LEARNING AND THE INFANT MIND

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An Account of Infants' Physical Reasoning

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Adults possess a great deal of knowledge about the physical world, and developmental researchers have long been interested in uncovering the roots of this knowledge in infancy. Two main questions have guided this research: What expectations do infants possess, at different ages, about physical events, and how do they attain these expectations?

Piaget (1952, 1954) was the first researcher to systematically investigate the development of infants' physical knowledge. He examined infants' actions in various tasks and concluded that young infants understand very little about the physical events they observe. For example, Piaget noted that infants younger than 8 months do not search for objects they have watched being hidden, and concluded that they do not yet realize that objects continue to exist when hidden.

One difficulty with Piaget's (1952, 1954) experimental approach is that action tasks do not test only infants' physical knowledge (e.g., Boudreau & Bushnell, 2000; Berthier et al., 2001; Keen & Berthier, 2004; Hespos & Baillargeon, 2006, 2008). In order to search for a hidden object, for example, infants must not only represent the existence and location of the object but also plan and execute appropriate actions to retrieve it. Because young infants' information-processing resources are sharply limited, they may fail at a search task not because they do not yet understand that objects continue to exist when hidden but because the combined demands of the task overwhelm their processing resources.

Because of the problems inherent in interpreting negative results in action tasks, researchers have developed alternative experimental approaches to study the development of infant's physical knowledge (e.g., Bower, 1974; Baillargeon, Spelke, & Wasserman, 1985; Leslie & Keeble, 1987; Luo, Baillargeon, Brueckner, & Munakata, 2003; Kaufman, Csibra, & Johnson, 2004). The most widely used of these alternative approaches is the violation-of-expectation (VOE) method. In a typical experiment, infants see two test events: an expected event, which is consistent with the expectation being examined in the experiment, and an unexpected event, which violates this expectation. With appropriate controls, evidence that infants look reliably longer at the unexpected than at the expected event is taken to indicate that infants (1) possess the expectation under investigation, (2) detect the violation in the unexpected event, and (3) are "surprised" by this violation. The term "surprise" is used here simply as a shorthand descriptor to denote a state of heightened attention or interest caused by an expectation violation (for discussion of the method, see Wang, Baillargeon, & Brueckner, 2004).

Experiments conducted using the VOE method, in our laboratory and elsewhere, have revealed two main findings: First, and contrary to Piaget's (1952, 1954) claims, even very young infants possess expectations about various physical events; second, infants' expectations undergo significant and systematic developments during the first year of life (for recent reviews, see Baillargeon, 2002, 2004; Baillargeon, Li, Luo, & Wang, 2006).

This chapter is divided into four sections. In the first, we propose an account of the development of infants' physical reasoning that builds on VOE and other findings. In presenting this account, for ease of description, we focus on infants' reasoning about events in which objects become hidden behind, inside, or under other objects. In the second and third sections of the chapter, we describe new lines of research that are designed to test and extend the account. In the final section, we offer a few concluding remarks.

AN ACCOUNT OF INFANTS' PHYSICAL REASONING

We assume that when infants watch a physical event, different computational systems form different representations simultaneously, for distinct purposes (Baillargeon et al., 2006; Li, Baillargeon, & Simons, 2006b; Wang & Baillargeon, 2006, 2008b). In particular, infants' object-representation system encodes information about the properties of the objects in the event, for recognition and categorization purposes. At the same time, infants' physical-reasoning system forms a specialized physical representation of the event, to interpret and predict its outcome. We focus here on this second system.

The information infants include in their physical representation of an event is interpreted in terms of their core knowledge. This knowledge is assumed to be innate and to consist of a few concepts and principles that provide infants with a shallow causal framework for understanding events (e.g., Spelke, Breinlinger, Macomber, & Jacobson, 1992; Carey & Spelke, 1994; Leslie, 1994; Spelke, 1994; Leslie, 1995; Spelke, Phillips, & Woodward, 1995b; Wilson & Keil, 2000; Baillargeon et al., 2006). For example, Leslie (1994) has suggested that, from birth, infants interpret physical events in accord with a primitive concept of force. When watching an object push another object, infants represent a force—like a directional arrow—being exerted by the first object onto the second one. In Leslie's words, infants' physical-reasoning system "takes, as input, descriptions that make explicit the geometry of the objects contained in a scene, their arrangements and their motions, and onto such descriptions paints the mechanical properties of the scenario" (p. 128).

Of most relevance to the present discussion is the *principle of persistence*, which states that objects exist continuously in time and space, retaining their physical properties as they do so (Baillargeon, 2008). The persistence principle has many corollaries; for example, that stationary objects, whether visible or hidden, exist continuously in time; that moving objects, whether visible or hidden, follow continuous paths; that two objects, whether visible or hidden and whether stationary or moving, cannot occupy the same space at the same time; and that an object of a particular size, shape, pattern, and color, whether stationary or moving and whether visible or hidden, cannot spontaneously become an object of a different size, shape, pattern, or color.

The principle of persistence subsumes and extends two of the principles proposed by Spelke and her colleagues (e.g., Spelke et al., 1992; Carey & Spelke, 1994; Spelke, 1994; Spelke et al., 1995b): the principles of continuity (objects exist and move continuously in time and space) and cohesion (objects are connected and bounded entities). According to these principles, infants should be surprised if an object disappears into thin air (continuity) or breaks apart (cohesion), but not if it simply changes size, shape, pattern, or color. According to the persistence principle, in contrast, infants should be surprised by all of these violations (provided, as always, that the infants represent sufficient information to detect them). The principle of persistence thus goes beyond the principles of continuity and cohesion: All other things being equal, objects are expected to retain all of their physical properties as events unfold—to persist, as they are, through time and space.[1] We return to these issues, and to the experimental evidence that led us to adopt the persistence principle, in a later section.

Detecting Basic Violations Through Core Knowledge

In the first few months of life, infants' physical representations tend to be rather sparse. When watching an event, infants typically represent only basic information about the event (see Fig. 4–1) (e.g., Spelke, 1982; Yonas & Granrud, 1984; Kestenbaum, Termine, & Spelke, 1987; Slater, 1995; Needham, 2000; Wu et al., 2006; Luo et al., in press). This basic information specifies primarily (1) how

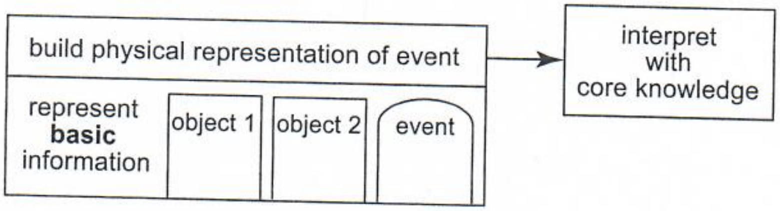


Figure 4–1. An account of infants' physical reasoning: How infants represent and interpret basic information.

many objects are involved in the event; (2) whether these objects are inert or self-propelled; (3) what the distribution of open and closed surfaces in each object is (e.g., is one object open at the top to form a container, open at the bottom to form a cover, or open at both ends to form a tube?); and (4) what the spatial arrangement of the objects is and how it changes over time (e.g., is one object being placed behind, inside, or under the other object?). The basic information infants include in their physical representation of the event thus captures essential aspects of the event but leaves out most of its details; for example, it includes no information about the size, shape, pattern, or color of each object. (Some or all of this information might well be included in infants' object-representation system (e.g., Li et al., 2006b; Wang & Baillargeon, 2008b); our only claim here is that it is not included in the physical-reasoning system and hence cannot be used to interpret and predict the event's outcome.)

Although the basic information young infants represent about events is limited, it is nevertheless sufficient, when interpreted by the persistence principle, to lead them to expect certain outcomes—and hence to detect certain persistence violations when events do not unfold as expected (e.g., Spelke et al., 1992; Wilcox, Nadel, & Rosser, 1996; Lécuyer & Durand, 1998; Aguiar & Baillargeon, 1999; Hespos & Baillargeon, 2001b; Luo & Baillargeon, 2005; Wang, Baillargeon, & Paterson, 2005). As Figures 4–2 and 4–3 illustrate, 2.5- to 3-month-old infants (the youngest tested successfully to date with the VOE method) are surprised when an object rolls behind a large screen, which is then removed to reveal the object resting on the far side of a barrier that should have blocked the object's path (Spelke et al., 1992); when an object is hidden behind one screen and then retrieved from behind a different screen (Wilcox et al., 1996); when an object disappears behind one (asymmetrical or symmetrical) screen and then reappears from behind another screen, without appearing in the gap between them (Aguiar & Baillargeon, 1999; Luo & Baillargeon, 2005); when an object is lowered inside a container through its closed top (Hespos & Baillargeon, 2001b); when an object is lowered into an open container, which is then slid forward and to the side to reveal the object standing in the container's initial position (Hespos & Baillargeon, 2001b); when a cover is lowered over an object, slid to the side, and lifted to reveal no object (Wang et al., 2005); and when a cover is lowered over an object, slid behind the left half of a screen taller than the object, lifted above the screen, moved to the right, lowered behind the right half of the screen, slid past the screen, and finally lifted to reveal the object (Wang et al., 2005).

To succeed in detecting these various persistence violations, infants need only represent the basic information about the events. For example, consider once again the finding that infants are surprised when a cover is lowered over an object, slid to the side, and lifted to reveal no object (Wang et al., 2005; see Fig. 4–3). We would argue that infants represent the following basic information: (1) a cover is held above a closed object; (2) the cover is lowered over the object (the persistence principle would specify at this point that the object continues to exist under the cover); (3) the cover is slid to the side (the persistence principle would specify at this point that the object cannot pass through the sides of the cover and hence must be displaced with the cover to its new location); and (4) the cover is lifted to reveal

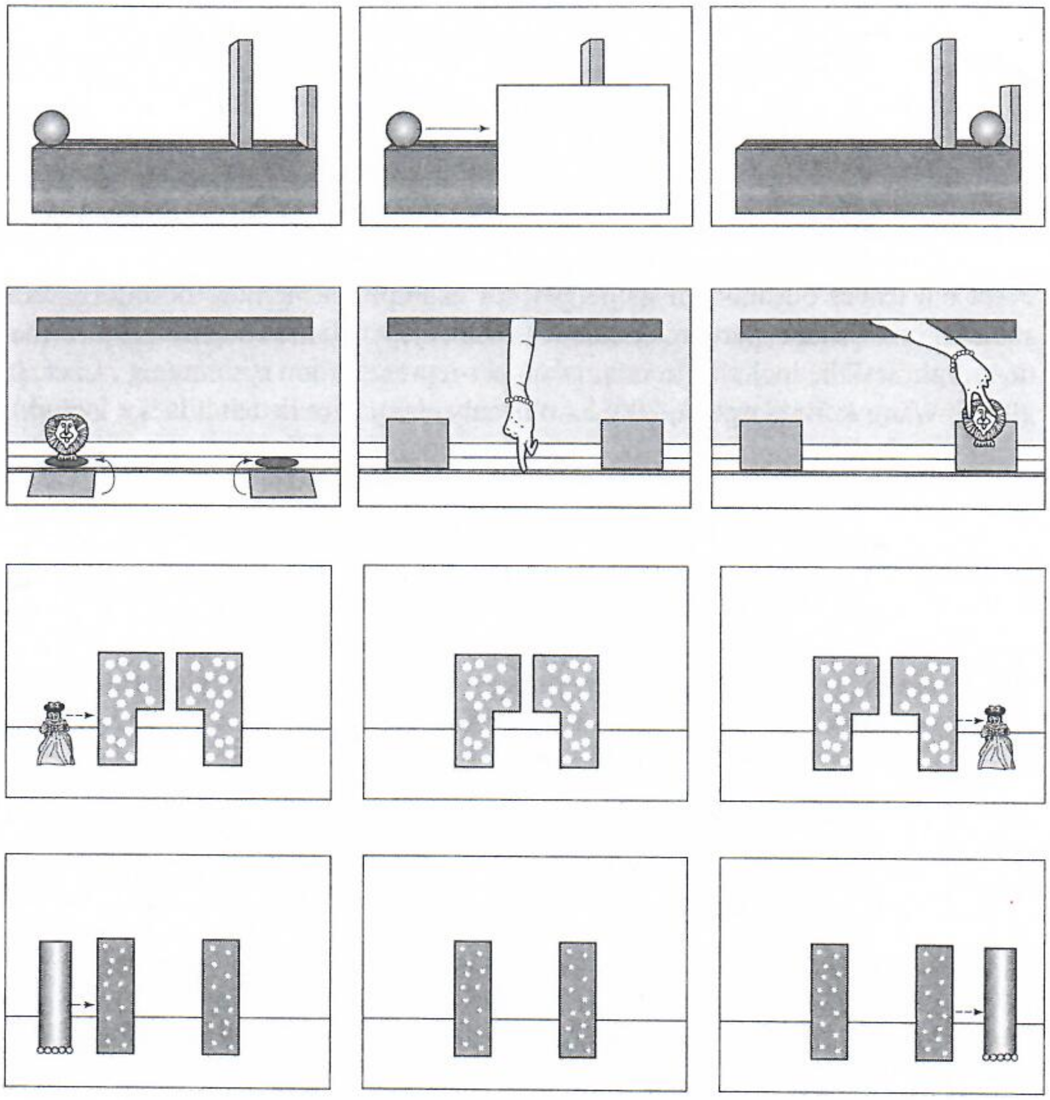


Figure 4–2. Examples of persistence violations that young infants are able to detect, as shown in Spelke et al. (1992), Wilcox et al. (1996), Aguiar and Baillargeon (1999), and Luo and Baillargeon (2005).

