CURRENT DIRECTIONS IN PSYCHOLOGICAL SCIENCE

How Do Infants Learn About the Physical World?

Renée Baillargeon

Until recently, young infants were assumed to lack even the most fundamental of adults' beliefs about objects. This conclusion was based largely on analyses of young infants' performance in object manipulation tasks. For example, young infants were said to be unaware that an object continues to exist when masked by another object because they consistently failed tasks that required them to search for an object hidden beneath or behind another object.[1]

In time, however, researchers came to realize that young infants might fail tasks such as search tasks not because of limited physical knowledge, but because of difficulties associated with the planning and execution of action sequences. This concern led investigators to seek alternative methods for exploring young infants' physical knowledge, methods that did not depend on the manipulation of objects.

Infants' well-documented tendency to look longer at novel than at familiar events[2] suggested one alternative method for investigating young infants' beliefs about objects. In a typical experiment, infants are presented with two test events: a possible and an impossible event. The possible event is consistent with the expectation or belief examined in the experiment; the impossible event, in contrast, violates this expectation. The rationale is that if infants possess the belief being tested, they will perceive the impossible event as more novel or surprising than the possible event, and will therefore look reliably longer at the impossible than at the possible event.

Renée Baillargeon is a Professor of Psychology at the University of Illinois at Urbana-Champaign. Address correspondence to Renée Baillargeon, Department of Psychology, University of Illinois, 603 East Daniel, Champaign, IL 61820.

Using this violation-of-expectation method, investigators have demonstrated that even very young infants possess many of the same fundamental beliefs about objects as adults do.[3,4] For example, infants aged 2.5 to 3.5 months are aware that objects continue to exist when masked by other objects, that objects cannot remain stable without support, that objects move along spatially continuous paths, and that objects cannot move through the space occupied by other objects.

The repeated demonstration of sophisticated physical knowledge in early infancy has led investigators in recent years to focus their efforts in a new direction. In addition to exploring what infants know about the physical world, researchers have become interested in the question of how infants attain their physical knowledge.

My colleagues and I have begun to build a model of the development of young infants' physical reasoning.[5–7] The model is based on the assumption that infants are born not with substantive beliefs about objects (e.g., intuitive notions of impenetrability, continuity, or force), as researchers such as Spelke[8] and Leslie[9] have proposed, but with highly constrained mechanisms that guide the development of infants' reasoning about objects. The model is derived from findings concerning infants' intuitions about different physical phenomena (e.g., support, collision, and unveiling phenomena). Comparison of these findings points to two developmental patterns that recur across ages and phenomena. We assume that these patterns reflect, at least indirectly, the nature and properties of infants' learning mechanisms. In this review, I describe the patterns and summarize some of the evidence supporting them.

FIRST PATTERN: IDENTIFICATION OF INITIAL CONCEPT AND VARIABLES

The first developmental pattern is that, when learning about a new physical phenomenon, infants first form a preliminary, all-or-none concept that captures the essence of the phenomenon but few of its details. With further experience, this *initial concept* is progressively elaborated. Infants slowly identify discrete and continuous *variables* that are relevant to the initial concept, study the effects of those variables, and incorporate this accrued knowledge into their reasoning, resulting in increasingly accurate predictions over time.

To illustrate the distinction between initial concepts and variables, I summarize experiments on the development of young infants' reasoning about support phenomena (conducted with Amy Needham, Julie DeVos, and Helen Raschke), collision phenomena (conducted with Laura Kotovsky), and unveiling phenomena (conducted with Julie DeVos).[3,5–7]

Support Phenomena

Our experiments on young infants' ability to reason about support phenomena have focused on simple problems involving a box and a platform. Our results indicate that by 3 months of age, if not before, infants expect the box to fall if it loses all 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 locus of contact between the box and the platform must be taken into account when judging the box's stability. Infants initially assume that the box will remain stable if placed either on the top or against the side of the platform. By 4.5 to 5.5 months of age, however, infants come to distinguish between the two types of contact and recognize that only the former ensures support. The second development is that infants begin to appreciate that the amount of contact between the box and the platform affects the box's stability. Initially, infants believe that the box will be stable even if only a small portion (e.g., the left 15%) of its bottom surface rests on the platform (see Fig. 1). By 6.5 months of age, however, infants expect the box to fall unless a significant portion of its bottom surface lies on the platform.

