism processes and stores new information and integrates it with prior information to yield new knowledge.

Jerry DeJong, Julie Sheehan, and I have been attempting to teach infants variables relevant to support events. Two series of experiments are under way, one focusing on the variable "amount of contact", and the other focusing on the variable "shape or proportional distribution". Due to lack of space, only the second series of experiments is described here.

We saw in the previous section that 12.5-month-old infants consider the shape or weight distribution of an asymmetrical box when judging its stability, whereas younger infants do not (e.g. Baillargeon, 1995). Part of the evidence for this conclusion was obtained with a possible and an impossible static display involving an L-shaped box resting on a platform (see Fig. 23.7). In each display, half of the box's bottom surface lay on the platform. In the possible display, the taller, heavier portion of the box rested on the platform; in the impossible display, the shorter, lighter portion of the box was on the platform. Results showed that 12.5-month-old infants looked reliably longer at the impossible than at the possible display; in contrast, younger infants tended to look equally, and equally low, at the two displays. These and other results indicated that infants less than 12.5 months of age expect any box—whether symmetrical or asymmetrical—to be stable as long as 50% or more of its bottom surface is supported.

In our first teaching experiment, 11.5-month-old infants were again shown the possible and impossible L-box test displays. Prior to seeing these displays, however, the infants received two pairs of training trials (see Fig. 23.8). These trials were designed to help the infants realize that a 50%-rule is inadequate for judging the stability of an asymmetrical object. In each pair of trials, the infants saw an asymmetrical box being deposited on a platform; the overlap between the box's bottom surface and the platform was always 50%, as in the L-box displays. In one trial, the heavier portion of the box was placed on the platform and

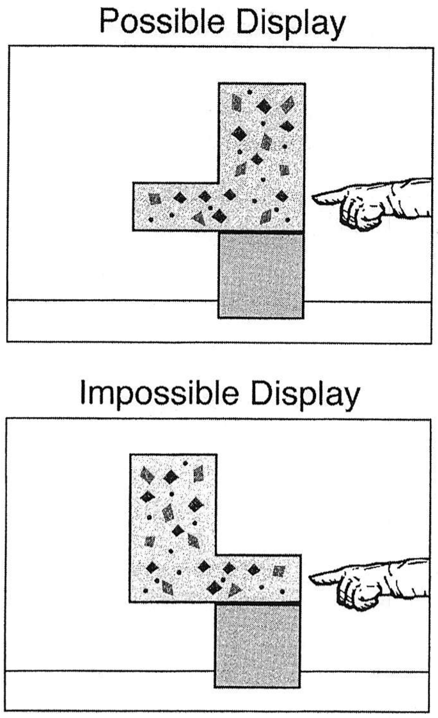


FIG. 23.7 Schematic drawing of the static test displays used in experiments on infants' knowledge of the support variable "shape or proportional distribution of the box". From "A model of physical reasoning in infancy" (p. 332), by R. Baillargeon, 1995, in C. Rovee-Collier and L. Lipsitt (Eds.), *Advances in infancy research* (Vol. 9, pp. 305–371). Norwood, NJ: Ablex. Copyright 1995 by Ablex Publishing Corporation. Reprinted with permission.

the box remained stable when released (box-stays event). In the other trial, the lighter portion of the box was placed on the platform and the box now fell when released (box-falls event). In each training trial, the event was shown repeatedly until the infant either (a) looked away for 2 consecutive seconds or (b) looked 60sec without looking away for 2sec. The infants thus had the opportunity to see the event several times per trial. The two pairs of training trials were identical except that different asymmetrical boxes were used. The box used in the first training pair was shaped like a "B" on its side and was covered with a pink paper decorated with yellow dots; the box used in the second training pair was a right triangle covered with a green paper decorated with white flowers.