no object (the persistence principle would signal at this point that a violation has occurred: The object should have been revealed when the cover was lifted).

Although 2.5- to 3-month-old infants can detect persistence violations that involve only the basic information they represent, they typically fail to detect persistence violations that can be detected only when additional information is represented. To illustrate, as shown in Figure 4–4, current evidence suggests that 3-month-old infants are not surprised when a tall object becomes fully hidden behind a short screen (Baillargeon & DeVos, 1991; Aguiar & Baillargeon, 2002; Luo & Baillargeon, 2005), inside a short container or tube (Hespos & Baillargeon, 2001a; Wang et al., 2005), or under a short cover (Wang & Baillargeon, 2005; Wang et al., 2005; Wang & Baillargeon, 2008a); when an object with a given shape is buried in one location in a sandbox and an object with a different shape is

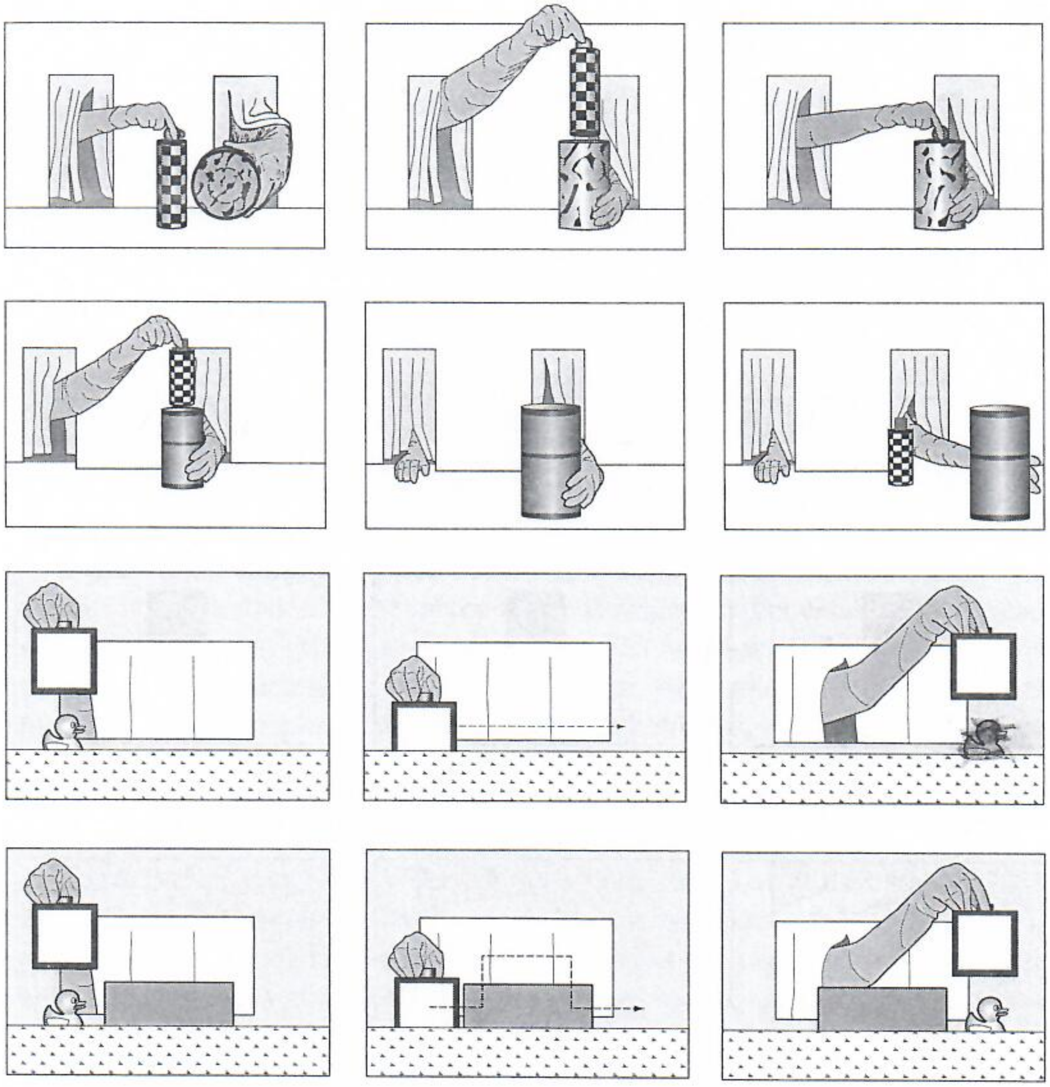


Figure 4–3. Examples of persistence violations that young infants are able to detect, as shown in Hespos and Baillargeon (2001b; top two rows) and Wang et al. (2005; bottom two rows).

retrieved from the same location (Newcombe, Huttenlocher, & Learmonth, 1999); when an object with a given pattern disappears behind a screen (too narrow to hide two objects) and an object with a different pattern reappears from behind it (Wilcox, 1999; Wilcox & Chapa, 2004); and when an object of a given color disappears behind a narrow screen (Wilcox, 1999; Wilcox & Chapa, 2004) or inside a narrow container (Ng & Baillargeon, 2006) and an object of a different color reappears from it.

According to our account, infants fail to detect these and many other persistence violations (as we will see throughout this chapter) because they have not yet learned to include size, shape, pattern, and color information in their physical representations of events. Infants who do not represent an object's physical properties cannot be surprised when the object interacts with other objects in

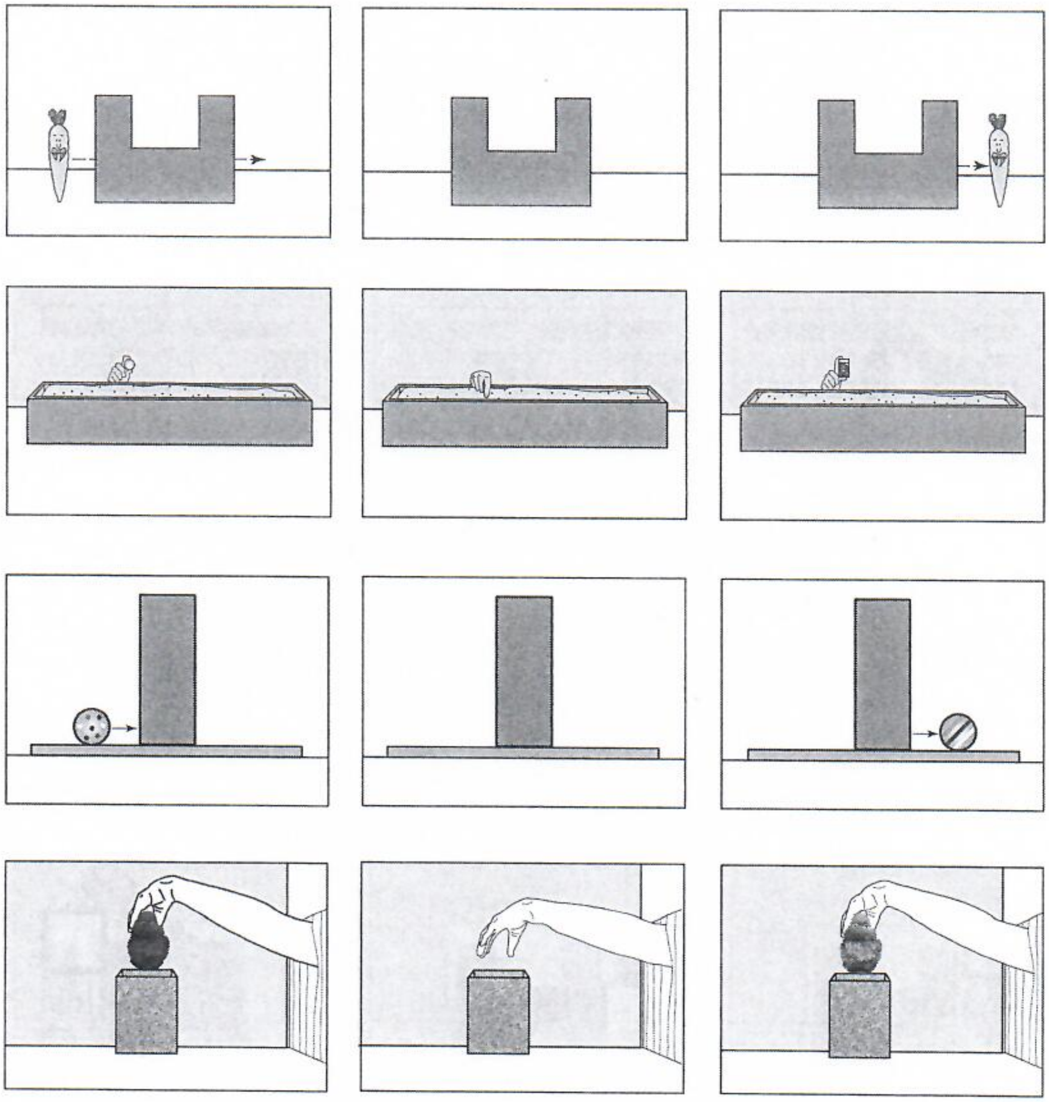


Figure 4–4. Examples of persistence violations that young infants fail to detect, as shown in Aguiar and Baillargeon (2002), Newcombe, Huttenlocher, and Learmonth (1999), Wilcox (1999), and Ng and Baillargeon (2006).

a manner inconsistent with these properties (e.g., when a tall object becomes fully hidden behind a short screen) or when these properties change while the object is out of view (e.g., when a purple toy becomes orange while briefly lowered inside a container). In the next section, we examine how infants come to include additional information in their physical representations of events.

Detecting Variable Violations Through Variable Knowledge

Over time, infants learn to include more and more information in their physical representations; this allows them to form more and more accurate expectations about events' outcomes, and hence to detect more and more violations when shown outcomes inconsistent with these expectations. How do infants come to include this additional information in their physical representations? Research over the past few years has begun to shed light on this process (for recent reviews, see Baillargeon, 2002, 2004; Baillargeon et al., 2006). We briefly review some of the main findings below.