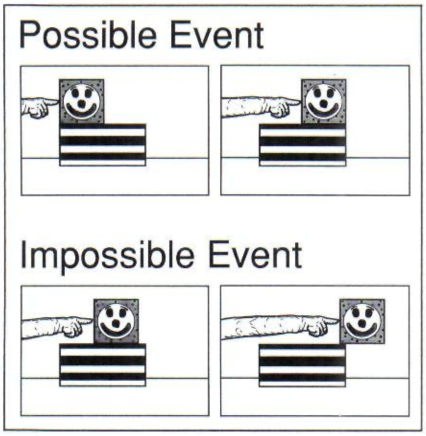

Fig. 1. Paradigm for studying infants' understanding of support phenomena. In both events, a gloved hand pushes a box from left to right along the top of a platform. In the possible event (top), the box is pushed until its leading edge reaches the end of the platform. In the impossible event (bottom), the box is pushed until only the left 15% of its bottom surface rests on the platform.

These results suggest the following developmental sequence. When learning about the support relation between two objects, infants first form an initial concept centered on a distinction between contact and no contact. With further experience, this initial concept is progressively revised. Infants identify first a discrete (locus of contact) and later a continuous (amount of contact) variable and incorporate these variables into their initial concept, resulting in more successful predictions over time.

Collision Phenomena

Our experiments on infants' reasoning about collision events have focused on simple problems involving a moving object (a cylinder that rolls down a ramp) and a stationary object (a large, wheeled toy bug resting on a track at the bottom of the ramp). Adults typically expect the bug to roll down the track when hit by the cylinder. When asked how far the bug will be displaced, adults are generally reluctant to hazard a guess (they are aware that the length of the bug's trajectory depends on a host of factors about which they have no information). After observing that the bug rolls to the middle of the track when hit by a medium-size cylinder, however, adults readily predict that the bug will roll farther with a larger cylinder and less far with a smaller cylinder made of identical material.

Our experiments indicate that by 2.5 months of age, infants already possess clear expectations that the bug should remain stationary when not hit (e.g., when a barrier prevents the cylinder from contacting the bug) and should be displaced when hit. However, it is not until 5.5 to 6.5 months of age that infants are able to judge, after seeing that the medium cylinder causes the bug to roll to the middle of the track, that the bug should roll farther with the larger but not the smaller cylinder (see Fig. 2). Younger infants are not surprised to see the bug roll to the end of the track when hit by either the larger or the smaller cylinder, even though all three of the cylinders are simultaneously present in the apparatus, so that their sizes can be readily compared, and even though the infants have no difficulty remembering (as shown in other experiments) that the bug rolled to the middle of the track with the medium cylinder. These results suggest that prior to 5.5 to 6.5 months of age, infants are unaware that the size of the cylinder can be used to reason about the length of the bug's trajectory.

One interpretation of these findings is that when learning about collision events between a moving and a stationary object, infants first form an initial concept centered on a distinction between impact and no impact. With further experience, infants begin to identify variables that influence this initial concept. By 5.5 to 6.5 months of age, infants realize that the size of the moving object can be used to predict how far the stationary object will be displaced. After seeing how far a stationary object travels with a moving object of a given size, infants readily use this information to calibrate their predictions about how far the stationary object will travel with moving objects of different sizes.

Unveiling Phenomena

Our experiments on unveiling phenomena have involved problems in which a cloth cover is removed to reveal an object. Our results indicate that by 9.5 months of age, infants realize that the presence (or absence) of a protuberance in the cover signals the presence (or absence) of an object beneath the cover. Infants are surprised to see a toy retrieved from under a cover that lies flat on a surface, but not from