After receiving the two pairs of training trials, the infants looked reliably longer at the impossible than at the possible L-box test display. The same positive result was obtained in a second experimental condition in which the B-box was replaced with a right triangle of the same color and pattern as the B-box

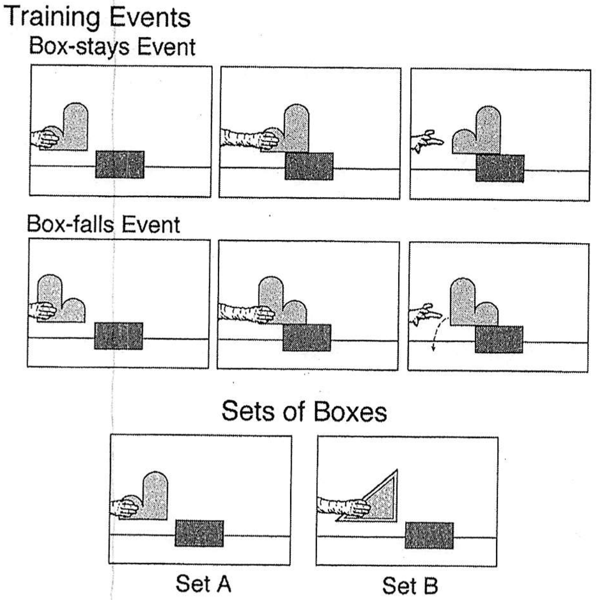
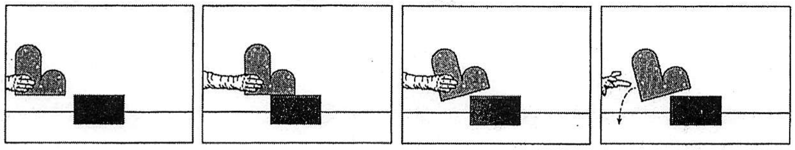


FIG. 23.8 Schematic drawing of the events shown in the experimental teaching condition (see text). Set A was used in the first pair of training trials, and set B in the second pair.

(pink with yellow dots). Together, these results suggest that the infants were able to use the training observations to acquire new knowledge about support. Instead of focusing only on the L-box's bottom surface, the infants now attended to the entire box: they expected it to remain stable when the proportion of the box resting on the platform was greater but not smaller than that off the platform.

There was, however, an alternative interpretation for our findings. Perhaps the infants preferred the impossible display because they had formed during the training trials a superficial association between the box's orientation and its lack of stability (e.g. "when the taller side of the box is on the left, it falls when released"). To test this interpretation, we conducted two control conditions identical to the first experimental condition just described, with one exception: The box-falls training trials were modified so that the infants could form the same association as before, but could no longer acquire new knowledge about support (see Fig. 23.9). In one condition (box-dropped condition), after depositing the B-box or triangle on the platform in each box-falls event, the hand swiftly lifted and released the box; the infants could thus explain the box's fall in terms of their prior knowledge that an object typically falls when released in midair (see Fig. 23.6). In the other control condition (25% condition), only the right 25% of the box's bottom surface was deposited on the platform in each box-falls event; the box's fall was thus consistent with the infants' prior knowledge that

Control Condition: Box Dropped



Control Condition: 25% Overlap

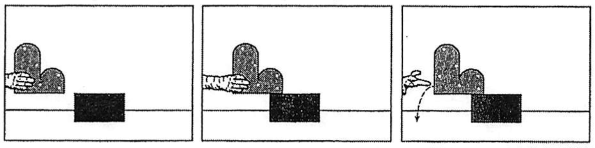


FIG. 23.9 Schematic drawing of the box-falls teaching event shown in each of the two control conditions (see text).

an object typically falls when less than half of its bottom surface is supported (see Fig. 23.6). Thus, in both control conditions, the infants could still learn the same superficial association as in the experimental conditions; however, they could acquire no new knowledge about support because they were shown only outcomes consistent with their existing knowledge.

The infants in the two control conditions tended to look equally at the impossible and possible L-box test displays. These results provided evidence that the infants in the experimental conditions preferred the impossible display because they had acquired new support knowledge during the training trials that affected their responses to the L-box displays during the test trials. These findings point to two important conclusions. First, infants can learn from observation alone important facts about support events. Although acting on objects may at times help infants focus more narrowly on the links between actions and their outcomes, the present data make clear that actions are not necessary for learning, at least for infants of this age learning this type of physical knowledge. Second, the present findings are exciting in that they reveal just how efficient is infants' learning mechanism: Our experiments demonstrate that just a few training trials are sufficient to induce a reliable change in infants' interpretation of support displays.