Event Categories, Vectors, and Variables

Recent research suggests that infants form distinct event categories. Many of these categories capture simple spatial relations between objects, such as "object behind other object, or occluder" (occlusion events), "object inside container" (containment events), "object inside tube" (tube events), and "object under cover" (covering events) (e.g., Hespos & Baillargeon, 2001a; Wilcox & Chapa, 2002; Aguiar & Baillargeon, 2003; Casasola, Cohen, & Chiarello, 2003; McDonough, Choi, & Mandler, 2003; Li & Baillargeon, 2005; Wang et al., 2005; Quinn, 2007).

In each event category, infants build one or more vectors, which correspond to distinct problems that must be solved within the category. For example, in the case of occlusion events, infants must learn to predict whether an object will be fully or only partly hidden when behind an occluder, when and where an object that moves behind an occluder will reappear from behind it, and whether an object that reappears from behind an occluder is the same object that disappeared behind it (e.g., Baillargeon & Graber, 1987; Baillargeon & DeVos, 1991; Spelke, Kestenbaum, Simons, & Wein, 1995a; Wilcox, 1999; Hespos & Baillargeon, 2001a; Aguiar & Baillargeon, 2002; Wilcox & Schweinle, 2003; Luo & Baillargeon, 2005; Kochukhova & Gredebäck, 2007; von Hofsten, Kochukhova, & Rosander, 2007). Similarly, in the case of containment events, infants must learn to predict whether an object can be lowered inside a container, how much of an object that is lowered inside a container will protrude above it, and whether the object that is removed from a container is the same object that was lowered into it (e.g., Sitskoorn & Smitsman, 1995; Aguiar & Baillargeon, 1998; Hespos & Baillargeon, 2001a, 2001b; Aguiar & Baillargeon, 2003; Wang et al., 2004; Li & Baillargeon, 2005; Wang et al., 2005; Hespos & Baillargeon, 2006; Ng & Baillargeon, 2006).

For each vector in an event category, infants identify one or more variables that enable them to better predict outcomes (e.g., Sitskoorn & Smitsman, 1995; Wilcox, 1999; Hespos & Baillargeon, 2001a; Aguiar & Baillargeon, 2002; Wang et al., 2005; Luo & Baillargeon, 2008). A variable both calls infants' attention to a certain type of information in an event and provides a causal rule for interpreting this information. In some cases, the rule is akin to a discrete function linking discrete values of the variable to different outcomes. For example, the variable width in containment events specifies that an object can be lowered inside a container if it is narrower, but not wider, than the opening of the container. Each value of the variable (narrower, wider) is thus linked to a different outcome (can be lowered inside, cannot be lowered inside). In other cases, the rule is akin to a continuous function linking continuously changing values of the variable to continuously changing outcomes. For example, the variable height in containment events specifies that an object that is taller than a container not only will protrude above the container when placed inside it but will protrude by an amount identical to the difference in their heights: If the object is 3, 6, or 12 centimeters taller than the container, then the top 3, 6, or 12 centimeters of the object, respectively, should remain visible above the rim of the container.[2] In either case, the principle of persistence provides a ready causal explanation for the rule: For both an object and a container to persist as they are, the two cannot occupy the same space at the time; therefore, the object can be lowered inside the container only if the opening of the container is wide enough for the object to pass through, and the object must retain its height when placed inside the container.

Each variable that is added along a vector revises and refines predictions from earlier variables. This process can be illustrated by a decision tree (for related ideas, see Siegler, 1978; Quinlan, 1993; Mitchell, 1997); with each new variable—or each new partition in the decision tree—infants' predictions slowly approximate those of older children and adults.

As an example, the decision tree in Figure 4–5 depicts some of the variables infants identify as they learn to predict when an object behind an occluder should be hidden or visible. At about 3 months of age, infants identify the variable lower-edge-discontinuity; they now expect an object to be visible when behind an occluder whose lower edge is not continuous with the surface on which it rests, creating an opening between the occluder and the surface (Aguiar & Baillargeon, 2002; Luo & Baillargeon, 2005). Thus, infants expect an object to remain visible when it passes behind a screen shaped like an inverted U, but not one shaped like a U.[3] At about 3.5 to 4 months of age, infants identify height and width as relevant variables; they now expect tall objects to remain partly visible when behind short occluders (Baillargeon & DeVos, 1991), and wide objects to remain partly

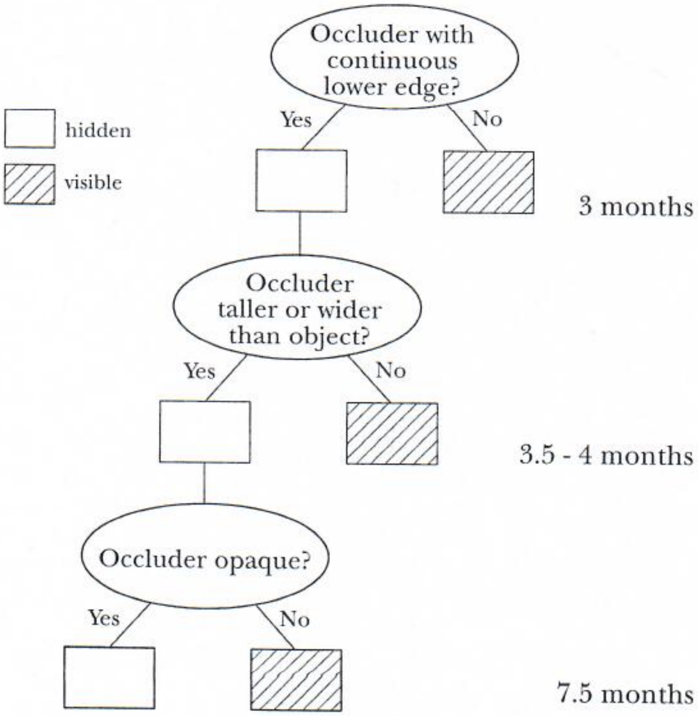


Figure 4–5. A decision tree representing some of the variables infants identify as they learn when an object behind an occluder is hidden or visible.

visible when behind narrow occluders (Wilcox & Baillargeon, 1998b; Wilcox, 1999; Wang et al., 2004).[4] Finally, at about 7.5 months of age, infants identify transparency as a variable; when an object is placed behind a transparent occluder, infants now expect the object to be visible through the front of the occluder and are surprised if it is not (Luo & Baillargeon, 2008).[5]

As another example, the decision tree in Figure 4–6 depicts some of the variables infants identify as they learn to predict, when an object disappears and then reappears from behind an occluder, whether the object that reappears is the same object that disappeared or a different object. Research by Wilcox and her colleagues suggests that, at least by 4.5 months of age, infants have identified size and shape as relevant variables; if a box disappears behind a screen and what reappears is a ball, infants conclude that two distinct objects, a box and a ball, are involved in the event (Wilcox & Baillargeon, 1998b; Wilcox, 1999).[6] At about 7.5 months of age, infants identify pattern as a variable; if a dotted ball disappears behind a screen and what reappears is a striped ball, infants recognize that two different balls, one dotted and one striped, are involved in the event (Wilcox, 1999; Wilcox & Chapa, 2004). Finally, at about 11.5 months, infants identify color as a variable; if a green ball disappears behind a screen and what reappears is a red ball, infants infer that two balls, one green and one red, are involved in the event (Wilcox, 1999; Wilcox & Chapa, 2004; Ng & Baillargeon, 2006).

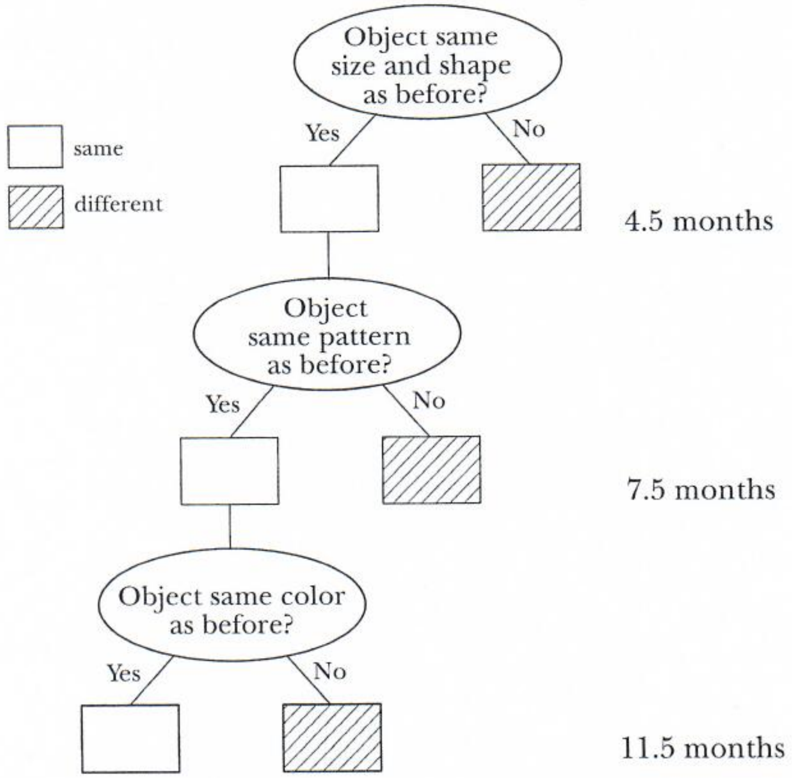


Figure 4–6. A decision tree representing some of the variables infants identify as they learn when an object that reappears from behind an occluder is or is not the same object that disappeared.

We have seen in this section that infants reason and learn in terms of event categories, vectors, and variables. Why would they do so? At a very general level, infants are trying to make sense of the physical events they observe. Infants' physical-reasoning system is designed to break this Herculean task down into small, meaningful components. By sorting events into distinct categories (e.g., containment events) and isolating different vectors within each category (e.g., whether the object can be lowered inside the container, whether the object will protrude above the container, and so on), the physical-reasoning system transforms this Herculean task into a manageable one: that of identifying, one by one, the variables relevant for each vector of each event category.

Reasoning About Variable Information

How does infants' physical reasoning change as they form event categories and identify the vectors and variables relevant for predicting outcomes in each category? According to our account (see Fig. 4–7), when watching an event, infants begin by representing the basic information about the event. Infants then use this information to categorize the event. Next, infants access their knowledge of the category selected; this knowledge specifies the variables that have been identified for the category. Information about each variable is then included in the physical representation and is interpreted in accord with the variable rule. Events whose outcomes are inconsistent with those predicted by the variable rules are flagged as violations.