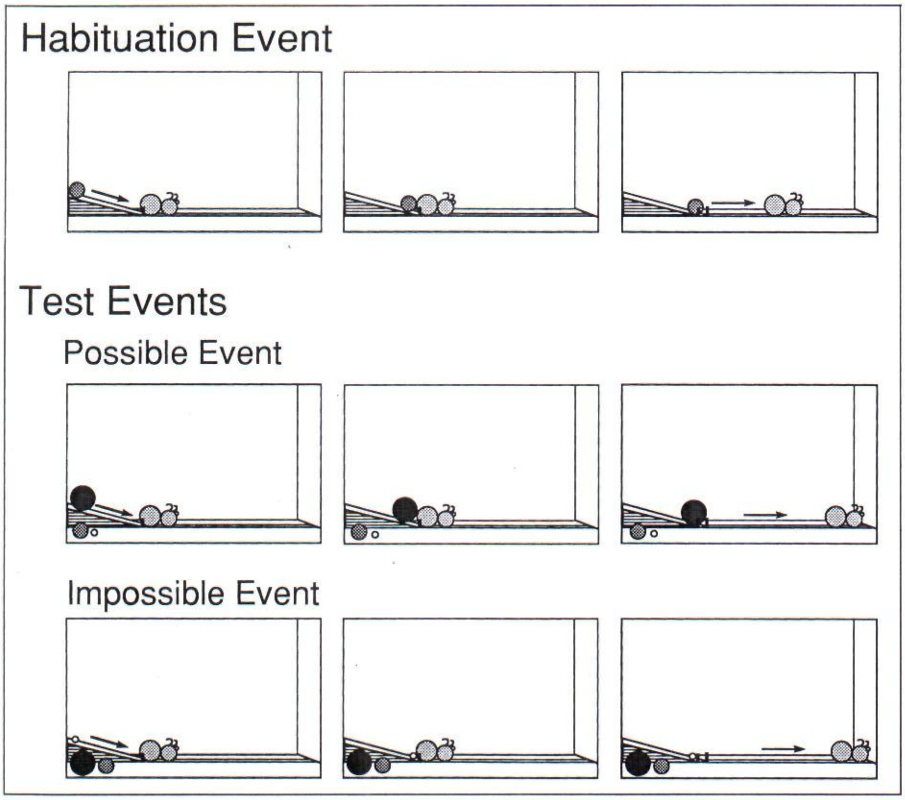

Fig. 2. Paradigm for studying infants' understanding of collision phenomena. First, infants are habituated to (i.e., repeatedly shown) an event in which a blue, medium-size cylinder rolls down a ramp and hits a bug resting on one end of a track; the bug then rolls to the middle of the track. In the test events, two new cylinders are introduced, and the bug now rolls to the end of the track. The cylinder used in the possible event is a yellow cylinder larger than the habituation cylinder; the cylinder used in the impossible event is an orange cylinder smaller than the habituation cylinder.

under a cover that displays a marked protuberance.

At this stage, however, infants are not yet aware that the size of the protuberance in the cover can be used to infer the size of the object beneath the cover. When shown a cover with a small protuberance, they are not surprised to see either a small or a large toy retrieved from under the cover. Furthermore, providing infants with a reminder of the protuberance's size has no effect on their performance. In one experiment, for example, infants saw two identical covers placed side by side; both covers displayed a small protuberance (see Fig. 3). After a few seconds, a screen hid the left cover; the right cover remained visible to the right of the screen. Next, a hand reached behind the screen's right edge twice in succession, reappearing first with the cover and then with a small (possible event) or a large (impossible event) toy dog. Each dog was held next to the visible cover, so that their sizes could be readily compared. At 9.5 months of age, infants judged that either dog could have been hidden under the cover behind the screen. At 12.5 months of age, however, infants showed reliable surprise at the large dog's retrieval.

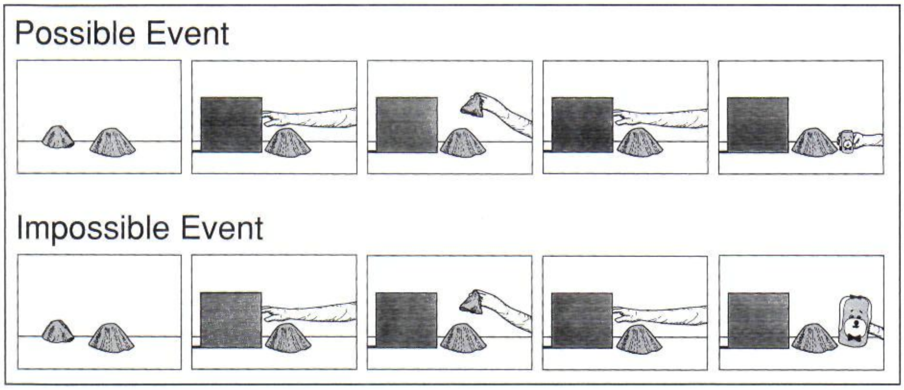

Fig. 3. Paradigm for studying infants' understanding of unveiling phenomena. Infants first see two identical covers placed side by side; both covers display a small protuberance. Next, a screen hides the left cover, and a gloved hand reaches behind the screen twice in succession, reappearing first with the cover and then with a small (top) or a large (bottom) toy dog. Each dog is held next to the visible cover, so that their sizes can be readily compared.