Would infants still show evidence of learning if given even less information during the training trials than was provided in our initial experiments? In one experiment, we asked whether infants would still succeed if the training trials they received involved a single box, as opposed to two distinct boxes. The infants received two pairs of training trials identical to those used in the experimental conditions described earlier, with one exception: Both pairs of trials were conducted with the same box (the B-box or one of the triangle boxes). The results indicated that the infants tended to look equally at the impossible and possible L-box test displays. This negative finding suggests that, at 11.5 months of age, infants must see at least two distinct boxes or exemplars behaving in the same general manner to abstract a variable. Whether the boxes differ in both shape and coloring, or only in coloring, is immaterial (recall that the infants in our experimental conditions succeeded whether they were trained with the B-box and green triangle or with the pink and green triangles). What matters, apparently, is that two perceptually distinct boxes be seen to behave according to the same physical pattern.

In additional experiments, we found that, unlike 11.5-month-old infants, 11-month-old infants showed no evidence of learning when given four training trials involving two distinct boxes. These younger infants did show a reliable preference for the impossible L-box test display, however, after receiving six training trials involving three distinct boxes (a staircase-shaped box was used in a third pair of training trials).

Why do 11-month-olds require three exemplars, and 11.5-month-olds only two exemplars, to demonstrate learning? One possibility is that older infants possess more efficient information processing abilities and hence need less data to identify variables. Another possibility is that older infants bring to the testing situation more relevant prior observations than younger infants. According to this account, infants slowly become aware in the course of their daily object manipulations that a 50%-rule does not fully account for objects' behavior in support situations: Objects sometimes fall even though half or more of their bottom surface is supported. Infants begin storing such observations, thereby building partial knowledge structures that eventually lead to the identification of the variable "shape or proportional distribution". Thus, 11.5-month-old infants require fewer exemplars to show learning because they bring to the test situation more extensive partial structures than younger, 11-month-old infants.

A final experiment suggests that the second of the two possibilities just described is more likely to be correct. This experiment examined whether 11.5-month-old infants would still show evidence of learning if trained with events depicting *reverse* outcomes—outcomes opposite from those that would normally occur in the world (see Fig. 23.10). As in our initial experiment, 11.5-month-old infants were given two pairs of training trials, one with the B-box and one with the green triangle. Each training pair was composed, as before, of a box-stays and a box-falls trial. The only difference was that outcomes were now reversed so that the box fell when released with its heavier portion on the platform (box-falls event), and remained stable when released with its heavier portion off the platform (box-stays event).

We reasoned that if the infants merely abstracted the invariant relation embedded in the training trials, they should expect the L-box to fall when its heavier portion was off the platform and be surprised when this expectation was violated; the infants should therefore look reliably longer at the possible than at the impossible L-box test display. On the other hand, if the infants attempted to integrate the information conveyed in the training trials with their prior knowledge

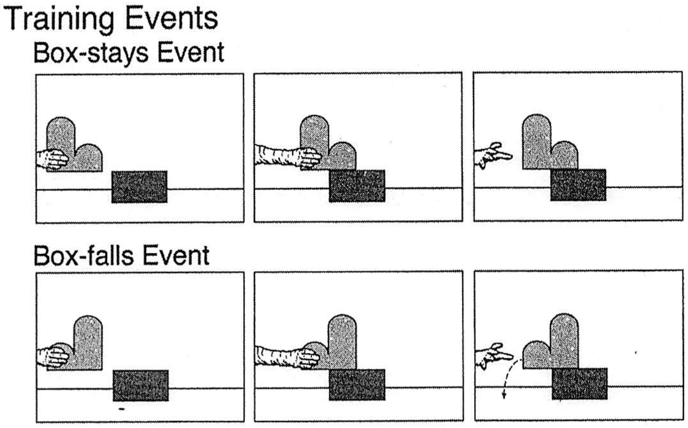


FIG. 23.10 Schematic drawing of the events shown in the reverse teaching condition (see text).

of support, then they should be puzzled by the training trials and show no preference for either the possible or the impossible L-box display.