To illustrate, consider the finding that infants aged 3.5 months and older are surprised when a tall object becomes fully hidden behind a short occluder (Baillargeon & Graber, 1987; Baillargeon & DeVos, 1991; Hespos & Baillargeon, 2001a). When watching this event, infants represent the basic information about

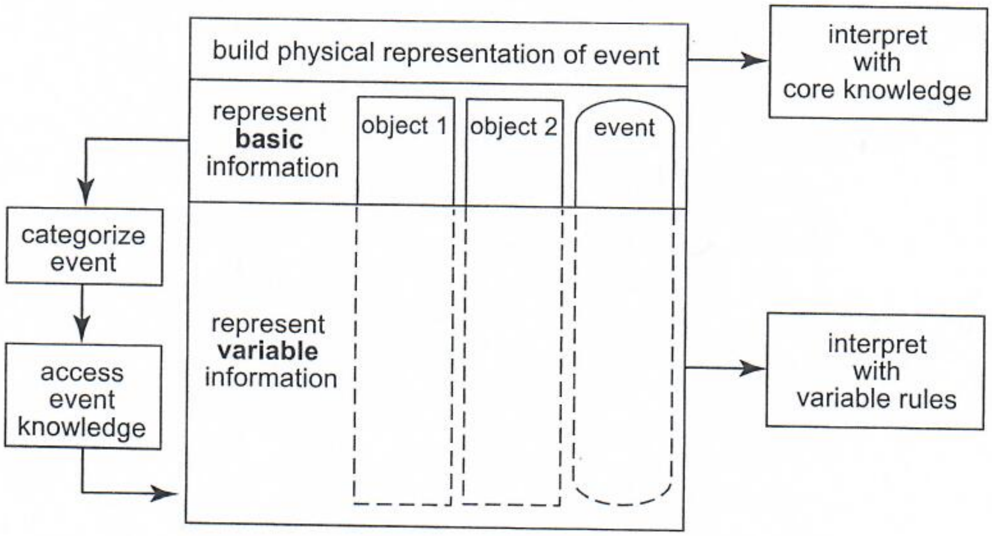


Figure 4–7. An account of infants' physical reasoning: How infants represent and interpret basic and variable information.

the event, categorize it as an occlusion event, and access their knowledge of this category. Because at 3.5 months this knowledge encompasses the variable height (see Fig. 4–5), infants include information about the relative heights of the object and occluder in their physical representation of the event. This information is then interpreted in terms of the variable rule. Because the outcome of the event contradicts this rule—the object is taller than the occluder and yet becomes fully hidden—the event is flagged as a variable violation. Infants younger than 3.5 months, who have not yet identified height as an occlusion variable, typically do not include height information in their physical representations of occlusion events (Baillargeon & DeVos, 1991; Aguiar & Baillargeon, 2002; Luo & Baillargeon, 2005). (This is not to say that young infants watching an occlusion event will represent no information at all about the heights of the object and occluder; as mentioned earlier, infants may include such information in their object-representation system [e.g., Li et al., 2006b; Wang & Baillargeon, 2008b], even if they do not include it in their physical-reasoning system.)

As another illustration, consider the finding that infants aged 11.5 months and older are surprised when a green ball changes into a red ball when passing behind a narrow screen (Wilcox, 1999; Ng & Baillargeon, 2006). When watching the event, infants represent the basic information about the event, categorize it as an occlusion event, and access their knowledge of this category. Because at 11.5 months this knowledge encompasses the variables width (see Fig. 4–5) and color (see Fig. 4–6), infants include information about these variables in their physical representation of the event. This information is then interpreted in accord with infants' width and color rules, and the event is flagged as a variable violation. Infants recognize that the green ball (1) fills most of the space behind the screen and (2) cannot spontaneously change from a green to a red ball. Infants younger than 11.5 months, who have not yet identified color as a relevant variable, do not include color information in their representation of the event. As a result, they assume that the same ball disappeared and reappeared from behind the narrow screen. (Once again, this is not to say that young infants watching an occlusion event represent no information at all about the color of the object that disappears and reappears from behind the occluder; infants may include such information in their object-representation but not their physical-reasoning system.)

Errors of Omission and Commission

If it is true that each new variable in a vector with multiple variables revises predictions from earlier variables, then it should be the case that infants who have acquired only the initial variable(s) in a vector err in systematic ways in their responses to events (Luo & Baillargeon, 2005). First, infants should respond to physically impossible events consistent with their faulty knowledge as though they were expected; we refer to this first kind of error—viewing an impossible event as a non-violation—as an error of omission. Second, infants should respond to physically possible events inconsistent with their faulty knowledge as though they were unexpected; we refer to this second kind of error—viewing a possible event as a violation—as an error of commission.

Do infants produce errors of commission as well as errors of omission in their responses to events? To address this question, Luo and Baillargeon (2005) recently examined 3-month-old infants' responses to physically possible and impossible occlusion events. The experiment focused on the vector in Figure 4–5: When is an object behind an occluder hidden or visible?

The infants were first familiarized with a cylinder that moved back and forth behind a screen; the cylinder was as tall as the screen (see Fig. 4–8). Next, a large portion of the screen's midsection was removed to create a very large opening; a short strip remained above the opening in the discontinuous-lower-edge test event, and below the opening in the continuous-lower-edge test event. For half of the infants, the cylinder did not appear in the opening in either event (CDNA condition); for the other infants, the cylinder appeared (CA condition).

The infants in the CDNA condition were shown two impossible test events. However, because at 3 months infants have identified lower-edge-discontinuity but not height as an occlusion variable (Aguiar & Baillargeon, 2002; see Fig. 4–5), Luo and Baillargeon (2005) predicted that the infants would view only one of these events as unexpected. Specifically, the infants should view the event in which the cylinder failed to appear behind the screen with a discontinuous lower edge as unexpected (a correct response), but they should view the event in which the cylinder failed to appear behind the screen with a continuous lower edge as expected (an error of omission). The infants should therefore look reliably longer at the discontinuous- than at the continuous-lower-edge event.

Unlike the infants in the CDNA condition, those in the CA condition were shown two possible test events. Again, because 3-month-old infants have identified lower-edge-discontinuity but not height as an occlusion variable, Luo and Baillargeon (2005) predicted that the infants would view only one of those events as expected. Specifically, the infants should view the event in which the cylinder appeared behind the screen with a discontinuous lower edge as expected (a correct response), but they should view the event in which the cylinder appeared behind the screen with a continuous lower edge as unexpected (an error of commission). The infants should therefore look reliably longer at the continuous- than at the discontinuous-lower-edge event.

As predicted, the infants in the CDNA condition looked reliably longer at the discontinuous- than at the continuous-lower-edge event, and those in the CA condition showed the opposite looking pattern. Their limited knowledge of occlusion thus (1) led the infants in the CDNA condition to view one of the impossible events they were shown as expected (an error of omission) and (2) led the infants in the CA condition to view one of the possible events they were shown as unexpected (an error of commission). To put it another way, the infants both failed to detect a violation where there was one and perceived a violation where there was none. For infants, as for older children and adults, what is surprising clearly lies in the mind of the beholder (e.g., Karmiloff-Smith & Inhelder, 1975; Siegler, 1978; Caramazza, McCloskey, & Green, 1981; McCloskey, 1983; Carey, 1985; Proffitt, Kaiser, & Whelan, 1990; Keil, 1991; Vosniadou & Brewer, 1992).

Additional experiments have brought to light other errors of commission in infants' responses to occlusion events (e.g., Luo & Baillargeon, 2008). For example,

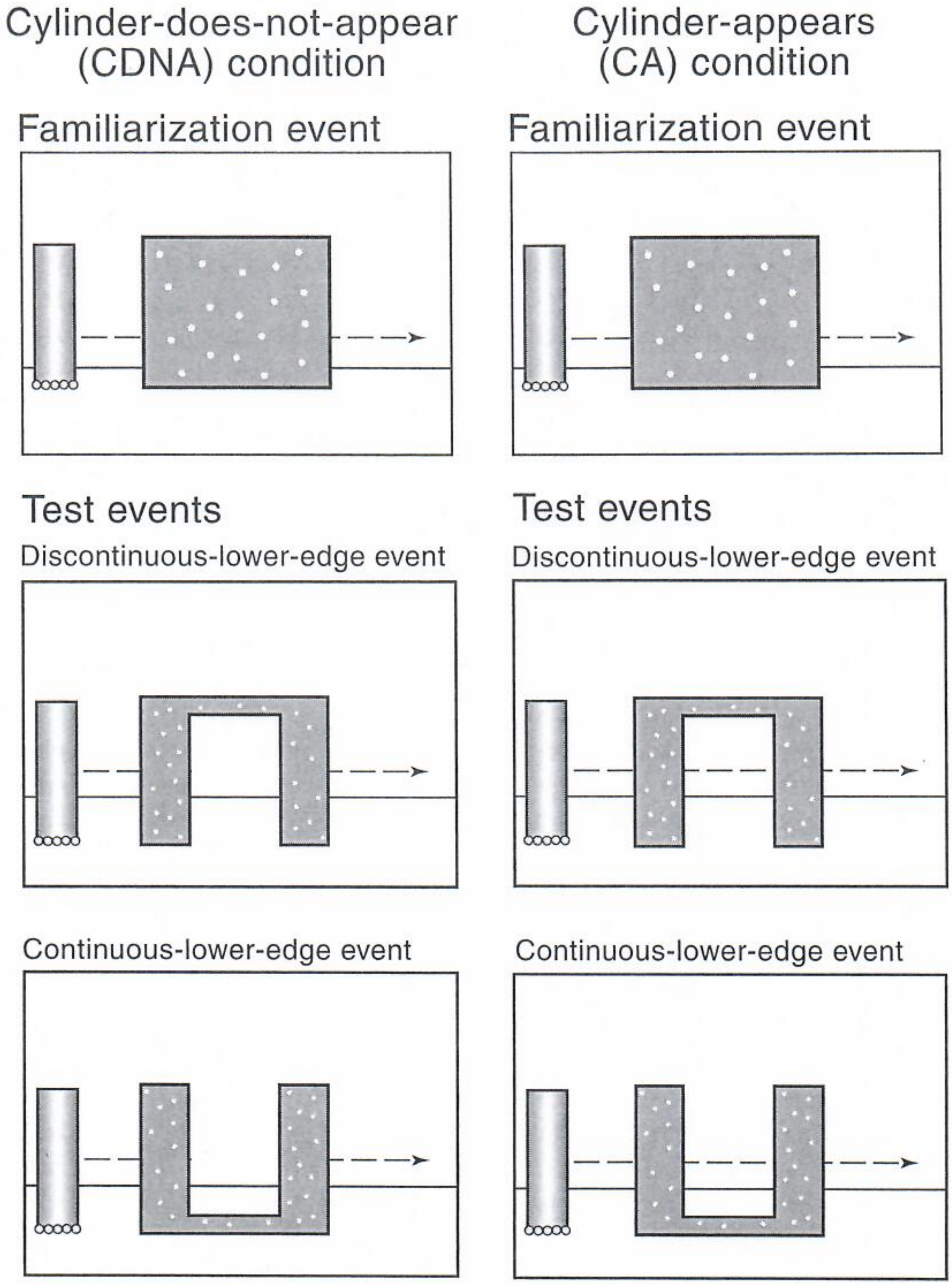


Figure 4–8. Familiarization and test events used in Luo and Baillargeon (2005).

7-month-old infants view as a violation a possible event in which an object placed behind a transparent occluder remains visible through the occluder (Luo & Baillargeon, 2008). At this age, infants have identified lower-edge-discontinuity, height, and width but not yet transparency as occlusion variables (see Fig. 4–5). Thus, when an object is placed behind an occluder that presents no internal or external openings and is taller and wider than the object, infants expect the object to be fully hidden when behind the occluder. Events whose outcomes appear inconsistent with these predictions are flagged as variable violations.

All of the errors of commission discussed above concern the vector in Figure 4–5: When is an object behind an occluder hidden or visible? We have recently completed an experiment (Ng, Baillargeon, & Wilcox, 2007) with 8.5-month-old infants focusing on the vector in Figure 4–6: When is an object that reappears from behind an occluder the same object that disappeared behind it, and when is it a different object? Recall that by 8.5 months of age, infants have identified size, shape, and pattern, but not yet color, as variables in this vector. Thus, it should be the case that infants (1) conclude that two different objects are present when an object is lowered behind a large screen and then an object with the same size and shape, but with a different pattern, is lifted from behind the screen, and (2) conclude that only one object is present when an object is lowered behind a large screen and then an object with the same size, shape, and pattern, but with a different color, is lifted from behind the screen. In the latter case, infants should thus be surprised—an error of commission—when given evidence that there is more than one object behind the screen. Results confirmed these predictions.