Together, these results suggest the following developmental sequence. When learning about unveiling phenomena, infants first form an initial concept centered on a distinction between 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 the cover can be used to infer the size of the object under the cover.

Comments

How can the developmental sequences described in this section be explained? As I mentioned earlier, we assume that these sequences reflect not the gradual unfolding of innate beliefs, but the application of highly constrained, innate learning mechanisms to available data. In this 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.

For example, one might propose that 3-month-old infants have already learned that objects fall when released in midair because this expectation is consistent with countless observations (e.g., watching their caretakers drop peas in pots, toys in baskets, clothes in hampers) and manipulations (e.g., noticing that their pacifiers fall when they open their mouths) available virtually from birth. Furthermore, one might speculate that it is not until 6.5 months that infants begin to appreciate how much contact is needed between objects and their supports because it is not until this age that infants have available pertinent data from which to abstract such a variable. Researchers 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.[10] For the first time, infants may have the opportunity to deposit objects on tables and to note that objects tend to fall unless significant portions of their bottom surfaces are supported. In the natural course of events, infants would be unlikely to learn about such a variable from observation alone because caretakers rarely deposit objects on the edges of surfaces. There is no a priori reason, however, to assume that infants could not learn such a variable if given appropriate observations (e.g., seeing that a box falls when released on the edge of a platform). We are currently conducting a "teaching" experiment to investigate this possibility; our preliminary results are extremely encouraging and suggest that very few observations may be necessary to set infants on the path to learning.

SECOND PATTERN: USE OF QUALITATIVE AND QUANTITATIVE STRATEGIES

In the previous section, I proposed that when learning about a novel physical phenomenon, infants first develop an all-or-none initial concept and later identify discrete and continuous variables that affect this concept. The second developmental pattern suggested by current evidence concerns the strategies infants use when reasoning about continuous variables. Following the terminology used in computational models of everyday physical reasoning,[11] a strategy is said to be *quantitative* if it requires infants to encode and use information about absolute quantities (e.g., object A is "this" large or has traveled "this" far from object B, where "this" stands for some absolute measure of A's size or distance from B). In contrast, a strategy is said to be *qualitative* if it requires infants to encode and use information about relative quantities (e.g., object A is larger than or has traveled farther than object B). After identifying a continuous variable, infants appear to succeed in reasoning about the variable qualitatively before they succeed in doing so quantitatively.

To illustrate the distinction between infants' use of qualitative and quantitative strategies, I report experiments on the development of infants' ability to reason about collision phenomena (conducted with Laura Kotovsky), unveiling phenomena (conducted with Julie DeVos), and barrier phenomena.[3,5–7]

Collision Phenomena

As I explained earlier, 5.5- to 6.5-month-old infants are surprised, after observing that a medium-size cylinder causes a bug to roll to the middle of a track, to see the bug roll farther when hit by a smaller but not a larger cylinder. Such a finding suggests that by 5.5 to 6.5 months of age, infants are aware that the size of the cylinder affects the length of the bug's trajectory.

In these initial experiments, the small, medium, and large cylinders were placed side by side at the start of each event, allowing infants to compare their sizes directly. In subsequent experiments, only one cylinder was present in the apparatus in each test event. Under these conditions, 6.5-month-old infants were no longer surprised when the small cylinder caused the bug to roll to the end of the track; only older, 7.5-month-old infants showed surprise at this event.

Our interpretation of these results is that at 5.5 to 6.5 months of age, infants are able to reason about the cylinder's size only qualitatively: They can predict the effect of modifications in the cylinder's size only when they are able to encode such modifications in relative terms (e.g., "this cylinder is smaller than the one used in the last trial"). When infants are forced to encode and compare the absolute sizes of the cylinders, because the cylinders are never shown side by side, they fail the task. By 7.5 months of age, however, infants have already overcome this initial limitation and succeed in the task even when they must rely on their representation of the absolute size of each cylinder to do so.[12]

Unveiling Phenomena

In the previous section, I reported that 9.5-month-old infants are not surprised to see either a small or a large toy dog retrieved from under a cover with a small protuberance, even when a second, identical cover is present. Unlike these younger infants, however, 12.5-month-old infants *are* surprised when the large dog is brought into view. This last finding suggests that by 12.5 months of age, infants are aware that the size of the protuberance in a cloth cover can be used to infer the size of the object under the cover.