The infants tended to look equally at the two test displays, suggesting that they had not abstracted during the training trials a rule which they then readily applied to the test trials. These results underscore the fact that infants' responses to training observations cannot be understood solely in terms of the number and content of these observations. When infants bring to a training situation prior knowledge structures relevant to the situation, the net effect of the training will depend on how readily infants can reconcile what they observe with what they know—or, to borrow well-known Piagetian terms, can assimilate their observations to their existing knowledge structures (e.g. Piaget, 1952, 1954, 1970).

Together, the results of these last experiments indicate that at least two factors affect whether training is likely to produce learning: (a) how many distinct exemplars are involved in the training observations; and (b) whether the observations are consistent or inconsistent with infants' prior knowledge of the event category. Although these findings represent only a first, preliminary step in the investigation of infants' responses to training observations, they already make clear how valuable this approach can be in shedding light on the fundamental processes of infants' learning mechanism.

ADDITIONAL INNATE CONTRIBUTIONS

Our account of infants' approach to the physical world holds that infants are born with a specialized learning mechanism that guides their formation of event categories and their identification for each category of a sequence of increasingly refined variables (e.g. Baillargeon, 1994, 1995; Baillargeon et al., 1995). Is infants' learning mechanism the primary innate structure involved in their acquisition of physical knowledge, or do additional innate structures contribute to this acquisition process? We briefly consider two other types of innate structures that have been proposed by other investigators.

Representational vocabulary

One type of innate structures that has been proposed has to do with the information infants would include from the start in their representations of physical events. Such information might include simple physical categories such as "object" and "surface", with object being defined initially as any collection of adjacent, bounded surfaces (e.g. a cup, a spoon, a toy car), and surface as any broad, unidimensional expanse (e.g. a wall, a floor, a table's surface) (e.g. Craton & Yonas, 1990; Kestenbaum, Termine, & Spelke, 1987; Needham et al., 1997; Spelke, 1982; Spelke, Breinlinger, Jacobson, & Phillips, 1993; Termine, Hrynick, Kestenbaum, Gleitman, & Spelke, 1987). Additional information might involve simple spatiotemporal relations between objects and surfaces. Infants would represent, in at least some situations, whether an object is in front of or behind another object, is adjacent to or spatially distant from another object or surface, moves immediately on being contacted by another object or only after some delay, and so on (e.g. Leslie, 1982; Leslie & Keeble, 1987; Oakes, 1994; Oakes & Cohen, 1995; Slater, Mattock, & Brown, 1990; Slater & Morison, 1985; Yonas & Granrud, 1984; Yonas, Pettersen, & Lockman, 1979).

Leslie (1995) has proposed that, in addition to spatiotemporal information, infants include from the start mechanical information in their representations of physical events. According to Leslie, infants are born with a primitive notion of mechanical force: "The general idea behind the FORCE representation is that (a) when objects move, they possess or bear FORCE, and (b) when objects contact other objects, they transmit, receive, or resist FORCE" (p. 124). In arguing that infants possess an innate notion of force, Leslie does not mean that infants fully understand from the start how forces operate in the world. As infants observe different ways in which objects interact, they would come to understand how forces are implemented in different interactions—how forces are resisted in one context or transmitted in another. A sensitivity to force relations between objects would thus allow infants to "make useful assumptions regarding simple mechanisms . . . and rapidly learn about them" (p. 130).