Décalages

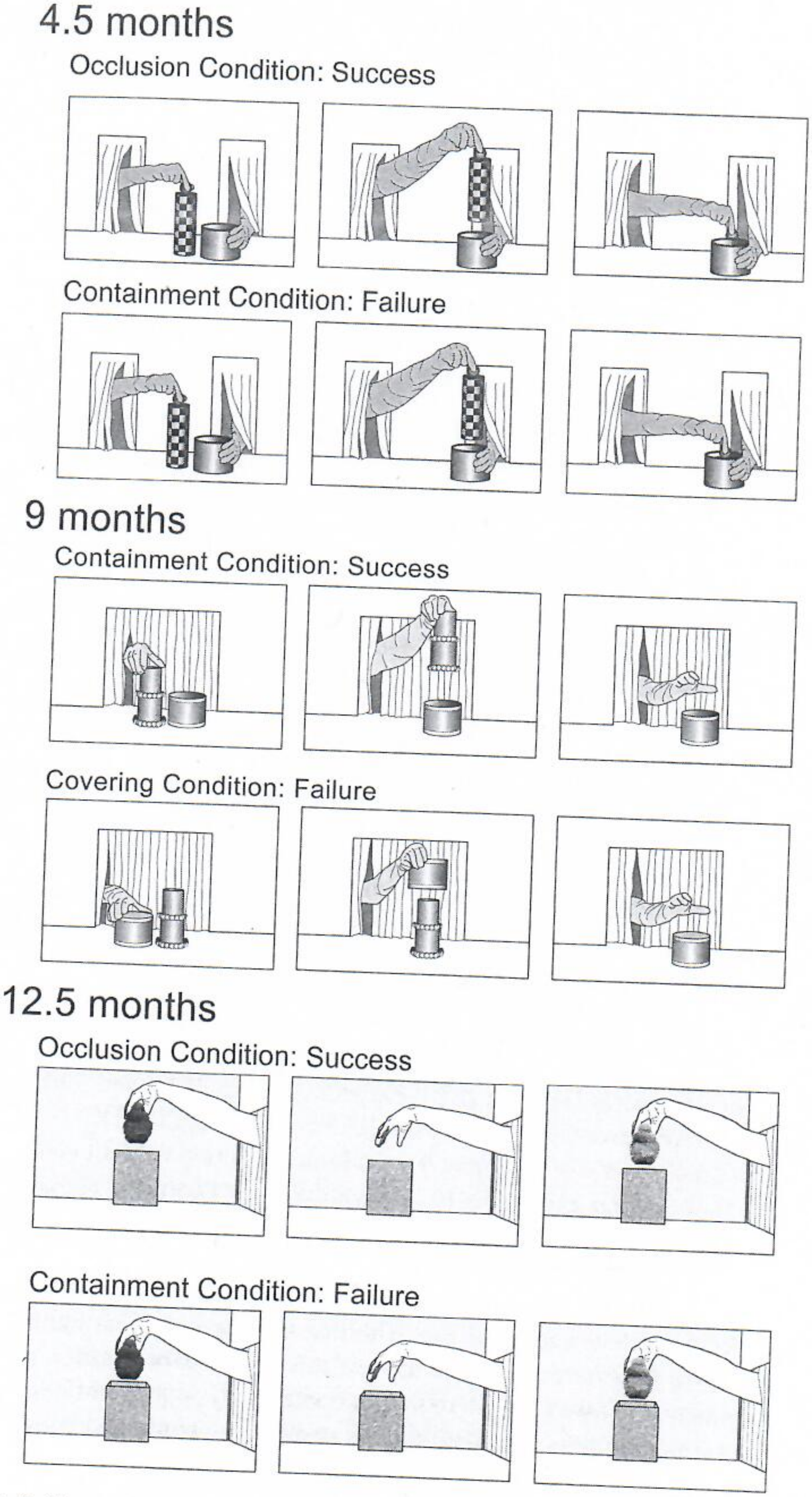
Recent research suggests that the process by which infants identify variables is event-specific; infants learn separately about each event category. A variable identified in one event category is not generalized to other categories, even when equally relevant; rather, it is learned independently in each category. In some cases, the variable may be identified at about the same age in the different categories. For example, the variable width is identified at about the same age in occlusion and in containment events; 4-month-old infants are surprised when a wide object becomes fully hidden either behind a narrow occluder or inside a narrow container (e.g., Wilcox & Baillargeon, 1998b; Wilcox, 1999; Wang et al., 2004). In other cases, however, there may be marked lags or décalages (to use a Piagetian term) in infants' identification of the same variable in different categories.

As an example, we saw above that infants identify the variable height at about 3.5 months in occlusion events (Baillargeon & DeVos, 1991); they are now surprised when a tall object becomes fully hidden behind a short occluder. However, infants this age are not surprised when a tall object becomes fully hidden inside a short container, under a short cover, or inside a short tube. The variable height is not identified until about 7.5 months in containment events (Hespos & Baillargeon, 2001a, 2006), until about 12 months in covering events (McCall, 2001; Wang et al., 2005; Wang & Baillargeon, 2006), and until about 14 months in tube events (Gertner, Baillargeon, & Fisher, 2005; Wang et al., 2005). Similarly, we saw earlier that the variable transparency is identified at about 7.5 months in occlusion events (Luo & Baillargeon, 2008); infants are now surprised when an object placed behind a transparent occluder is not visible through the occluder. However, it is not until infants are about 9.5 months of age that they identify the same variable in containment events and expect an object placed inside a transparent container to be visible through the container (Luo & Baillargeon, 2008).[7]

When infants of a given age have identified a variable in one event category but not another, striking discrepancies can be observed in their responses to events—even perceptually similar events—from the two categories (see Fig. 4–9). Thus, 4.5-month-old infants, who have identified the variable height in occlusion but not containment events, are surprised when a tall object becomes fully hidden behind but not inside a short container (Hespos & Baillargeon, 2001a). Similarly, 9-month-old infants, who have identified the variable height in containment but not covering events, are surprised when a tall object becomes fully hidden inside a short container but not under a short cover (the short container turned upside down) (Wang et al., 2005). Finally, 12.5-month-old infants, who have identified the variable color in occlusion but not containment events, are surprised when a toy is lowered behind a narrow occluder and then another toy, identical except for color, is removed from behind the occluder; however, they are not surprised when the narrow occluder is replaced with a narrow container—even though the occluder is identical to the front of the container, so that the two events are perceptually highly similar (Ng & Baillargeon, 2006). According to our reasoning account, in each case infants succeed in detecting the variable violation in the first but not the second event category because they have not yet identified the variable as relevant to the second event category. As a result, they include information about the variable in their physical representation of the event from the first but not the second category.

In the findings just described, infants were shown perceptually similar but not identical events: The object was placed behind or inside a container, inside a container or under a cover, and so on. In recent experiments, we asked whether infants might respond differently to *identical* events, if they were led to believe, based on prior information, that the events belonged to two different event categories (Li & Baillargeon, 2005; Wang et al., 2005). The point of departure for these experiments was the finding that the variable height is identified at about 7.5 months in containment events (Hespos & Baillargeon, 2001a, 2006), but only at about 14 months in tube events (Gertner et al., 2005; Wang et al., 2005).

In one experiment, for example, 9-month-old infants watched two test events in which they saw an experimenter lower a tall object inside a container (containment condition) or a tube (tube condition) until it became fully hidden (see Fig. 4–10) (Wang et al., 2005). In one event, the container or tube was slightly taller than the object (tall event); in the other event, the container or tube was only half as tall (short event), so that it should have been impossible for the object to become fully hidden. Before the test session, in an orientation procedure, the experimenter showed the infants each container (containment condition) or tube (tube condition) one at a time, calling attention to its top and bottom. When standing upright on the apparatus floor during the test events, the containers and tubes were indistinguishable. The infants in the containment and tube condition thus saw perceptually identical test events; only the information provided in the orientation procedure could lead them to believe that they were watching events involving containers or tubes.



4.5 months

Occlusion Condition: Success

Containment Condition: Failure

9 months

Containment Condition: Success

Covering Condition: Failure

12.5 months

Occlusion Condition: Success

Containment Condition: Failure

Figure 4–9. Examples of décalages: height in occlusion and containment events (Hespos & Baillargeon, 2001a), height in containment and covering events (Wang et al., 2005), and color in occlusion and containment events (Ng & Baillargeon, 2006).

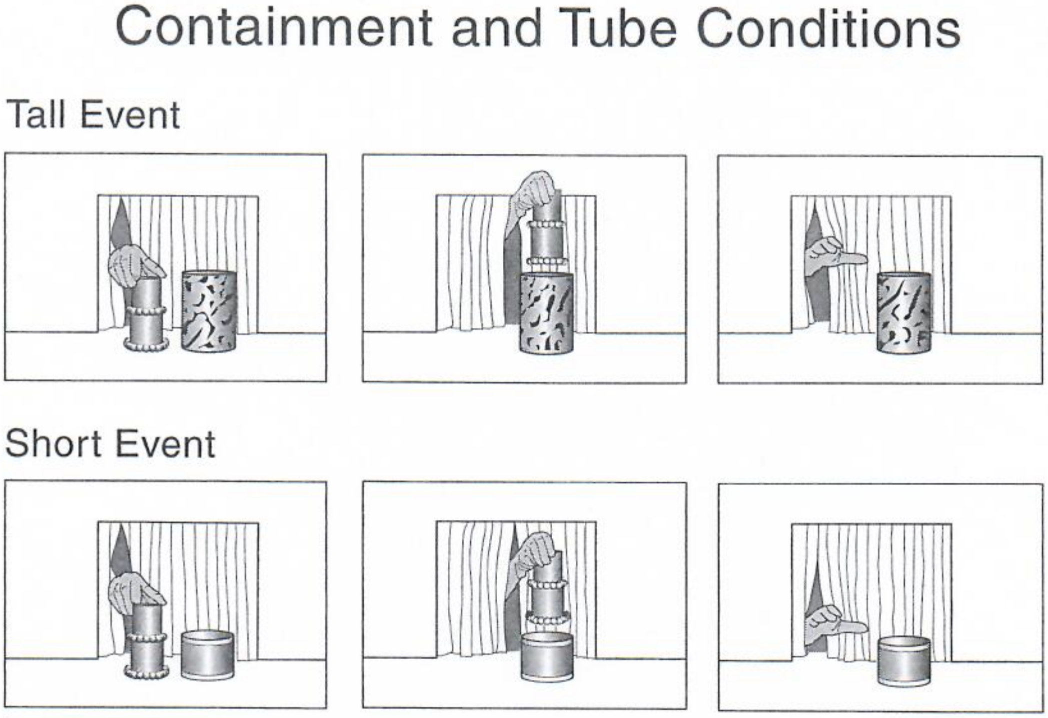


Figure 4–10. Test events used in Wang et al. (2005).

As expected, the infants in the containment condition looked reliably longer at the short than at the tall event, but those in the tube condition tended to look equally at the two events. The infants thus detected the height violation they were shown when they believed they were facing containers, but not tubes.

Identifying Variables

We have seen that, for each event category, infants identify variables, ordered along vectors, which enable them to predict outcomes within the category more and more accurately over time. How do infants identify these variables?

We have proposed that the process by which infants identify a new variable in an event category is one of explanation-based learning (EBL) and involves three main steps (Baillargeon, 2002; Baillargeon et al., 2006; Wang & Baillargeon, 2008a; for a computational description of EBL in the machine-learning literature, see DeJong, 1993). First, infants notice contrastive outcomes relevant to the variable. This occurs when infants watch events, build similar physical representations for the events—and notice that the outcomes of the events differ along some vector (e.g., the object can or cannot be placed inside the container; the object does or does not protrude above the container; and so on). In other words, infants notice contrastive outcomes they cannot predict or interpret; similar physical representations are leading to different outcomes, suggesting that some crucial piece of information is missing from the representations. At this point, infants begin to search for the conditions that map onto the observed contrastive outcomes.

Eventually (research is needed to shed light on the mechanisms at work here), infants identify a possible rule linking conditions and outcomes. Finally, infants attempt to supply an explanation for this condition–outcome rule, using their core knowledge. According to the EBL process, only condition–outcome rules for which causal explanations can be provided are recognized as new variables. After a new variable has been identified, infants begin to routinely include information about the variable in their physical representations of all new events from the category, thus ensuring a powerful, yet appropriate, generalization.