In our initial experiment, 12.5-month-old infants were tested with the second cover present to the right of the screen (see Fig. 3). Subsequent experiments were conducted without the second cover (see Fig. 4, top panel) or with the second cover placed to the left, rather than to the right, of the screen (see Fig. 4, bottom panel); in the latter condition, infants could no longer compare in a single glance the size of the dog to that of the cover. Our results indicated that 12.5-month-old infants fail both of these conditions: They no longer show surprise when the large dog is retrieved from behind the screen. By 13.5 months of age, however, infants are surprised by the large dog's retrieval even when no second cover is present.

These results suggest that at 12.5 months of age, infants are able to reason about the size of the protuberance in the cover only qualitatively: They can determine which dog could have been hidden under the cover only if they are able to compare, in a single glance, the size of the dog with that of a second, identical cover (e.g., "the dog is bigger than the cover"). When infants are forced to represent the absolute size of the protuberance in the cover, they fail the task. By 13.5 months of age, however, infants have already progressed beyond this initial limitation; they no longer have difficulty representing the absolute size of the protuberance and comparing it with that of each dog.

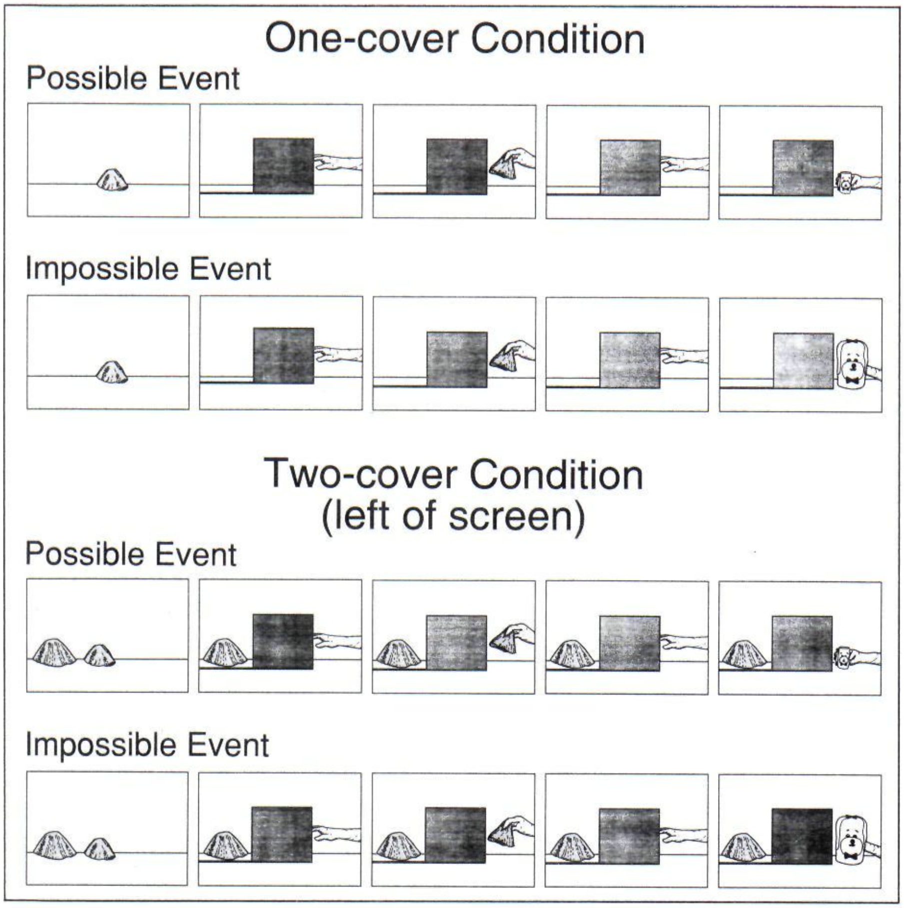

Fig. 4. Further experiments examining infants' understanding of unveiling phenomena. These test events are identical to those depicted in Figure 3 except that only one cover is used (top) or the second, identical cover is placed to the left of the screen (bottom). In the latter condition, infants can no longer compare in a single glance the height of the dog to that of the second cover.