Leslie's (1995) proposal that infants represent interactions between objects in terms of force reations suggests an intriguing interpretation for our findings on the development of infants' knowledge about collision events, described in an earlier section (e.g. Kotovsky & Baillargeon, 1994, in press a, in prep.). For example, Leslie's view suggests that, as early as 2.5 months of age, infants include in their representation of each collision between the cylinder and the bug a unidirectional force or push exerted by the cylinder onto the bug. Furthermore, the fact that 5.5- to 6.5-month-old infants expect a larger cylinder to displace the bug farther than a smaller cylinder could be taken to mean that infants expect the larger cylinder to exert a greater force onto the bug, thereby producing a greater displacement. Conversely, the finding that younger infants have no expectation that the bug should roll farther after contact with a larger than with a smaller cylinder would suggest that they have not yet learned that larger objects typically exert greater forces than smaller objects, and/or that greater forces typically translate into greater displacements than smaller forces.

Although it is obvious how Leslie's (1995) proposal can be applied to our findings on infants' knowledge of collision events, it is less clear how well the notion of a core force representation can be extended to our findings concerning other event categories, such as occlusion or support events. In the case of occlusion events, forces simply do not come into play; the representation of the relations between objects and their occluders will involve spatiotemporal rather than mechanical information. As occlusion events appear to follow the same developmental pattern as other event categories, one wonders whether Leslie's (1995) assumption that infants' notion of force lies at the core of their "theory of body" may be overstating the case. Similarly, it is not clear at present whether infants represent support events in terms of force relations or more simply in terms of spatiotemporal regularities.

Considerable empirical research needs to be carried out before we can ascertain whether infants include force relations in their representations of physical events, and, if yes, whether all or only some event categories are concerned with such relations. From the perspective of our model of infants' acquisition of physical knowledge, there are at least two reasons why such research is important. First, at a concrete level, the results of these investigations will literally determine how we describe the variables that infants identify as they learn about specific event categories. For example, in the case of collisions between moving and stationary objects, are infants initially learning that the larger the moving objects, the farther the stationary objects are displaced, or are they learning that the larger the moving objects, the greater the force they exert on the stationary objects, leading to longer displacements? What infants learn will depend on what they represent, and what they represent will in turn depend on both their innate vocabulary and their accumulated physical knowledge.

The second reason why considerations of infants' mechanical intuitions can enrich our approach is that they make room within our model for an explicit notion of mechanical causality that was hitherto lacking. Causal reasoning can be defined at a very general level in terms of an ability to detect and reason about regularities in objects' displacements and interactions with other objects. Causal reasoning can also be defined more narrowly in terms of an ability to identify mechanical sequences in which one event brings about another event through the transmission of a physical force. In our work to date, infants' reasoning has been characterized exclusively in terms of the first, more general type of causal reasoning. By admitting that forces may be a part of infants' event representations, however, we can make explicit the place of mechanical causality within our approach. In this new perspective, infants still bring order to their physical world by forming event categories and identifying increasingly refined variables. The main difference is that event categories are now acknowledged to fall into two broad types: those that are defined purely in spatiotemporal terms (e.g. occlusion events), and those that depend on both mechanical and spatiotemporal relations (e.g. collision events). As Leslie (1995) suggested, these rudimentary mechanical intuitions may pave the way for the more complex mechanistic reasoning that is observed in children and adults.

Physical principles

A second type of innate structures that has been posited has to do with physical principles that would from the start constrain objects' displacements and interactions within infants' event representations. Spelke (1994; Spelke et al., 1995b), in particular, has argued that infants are born with a number of core physical principles that guide their interpretation of physical events. One such principle is the continuity principle, which states that objects exist and move continuously. Another, related principle is the solidity principle, which states that objects move on continuous, unobstructed paths, so that two distinct objects can never occupy the same space at the same time (Spelke et al., 1995b).

The claim that infants possess a continuity or a solidity principle is sometimes taken to mean that infants should readily detect *any* violation of the principles (e.g. Spelke, 1991; Spelke et al., 1992). Thus, an infant should be surprised if all or only part of an object fails to become visible when passing behind an occluder with an opening. Similarly, an infant should be surprised if an object moves through all or only part of an object placed behind it.