The identification of a new variable is thus described as an EBL process because infants' core knowledge must provide a causal explanation for the variable; it must make clear why one condition, or one value of the variable, would lead to one outcome, and why another condition, or another value of the variable, would lead to a different outcome. The explanations supplied by the core knowledge are no doubt shallow (e.g., Keil, 1995; Wilson & Keil, 2000), but they still serve to integrate new variables with infants' prior causal knowledge.

To illustrate the EBL process, consider the variable height in containment events, which is identified at about 7.5 months of age (Hespos & Baillargeon, 2001a, 2006). We suppose that at some point prior to 7.5 months, infants begin to notice—either as they themselves manipulate objects and containers or as they observe others doing so—that objects that are placed in containers sometimes protrude above the rim and sometimes do not. Because at this time infants include only the information "object placed inside wider, open container" in their physical representations of the events (recall that width is identified at about 4 months as a containment variable) (Wang et al., 2004), they have no way of interpreting these contrastive outcomes. Identical physical representations are leading to different outcomes; sometimes the object protrudes above the rim of the container, and sometimes it does not. Infants then begin to search for the conditions that might be associated with each outcome. By about 7.5 months of age, infants recognize that the relative heights of the object and container are critical; the object protrudes above the rim of the container when it is taller but not shorter than the container. This condition–outcome rule is immediately interpretable by infants' core knowledge: For both a tall object and a short container to exist continuously in time and space, retaining their individual physical properties, the tall object must protrude above the rim of the short container when placed inside it. Infants have thus identified a new vector (when does an object inside a container protrude above it?) and a new variable (height).[8]

From this point on, infants routinely include height information in their representations of containment events and interpret this information in accord with their new variable rule. Thus, infants are surprised whenever a tall object is lowered inside a short container until it becomes fully hidden (e.g., Hespos & Baillargeon, 2001a; Wang et al., 2005). In addition, infants show evidence of attending to height information in simple action tasks involving containers. In a recent experiment (see Fig. 4–11) (Hespos & Baillargeon, 2006), 7.5-month-old infants were shown a tall frog. Next, the frog was placed behind a large screen, which was then removed to reveal a short and a tall container; each container had two frog feet protruding from small holes at the bottom of the container. The

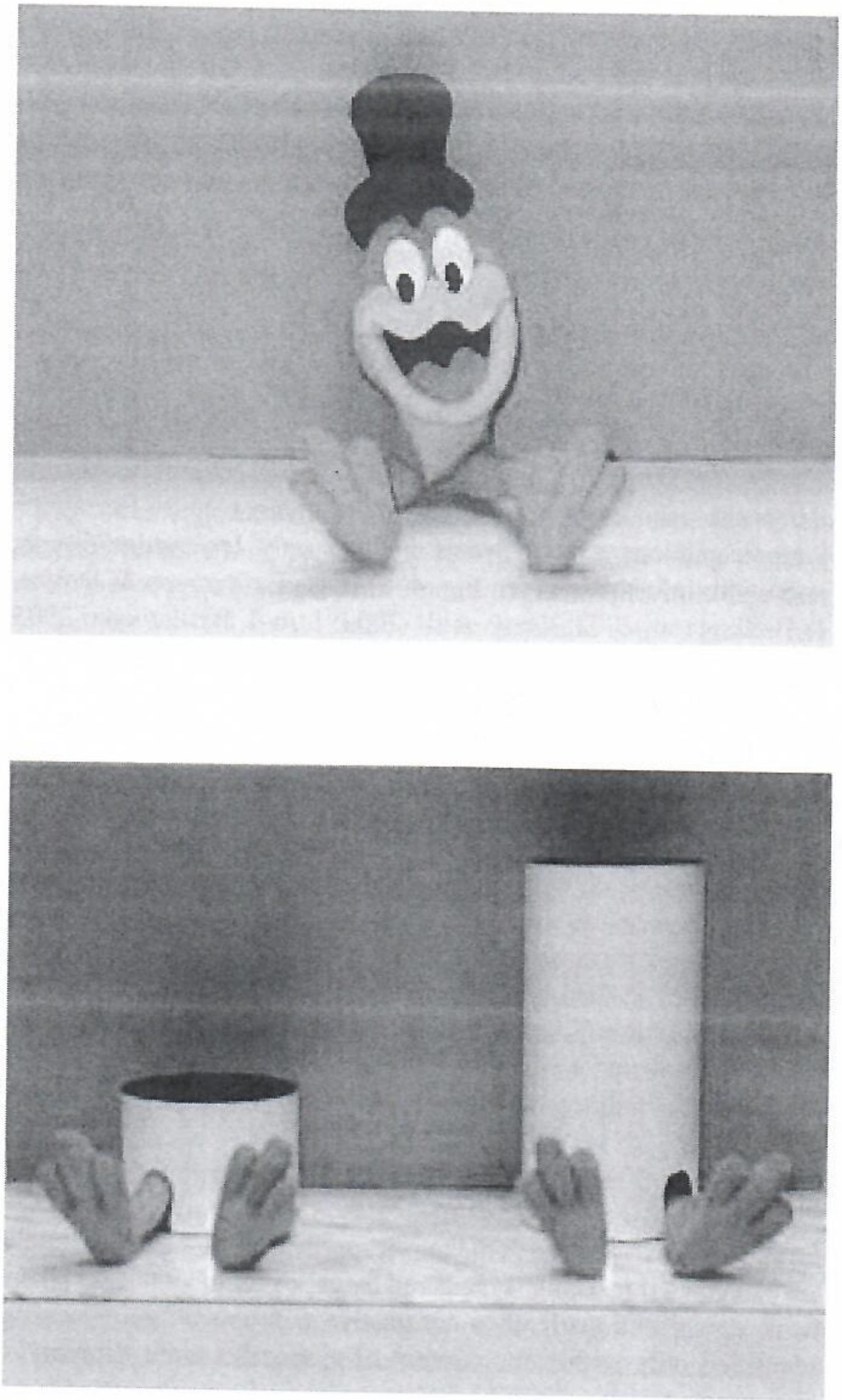


Figure 4–11. Test event used in Hespos and Baillargeon (2006): pretrial (top row) and main trial (bottom row).

infants reached reliably more often for the tall than for the short container, suggesting that they wanted to find the tall frog and realized that it could be hidden inside only the tall container. Control infants who did not see the tall frog tended to reach equally often for the two containers.

In the example discussed above, the identification of the variable height went hand in hand with the creation of a new vector (when does an object placed inside a container protrude above it?). In other cases, the newly identified variable is added to an existing vector. To illustrate, consider the variable transparency in occlusion events, which is identified at about 7.5 months of age (see Fig. 4–5) (Luo & Baillargeon, 2008). As noted earlier, at about 7 months (Johnson & Aslin, 2000), infants become able to detect clear surfaces and begin to include information about the presence—though not the appearance—of these surfaces in their physical representations of events (younger infants presumably simply see and represent openings instead). As a result, infants will now be faced with contrastive outcomes they cannot interpret; they will notice that objects that move behind large occluders sometimes become hidden, as infants' current occlusion knowledge predicts they should be, and sometimes remain visible. Because infants' physical representations of the events include only lower-edge-discontinuity, height, and width information (see Fig. 4–5) (e.g., Baillargeon & DeVos, 1991; Aguiar & Baillargeon, 2002; Wang et al., 2004; Luo & Baillargeon, 2005), they cannot make sense of what they see; the same physical representation "object placed behind taller and wider occluder with no internal or external opening" leads to a predicted (hidden) or an unpredicted (visible) outcome. At this point, infants will begin to look for the condition associated with each observed outcome. By about 7.5 months of age, infants recognize that the opacity or transparency of the occluder is critical; objects become hidden behind opaque but not transparent occluders. Infants' core knowledge allows them to immediately make sense of this information; because an object continues to exist when placed behind a transparent occluder, it must be visible through the occluder. The newly identified variable transparency is then added to the vector "when is an object behind an occluder hidden or visible?" From then on, infants include information about the transparency of the occluder when representing occlusion events (e.g., Wilcox & Chapa, 2002; Luo & Baillargeon, 2008).

Why Décalages?

The EBL process described above makes clear why infants learn separately about each event category; if learning is triggered by exposure to situations where similar physical representations lead to contrastive outcomes, then a new variable can be identified only within the context of a specific event category. Events from different categories will yield different physical representations, and contrastive outcomes associated with these different representations will not elicit learning, even if they are in fact contrastive from an abstract or adult point of view (e.g., "object placed inside container—object does not protrude above container" versus "object placed inside tube—object protrudes above tube"). The reason why the learning process is so rapid (or indeed, possible) is thus that it is highly constrained. Infants do not compare arbitrary groups of events and look for invariants or critical variables that might explain similarities or differences between them. The only situation that can trigger variable learning is one where events with similar physical representations yield outcomes that differ along a specific vector.

The preceding discussion helps make clear why infants would learn separately about each event category—but it does not explain why several months sometimes separate the acquisition of the same variable in different event categories. For example, why do infants identify the variable height at about 3.5 months in occlusion events, but only at about 7.5 months in containment events, 12 months in covering events, and 14 months in tube events (e.g., Baillargeon & DeVos, 1991; Hespos & Baillargeon, 2001a; Gertner et al., 2005; Li & Baillargeon, 2005; Wang et al., 2005; Hespos & Baillargeon, 2006; Wang & Baillargeon, 2006)?

The EBL account suggests two possible reasons for such décalages. One has to do with the first step in the EBL process; because exposure to appropriate contrastive outcomes is necessary to trigger learning, it follows that variables will be learned later when exposure is less frequent. Thus, infants may identify height as a containment variable long before they identify it as a covering variable simply because, in everyday life, infants have more opportunities to notice that objects inside containers sometimes protrude above them and sometimes do not than to notice that objects placed under covers sometimes extend beneath them and sometimes do not.

A second reason why infants may identify a variable sooner in one event category than in another has to do with the second step in the EBL process. After noticing the contrastive outcomes for a variable, infants must discover what conditions map onto these outcomes; this discovery may be more difficult in some categories than in others. To illustrate, consider once again the finding that infants identify height as an occlusion variable several months before they identify it as a containment variable. Prior research (e.g., Baillargeon 1994, 1995) indicates that when infants begin to reason about a continuous variable in an event category, they can reason about the variable qualitatively but not quantitatively; they are not able at first to encode and reason about absolute amounts. In order to encode the heights of objects and occluders or containers qualitatively, infants must compare them as they stand side by side. It may be that infants have more opportunities to perform such qualitative comparisons with occlusion than with containment events. In the case of occlusion events, infants will often see objects move behind the side edges of occluders, making it easy to compare their heights as they stand next to each other (e.g., when a bowl is pushed behind a cereal box). In the case of containment events, however, there may be relatively few instances in which objects are placed first next to and then inside containers; caretakers will more often lower objects directly into containers, giving infants no opportunity to compare their heights (e.g., Hespos & Baillargeon, 2001a; Wang et al., 2004).

The preceding analysis predicts that infants who are exposed in the laboratory (or at home) to appropriate observations for a variable should identify it earlier than they otherwise would. Wang and Baillargeon (2008a) recently tested this prediction: They attempted to "teach" 9-month-old infants the variable height in covering events (recall that this variable is typically not identified until about 12 months of age) (Wang et al., 2005; Wang & Baillargeon, 2006). The results of these teaching experiments were positive and as such support both the EBL account and the speculation above that the décalage in infants' identification of the variable height in containment and covering events stems from the fact that infants are typically exposed to appropriate observations for this variable at different ages in the two categories.

Detecting Variable Violations Through Core Knowledge

So far, we have considered two different processes by which infants reason about physical events. First (see Fig. 4–1), we saw that infants—even very young infants—represent basic information about events and interpret this information in accordance with their core knowledge. Events whose outcomes are inconsistent with the core knowledge are flagged as violations.