Barrier Phenomena

Our experiments on barrier phenomena have focused on problems involving a moving object (a rotating screen) and a stationary barrier (a large box). In the test events, infants first see the screen lying flat against the apparatus floor; the box stands clearly visible behind the screen. Next, the screen rotates about its distant edge, progressively occluding the box. At 4.5 months of age, infants expect the screen to stop when it reaches the occluded box; they are surprised if the screen rotates unhindered through a full 180° arc. However, infants are initially poor at predicting at what point the screen should encounter the box and stop. When shown a possible event in which the screen stops against the box (112° arc) and an impossible event in which the screen stops after rotating through the top 80% of the space occupied by the box (157° arc), 6.5-month-old infants give evidence of detecting this 80% violation, but 4.5-month-old infants do not: They judge both the 112° and the 157° stopping points to be consistent with the box's height and location (see Fig. 5).

In subsequent experiments, we examined whether 4.5-month-old infants would succeed in detecting the 80% violation if provided with a second, identical box. In one condition, this second box was placed to the right of and in the same frontoparallel plane as the box behind the screen (see Fig. 6, left panel). In the possible event, the screen stopped when aligned with the top of the second box; in the impossible event, the screen rotated past the top of the second box. In another condition, the second box was placed to the right of but slightly in front of the box behind the screen (see Fig. 6, right panel). In this condition, the screen

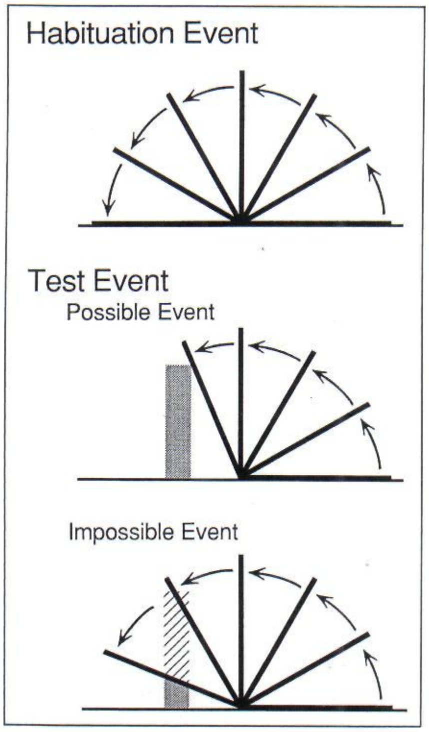

Fig. 5. Paradigm for studying infants' understanding of barrier phenomena. Infants are first habituated to a screen that rotates through a 180° arc, in the manner of a drawbridge. Next, a large box is placed behind the screen. In the possible event, the screen stops when it encounters the box (112° arc); in the impossible event, the screen stops after rotating through the top 80% of the space occupied by the box (157° arc).

rotated past the top of the second box in each test event. The infants succeeded in detecting the 80% violation in the first but not the second condition.

These results suggest that at 4.5 months of age, infants are able to reason about the box's height and location only qualitatively: They can predict the screen's stopping point only when they are able to rely on a simple alignment strategy (e.g., "the screen is aligned with the top of the visible box"). By 6.5 months of age, however, infants have already progressed beyond this point; they can use their representations of the occluded box's height and distance from the screen to estimate, within broad limits, at what point the screen will stop.

Comments

How should the developmental sequences described in this section be explained? We think it unlikely that these sequences reflect the maturation of infants' general quantitative reasoning or information processing because the same pattern recurs at different ages for different phenomena. What phenomenon-specific changes could account for the findings reported here? At least two hypotheses can be advanced. On the one hand, it could be that when first reasoning about a continuous variable, infants either do not spontaneously encode information about this variable or do not encode this information swiftly enough or precisely enough for it to be of use in the tasks examined here (e.g., infants do not encode the size of the protuberance in the cover and hence are unable to judge which dog could have been hidden beneath it). On the other hand, infants could encode the necessary quantitative information but have difficulty accessing or processing this information in the context of deriving new and unfamiliar predictions (e.g., infants encode the protuberance's size and realize that they must compare it with that of the dog, but are thwarted in performing this comparison by the added requirement of having to retrieve part of the information from memory). Future research will no doubt help determine which, if either, of these hypotheses is correct.

CONCLUDING REMARKS

I have argued that in learning to reason about a novel physical phenomenon, infants first form an all-or-none concept and then add to this initial concept discrete and continuous variables that are discovered to affect the phenomenon. Furthermore, I have proposed that after identifying continuous variables, infants succeed in reasoning first qualitatively and only later quantitatively about the variables.