Existing evidence does not support these predictions. As we saw when discussing the development of infants' knowledge about occlusion events, infants aged 2.5 to 3 months detect some but by no means all continuity violations (e.g. Aguiar & Baillargeon, submitted b; Baillargeon & DeVos, 1991). The range of violations infants detect steadily grows over the first few months of life, as their understanding of occlusion develops. The same is true for solidity violations. For example, when watching a screen rotate through a box placed behind it, 4.5-month-old infants show surprise when the screen stops after rotating through 100% but not 80% of the box (Baillargeon, 1991). Infants understand *that* the screen should stop when it encounters the box, but they are unable to use the box's height to predict *when* the screen should stop; therefore, the only violation they can detect is one in which the screen fails to stop altogether.

In light of this evidence, at least two options are possible. The first is to conclude that infants do not possess core physical principles that guide their interpretation of events. The second option is to assume that infants do possess core principles, but that these principles are only rudimentary notions that facilitate but still leave open considerable room for learning. In this view, infants' notions of continuity and solidity would thus be similar to the primitive notion of force discussed by Leslie (1994, 1995). Infants would progressively learn, in the course of observing and interacting with objects, how continuity and solidity operate in different physical contexts. To illustrate, consider the case of occlusion events. Because of their continuity principle, infants would realize that an object continues to exist and follows its trajectory when passing behind a screen —however, this is all that their continuity principle would tell them. Infants would need to learn what variables can be used to predict whether the object will remain hidden or become temporarily visible when behind the screen, how soon the object will reappear at the far edge of the screen, and so on.

How can we decide which of these two options—no innate principles, or weak innate principles—is correct? There is no firm evidence available today that enables us to select one option rather than the other. Our own intuition is that, in the end, the second option (or some version of this option) will be proved correct. This intuition is derived from a consideration of the type of data infants appear to require to identify physical variables. Earlier we suggested that infants cannot acquire a new variable unless they have *contrastive* data pertinent to the variable: positive data showing that an outcome occurs when a condition is met and negative data showing that an outcome does not occur when the condition is not met. We speculated, for example, that infants less than 5.5 to 6.5 months of age do not learn the variable "amount of contact" in support events because they typically see only positive outcomes—situations in which objects are placed on surfaces with sufficient contact to be adequately supported. At about 5.5 to 6.5 months, however, infants begin to generate their own negative data—they release objects on the edges of surfaces, causing them to fall—and then quickly identify "amount of contact" as an important support variable.

These speculations on infants' need for contrastive inputs suggest a new approach to the issue of innate physical principles. Essentially, we must ask ourselves: What contrastive data could infants use to learn that objects exist continuously in time? Or move continuously in space? Or move only through unoccupied space? We know that infants aged 2.5 months already detect at least some violations of these principles (e.g. Aguiar & Baillargeon, submitted b; Kotovsky & Baillargeon, in prep.; Spelke et al., 1992). If we cannot identify contrastive data that infants could use in the first two months of life to acquire the principles, then we have only two recourses: We must conclude that the principles are, in some fashion, available at birth; or we must assume that infants are born with two distinct learning mechanisms, one that requires contrastive evidence and one that does not.

Before these issues can be resolved, considerable research will need to be carried out on two fronts. One will be to specify more fully the nature and operation of infants' learning mechanism, and to test directly the hypothesis that learning typically occurs only in the presence of contrastive evidence. The other front will be to examine the implications of these findings for infants' early competences. If infants' learning mechanism is shown to learn only under conditions "x", and infants at a very early age reveal physical knowledge for which learnability conditions "x" could not have been met, we may be compelled to agree with Spelke et al. (1995b) that a number of innate physical principles direct from birth infants' approach to the physical world.

CONCLUSION

The research reviewed in this chapter makes clear that a full account of how infants attain their physical knowledge is likely to include many distinct parts: a description of the representational vocabulary infants draw on to represent objects' displacements and interactions, and of how this vocabulary develops over time; a description of the physical principles that guide from birth infants' interpretation of objects' displacements and interactions; a description of the learning mechanism that makes possible infants' formation of event categories and identification of initial concepts and variables; and finally, a discussion of the role that infants' accumulated physical knowledge plays in their representation and interpretation of physical events, and hence in infants' acquisition of new knowledge.

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