Second (see Fig. 4–7), we saw that, with experience, infants come to include additional information, or variable information, in their physical representations of events. For each event category, infants identify vectors and variables relevant for predicting outcomes in the category. When watching an event, infants first categorize it, access their knowledge of the variables that have been identified as relevant for the category, and include information about each of these variables in their physical representation of the event. This information is then interpreted in accordance with the variable rules. Events inconsistent with the rules are flagged as violations. When infants' knowledge is still limited—because they have acquired no variable, or have acquired only the initial variable(s), in a vector—they typically err in their responses to events; they fail to flag as violations impossible events consistent with their faulty knowledge (e.g., a tall object that fails to remain visible above a short occluder), and they flag as violations ordinary and even commonplace events that happen to be inconsistent with their faulty knowledge (e.g., a tall object that remains visible above a short occluder).

In this section, we examine a third process by which infants reason about physical events. We suggested at the start of this chapter that all of the information infants include in their physical representation of an event is interpreted in terms of their core knowledge. If this is correct, and the information infants represent about a variable is interpreted not only in terms of the variable rule but also in terms of their core knowledge, then infants might be able to detect additional violations involving the variable. Here we focus on change violations.

Change Violations

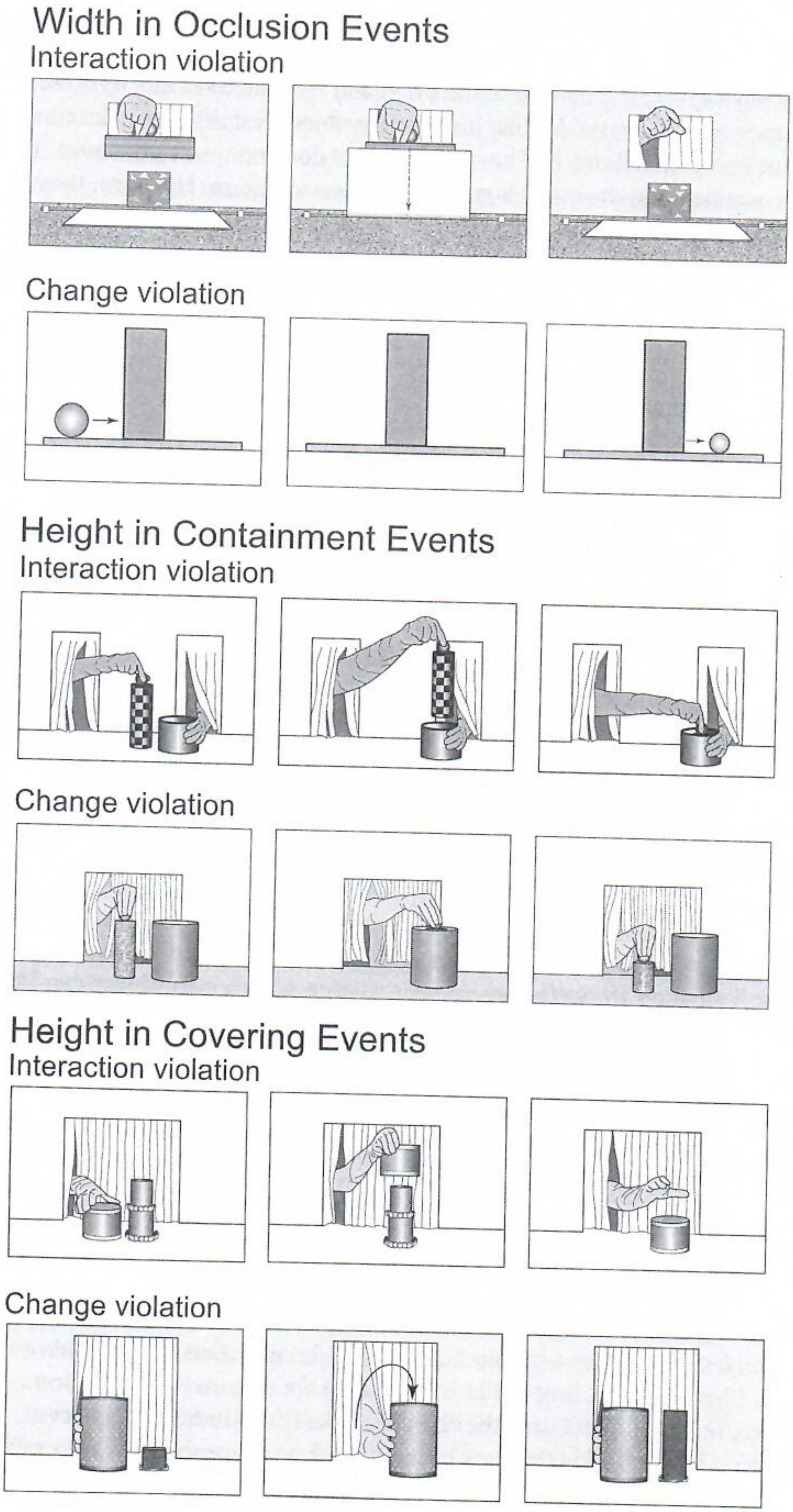
Consider the variable height in containment events, which is identified at about 7.5 months of age; infants now recognize that a tall object should protrude above a short but not a tall container (Hespos & Baillargeon, 2001a, 2006). Let us assume that infants this age are shown an event in which a tall object is lowered inside a very tall container. Infants will represent the basic information about the event, categorize it as a containment event, and access their knowledge of this event category, which will specify height as a relevant variable. Infants will then include information about the relative heights of the object and container in their physical representation of the event and will interpret this information in accordance with the variable rule; because the object is shorter than the container, it will not protrude above it. The object in fact does not protrude above the rim of the container, and the event is not flagged as a violation. However, what if the object is then removed from the container and is revealed to be much shorter than before? If infants can use the height information only to predict whether the object should be visible above the rim of the container, then they will fail to detect this violation. On the other hand, if the height information, once represented, becomes subject to the core knowledge, then infants should have no difficulty detecting this change violation. According to the persistence principle, objects exist continuously in time and space, retaining their physical properties as they do so. Thus, a tall object cannot spontaneously change into a shorter object, and the event should be flagged as a violation.

This line of reasoning suggests that infants who have identified height or width as a relevant variable in an event category should be able to detect both interaction and change violations involving the variable. Interaction violations refer to events in which two or more objects interact in a manner inconsistent with their respective individual properties (e.g., a tall object that becomes fully hidden inside a short container). Change violations, in contrast, refer to events in which the individual properties of objects are not maintained over time (e.g., a tall object that becomes much shorter while briefly hidden inside a tall container).

Several experiments provide evidence for the preceding analysis (see Fig. 4–12). First, consider the variable width in occlusion events. Results show that (1) 4-month-olds are surprised when a wide object becomes fully hidden behind a narrow occluder (Wang et al., 2004) and (2) 4.5-month-olds are surprised when a large ball changes into a small ball when passing behind a narrow occluder (too narrow to hide both balls simultaneously) (Wilcox, 1999). Infants can thus use width information in occlusion events to judge whether an object can become fully hidden behind an occluder and to detect a change to the object's width as it emerges from behind the occluder.[9]

Next, consider the variable height in containment events. Results indicate that (1) 7.5-month-olds are surprised when a tall object is lowered into a short container until it becomes almost fully hidden (Hespos & Baillargeon, 2001a) and (2) 8-month-olds are surprised when a tall object lowered into a tall container is much shorter when removed from the container (Li & Baillargeon, 2005). Infants can thus use height information in containment events to predict whether an object will protrude above the rim of a container and also to detect a change to the object's height as it emerges from the container.

Finally, consider the variable height in covering events. Results have shown that (1) 12-month-olds (but not 11-month-olds) are surprised when a short cover is lowered over a tall object until the object becomes fully hidden (Wang et al., 2005) and (2) 12.5-month-olds (but not 11-month-olds) are surprised when a tall cover is lowered over a tall object and then removed to reveal a much shorter object (Wang & Baillargeon, 2006). Infants can thus use height information in covering


Width in Occlusion Events
Interaction violation
Change violation
Height in Containment Events
Interaction violation
Change violation
Height in Covering Events
Interaction violation
Change violation

events to predict whether an object will extend beneath the rim of a cover and also to detect a change to the object's height when uncovered.

Additional research is needed to more fully explore the relation between infants' ability to detect interaction and change violations involving height or width information. The present analysis suggests, for example, that infants who were "taught" (through exposure to appropriate condition–outcome observations in the home or laboratory) that a tall object will protrude above a short but not a tall container should ipso facto (1) be able to detect surreptitious changes to the height of an object that is briefly lowered into a container and also (2) be able to use height information to determine whether an object that is retrieved from a large container is the same object that was placed inside it or a different object. Thus, if a short object is placed inside a large bucket, and a tall object is next retrieved from inside it, infants should be surprised if the bucket is then shown to be empty. Furthermore, the reverse should also be true: Infants who are "taught" that height information is useful for determining whether the object that is retrieved from a container is the same object that was placed inside it should ipso facto be able to detect violations in which tall objects fail to protrude above short containers.

Core Knowledge and Variable Rules

Implicit in the preceding discussion is a fundamental claim about the development of infants' physical reasoning: With experience, infants learn *what* variable information to include in their physical representations of events, not *how* to interpret this information. Infants' core knowledge provides a causal framework that enables them to immediately interpret variable information once represented.

Of course, the causal framework provided by infants' core knowledge is sharply limited; it will not help them understand the day–night cycle or the workings of refrigerators, telephones, televisions, light bulbs, and space shuttles. But it is sufficient to help infants understand the implications of simple variables for objects' displacements and interactions: for example, to help them understand that tall objects cannot become fully hidden behind short occluders, that wide objects cannot be lowered inside narrow containers, that small frog-like objects cannot spontaneously change into tall prince-like objects, and that an object that disappears at one end of a wide occluder cannot instantaneously reappear at the other end of the occluder.

One question that might be raised at this juncture is the following: If infants' core knowledge enables them to reason about any variable information once represented, then why are variable rules necessary? Why not assume that infants (1) learn what variable information to include in their physical representations of events and (2) simply interpret this information in terms of their core knowledge? The answer, we believe, is that variable rules facilitate the process of variable

Figure 4–12. Examples of interaction and change violations infants detect that involve: (a) width in occlusion events (Wilcox, 1999; Wang et al., 2004), (b) height in containment events (Hespos & Baillargeon, 2001a; Li & Baillargeon, 2005), and (c) height in covering events (Wang et al., 2005; Wang & Baillargeon, 2006).

identification in everyday life by leading infants to form specific expectations about events' outcomes and—most importantly—to adjust these expectations when different outcomes arise.

Infants' core knowledge is used to interpret an event as it *actually* unfolds; whatever basic and variable information is included in the event's physical representation is interpreted in terms of the core knowledge, and the event is flagged as a violation if and only if it unfolds in a manner inconsistent with this knowledge. Outside of the laboratory, infants will of course rarely encounter such core violations. Infants' variable rules, in contrast, represent hypotheses about how an event is *likely* to unfold; they specify the conditions under which each outcome in a vector will occur. As infants identify more variables, their hypotheses about these conditions become more accurate—or more finely tuned, one might say. In the initial stages, however, when infants' hypotheses are still coarse, they will often be confronted—as they observe events in daily life—with events inconsistent with their rules (thus producing what we called errors of commission). These violations provide infants with negative feedback; they signal to infants that their current physical knowledge is flawed and that additional variables are needed to specify the conditions under which the contrastive outcomes in the vector are likely to occur. As Leslie (2004) put it, "Paying more attention is what you do if you are an active learner who has identified a learning opportunity. A violation of expectation happens when you detect that the world does not conform to your representation of it. Bringing representation and world back into kilter requires representation change, and computing the right change is a fair definition of learning" (p. 418).

INDUCING INFANTS TO SUCCEED AT DETECTING VARIABLE VIOLATIONS: PRIMING MANIPULATIONS

The account of infants' physical reasoning presented in the previous section rests on two central claims. The first is that infants' physical representations of events initially include only basic information and become increasingly richer and more detailed as infants gradually identify relevant variables. Event category by event category, vector by vector, variable by variable, infants identify the variables that are useful for predicting outcomes, and begin to include information about these variables in their physical representations. The second central claim of our account is that infants primarily learn what information to include in their physical representations of events, not how to interpret this information once represented. Infants' core knowledge provides a causal framework for interpreting both the basic and the variable information infants include in their physical representations of events.