This sketchy description may suggest a rather static view of development in which accomplishments, once attained, are retained in their initial forms. Nothing could be further from the truth, however. Our data suggest that the variables infants identify evolve over time, as do the qualitative and quantitative strategies infants devise. When judging whether a box resting on a platform is stable, for example, infants initially focus exclusively on the amount of contact between the box's bottom surface and the platform, and as a consequence treat symmetrical and asymmetrical boxes alike. By the end of the 1st year, however, infants appear to have revised their definition of this variable to take into account the shape (or weight distribution) of the box.[5] Similarly, evidence obtained with the rotating-screen paradigm suggests that infants' quantitative reasoning continues to improve over time (e.g., 6.5-month-old infants can detect 80% but not 50% violations, whereas 8.5-month-old infants can detect both), as does their qualitative reasoning (e.g., 6.5-month-old infants will make use of a second box to detect a violation even if this second box differs markedly in color from the box behind the screen, whereas 4.5-month-old infants will not).[3]

The model of the development of infants' physical reasoning proposed here suggests many questions for future research. In particular, what are the innate constraints that guide this development? Are infants born with core principles (e.g., intuitive notions of impenetrability and continuity) that direct their interpretations of physical events? Or are infants, as I suggested earlier, equipped primarily with learning mechanisms that are capable, when applied to coherent sets of observations, of producing appropriate generalizations? What

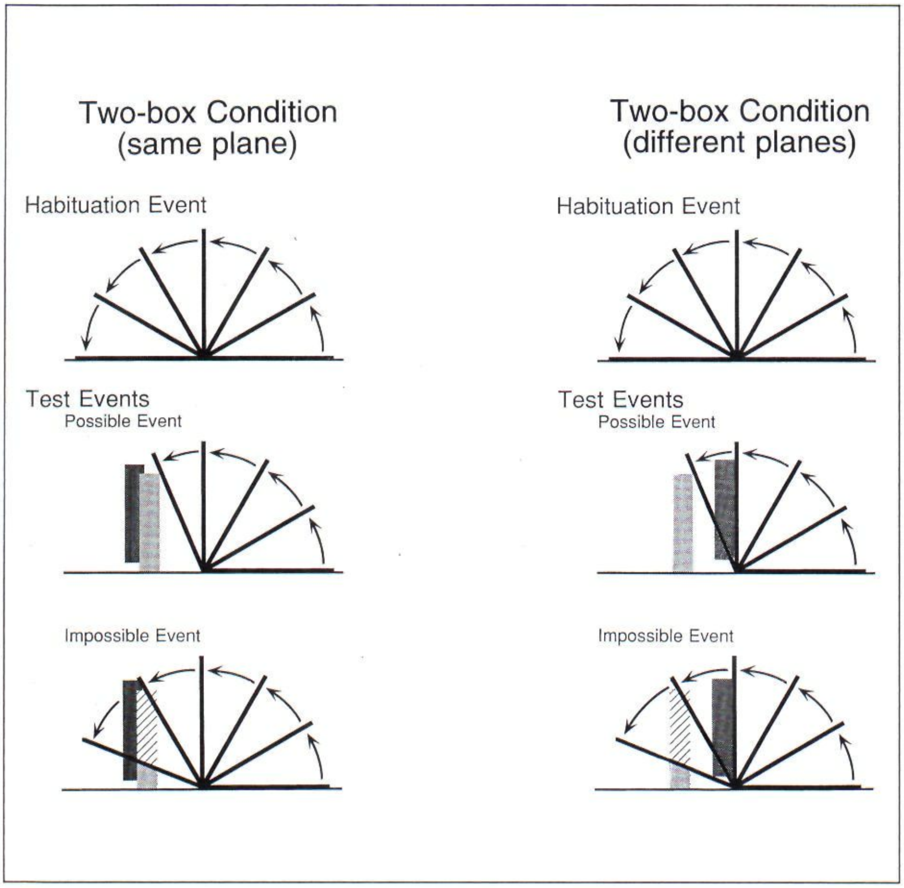

Fig. 6. Further experiments examining infants' understanding of barrier phenomena. These events are identical to those depicted in Figure 5 except that a second, identical box stands to the right of and in the same fronto-parallel plane as the box behind the screen (left) or to the right and in front of the box behind the screen (right).

evidence would help distinguish between these two views?

Some insight into this question may be gained by considering two predictions that proponents of the innate-principles view might offer. The first prediction is that when reasoning about a physical event involving a core principle, infants should succeed at about the same age at detecting all equally salient violations of the principle. Thus, researchers who deem impenetrability a likely core principle might expect infants who realize that a small object cannot pass through a gapless surface to understand also that a large object cannot pass through a small gap; provided that the two situations violate the impenetrability principle to a similar degree, they would be expected to yield identical interpretations. The second prediction is that infants should succeed at about the same age at reasoning about different physical events that implicate the same underlying core principle. Thus, it might be proposed that infants who are successful at reasoning about objects' passage through gaps should be just as adept at reasoning about objects' entry into containers, because both phenomena would trigger the application of the impenetrability principle.

The model presented here departs systematically from the two predictions just described. First, the model predicts explicitly that when reasoning about physical events, infants succeed in detecting certain types of violations before others. Thus, in contrast to the innate-principles view, the model would expect infants to recognize that a small object cannot pass through a gapless surface before they recognize that a large object cannot pass through a smaller gap. This developmental sequence would be cast in terms of the formation of an initial concept centered on a distinction between gap and no gap, followed by the identification of size as a continuous variable relevant to the phenomenon.

Second, the present model also diverges from the prediction that different physical events that implicate the same core principle should be understood at about the same age. The results summarized in the preceding sections and elsewhere[6]—such as the finding that unveiling tasks yield the same developmental patterns as rotating-screen tasks, but at much later ages—suggest that infants respond to physical events not in terms of abstract underlying principles, but in terms of concrete categories corresponding to specific ways in which objects behave or interact. Thus, according to our model, it would not be at all surprising to find that infants succeed in reasoning about gaps several weeks or months before they do containers; the order of acquisition of the two categories would be expected to depend on the content of infants' daily experiences. The model does not rule out the possibility that infants eventually come to realize that superficially distinct events—such as those involving gaps and containers, or rotating screens and cloth covers—can be deeply related; unlike the innate-principles view, however, the model considers such a realization a product, rather than a point of departure, of learning.

One advantage of the view that infants process physical events in terms of concrete categories focusing on specific types of interactions between objects is that this view makes it possible to explain incorrect interpretations that appear to stem from miscategorizations of events. Pilot data collected in our laboratory suggest that young infants expect a moving object to stop when it encounters a tall, thin box but not a short, wide box, even when the latter is considerably larger in volume than the former. We suspect that infants are led by the dominant vertical axis of the tall box to perceive it as a wall-like, immovable object, and hence categorize the event as an instance of a barrier phenomenon; in contrast, infants tend to view the wide box as a movable object, and hence categorize the event as an instance of a collision phenomenon, resulting in incorrect predictions.

The foregoing discussion highlighted several types of developmental sequences that would be anticipated in an innate-mechanisms view but not (without considerable elaboration) in an innate-principles view. To gain further insight into the nature and origins of these developmental sequences, we have adopted a dual research strategy. First, we are examining the development of infants' understanding of additional physical phenomena (e.g., gap, containment, and occlusion phenomena) to determine how easily these developments can be captured in terms of the patterns described in the model and to compare more closely the acquisition time lines of phenomena that are superficially distinct but deeply related. Second, as was alluded to earlier, we are attempting to teach infants initial concepts and variables to uncover what kinds of observations, and how many observations, are required for learning. We hope that the pursuit of these two strategies will eventually allow us to specify the nature of the learning mechanisms that infants bring to the task of learning about the physical world.

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Notes

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12. This example focused exclusively on the size of the cylinder, but what of the distance traveled by the bug in each event? It seems likely that infants encode this information not in quantitative terms (e.g., "the bug traveled *x* as opposed to *y* distance"), but rather in qualitative terms, using as their point of reference the track itself (e.g., "the bug rolled to the middle of the track"), their own spatial position (e.g., "the bug stopped in front of me"), or the brightly decorated back wall of the apparatus (e.g., "the bug stopped in front of such-and-such section of the back wall").

An Epigenetic Perspective on the Development of Self-Produced Locomotion and Its Consequences

Bennett I. Bertenthal, Joseph J. Campos, and Rosanne Kermoian

One of the most striking characteristics of early human development is its consistency and stability. Infants show considerable uniformity in the nature and timing of new behaviors. A principal contributor to this early uniformity is the development of species-typical behaviors, such as vocalization, locomotion, and reaching. These behaviors ensure a common set of experiences with far-reaching consequences for development. In this article, we review a specific example of this epigenetic process involving the development of self-produced locomotion.

EXTERNAL VERSUS SELF-PRODUCED FORMS OF EXPERIENCE

The importance of self-produced experiences is often overlooked by researchers, and, indeed, most studies investigating early development focus on the effects of stimulation from the environment. A paradigmatic example is the study of infants'