If these two claims are correct, then the following prediction should hold: If infants could be induced, through some contextual manipulation, to include information about a variable they have not yet identified in their physical representation of an event, then this information should become subject to their core knowledge, allowing them to immediately detect violations involving the variable (see Fig. 4–13).

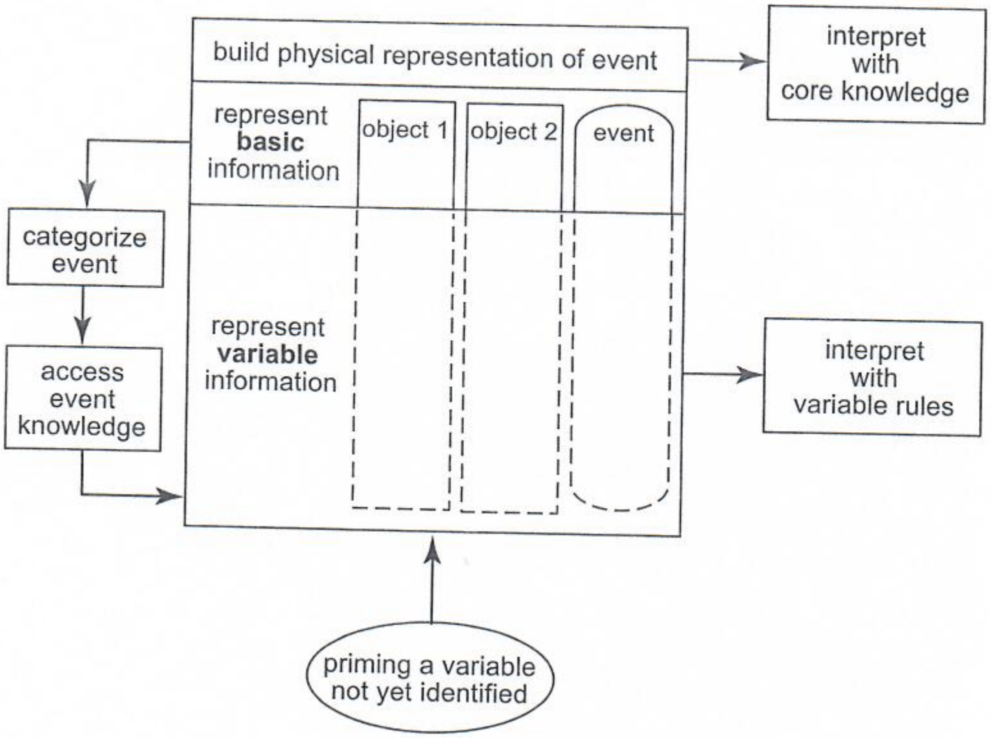


Figure 4–13. An account of infants' physical reasoning: How priming helps infants represent information about a variable they have not yet identified.

Several recent lines of experimentation support this prediction; it turns out that there are many different ways of temporarily inducing infants who have not yet identified a variable to include information about it in their physical representation of an event (e.g., Wilcox & Chapa, 2004; Gertner et al., 2005; Li & Baillargeon, 2005; Yuan & Baillargeon, 2005; Li & Baillargeon, 2006; Ng & Baillargeon, 2006; Wilcox, this volume). From this perspective, infants' physical-reasoning system thus appears extremely porous—a highly desirable characteristic in a system that must primarily learn to attend to more and more information over time.

In this section, we focus on priming manipulations, which are typically designed to make a particular variable (or particular values of a variable) salient to infants. Highlighting the variable renders infants more likely to include information about it when watching a subsequent physical event; this information then becomes subject to infants' core knowledge, allowing them to detect violations they would not have detected otherwise.

Priming Infants to Attend to Color Information in an Occlusion Event

We saw earlier that young infants are not surprised when a green ball disappears behind a narrow screen and a red ball then reappears from behind it (Wilcox, 1999). Although width is identified as an occlusion variable by 4 months of age (e.g., Wang et al., 2004), color is not identified until much later, at about 11.5

months of age (e.g., Wilcox, 1999; Ng & Baillargeon, 2006). As a result, young infants typically include no color information in their physical representation of the narrow-screen event, and assume that the same ball is moving back and forth behind the screen. In a seminal series of experiments, Wilcox and Chapa (2004) asked whether 9.5-month-old infants could be primed to attend to the color information in this event.

The infants first received two pairs of priming trials. Each pair consisted of a pound event, in which a green cup was used to pound a peg, and a pour event, in which a red cup was used to pour salt. Different green and red cups were used in the two pairs of trials. Next, the infants saw a test event in which a green and a red ball appeared successively from behind a narrow (narrow-screen event) or a wide (wide-screen event) screen. Results indicated that, following the priming trials, the infants who saw the narrow-screen event looked reliably longer than did those who saw the wide-screen event. Additional results revealed that 7.5-month-old infants could also be primed to detect the violation in the narrow-screen event but required three pairs of priming trials (with three different pairs of green and red cups) to do so. Together, these results suggested that the infants perceived the association in the priming trials between the color and function of the cups (green–pound, red–pour). This association made the colors green and red more salient for the infants. As a result, the infants were more likely to include information about the colors of the green and red balls in their physical representations of the test events. This information, once represented, became subject to the persistence principle, and the infants realized, when watching the narrow screen, that the green ball (1) filled most of the space behind the narrow screen and (2) could not spontaneously change from a green to a red ball.

In subsequent experiments, Wilcox and her colleagues (this volume) replicated their initial findings with 9-month-old infants using new color–function pairings. The infants now saw priming events in which long-handled spoons of different colors were used to stir salt in a bowl or to lift a bowl by its hook. Results indicated that the infants looked reliably longer at the narrow- than at the wide-screen event when the spoons used in the priming trials were the same colors as the balls (green and red)—but not when they were different (yellow and blue). These results suggest that the effect of the priming manipulation was quite specific; because the colors green and red were paired with different object functions in the situation, the infants were more likely to attend to these same colors when they next encountered them in another, very different event. However, watching priming events involving yellow and blue spoons did not serve to make infants more likely to include information about the colors of the balls in the narrow- and wide-screen events. The priming manipulation thus served to highlight the colors green and red for the infants—not color information generally.

In another series of experiments, Wilcox and Chapa (2004) primed 5.5-month-old infants to attend to pattern information in an occlusion event. These experiments built on the finding that infants younger than 7.5 months of age are not surprised when a dotted ball disappears behind a narrow screen and a striped ball reappears from behind it (Wilcox, 1999). Using a pound-pour manipulation similar to that described above, Wilcox and Chapa found that, after receiving three pairs of priming trials involving three different dotted and striped green cups, infants looked reliably longer at the narrow- than at the wide-screen event. Finally, 4.5-month-old infants could also be primed to include pattern information in their physical representation of the narrow-screen event, but both cups had to be present in each priming trial to allow simultaneous comparison of their patterns.

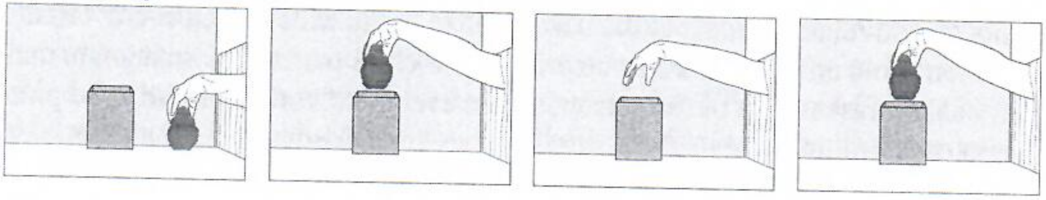
The priming results obtained by Wilcox and her colleagues (Wilcox & Chapa, 2004; this volume) provide strong support for the central claim of our account of infants' physical reasoning: Infants learn *what* information to include in their physical representations of events, not *how* to interpret this information once represented. Infants aged 4.5 to 9.5 months who could be induced to represent information about the colors (green and red) or patterns (dotted and striped) of the balls in a narrow-screen event immediately detected the persistence violation in the event.

Priming Infants to Attend to Color Information in a Containment Event

We saw earlier that 12.5-month-old infants are not surprised when a toy is lowered into a narrow container (slightly larger than the toy) and another toy, identical except for color, is then removed from the container (Ng & Baillargeon, 2006). Although width is identified as a containment variable at about 4 months of age (e.g., Wang et al., 2004), color is not identified until some (as yet unspecified) time after 12.5 months of age (Ng & Baillargeon, 2006). As a result, 12.5-month-old infants typically include no color information in their physical representation of the narrow-container event and assume that the same toy is being lowered into and retrieved from the container. In a recent experiment, we attempted to prime 12.5-month-olds to include color information in their physical representations of containment events (Ng & Baillargeon, 2006). This experiment also examined whether it might be possible to highlight a variable for infants through a simple perceptual contrast, by showing them objects that exhibit different values of the variable but are otherwise identical.

The infants were assigned to a baseline or a priming condition. The infants in the baseline condition received two pairs of test trials (see Fig. 4–14). Each pair consisted of a change and a no-change event, and order of presentation was counterbalanced across infants. At the start of each event, the infants saw a "Boohbah" toy resting on an apparatus floor to the right of a small container. The container was only large enough to hide a single Boohbah; the infants were shown the container in a brief orientation procedure before the test session. An experimenter's gloved hand grasped the toy, lifted it, and lowered it into the container. The hand then paused briefly above the container. Next, the hand retrieved the toy from inside the container and returned it to its original position on the apparatus floor. For one quarter of the infants (purple-orange condition), a purple Boohbah was placed inside the container, and an orange (change event) or a purple (no-change event) Boohbah was removed from it. The other infants were assigned to an orange-purple, a pink-yellow, or a yellow-pink condition. The infants in the priming condition received a single priming trial before the test trials, in which they saw all

No-change Event



Change Event

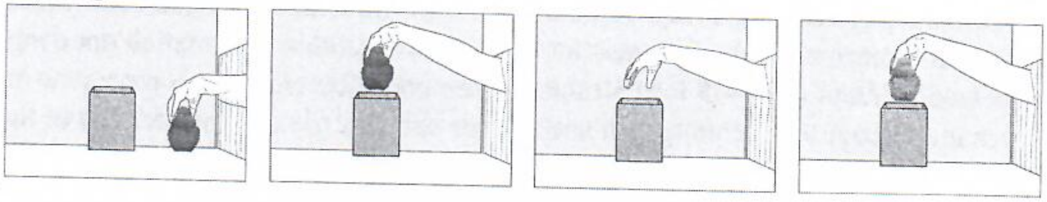


Figure 4–14. Test events used in Ng and Baillargeon (2006).

four Boohbahs resting side by side on the apparatus floor in front of the container (see Fig. 4–15). From left to right, the Boohbahs were purple, yellow, pink, and orange and were identical except for color.

We reasoned that if the priming trial highlighted the fact that Boohbahs came in a variety of colors, then the infants might be more likely to include information about the color of the Boohbah shown at the start of each test event (e.g., to determine which specific Boohbah was being used in the event). This color information would then become subject to the persistence principle, allowing the infants to detect the violation in the change event; a purple toy cannot spontaneously turn into an orange toy, or a pink toy into a yellow one.

The infants in the priming condition looked reliably longer at the change than at the no-change event, whereas those in the baseline condition tended to look equally at the two events. These results suggest that the priming trial was sufficient to induce the infants in the priming condition to include information about the color of the Boohbah in the test events. Thus, the infants in the purple-orange priming condition, for example, presumably reasoned that the purple Boohbah (1) filled most of the narrow container and (2) could not spontaneously change into an orange Boohbah. Like the results of Wilcox and Chapa (2004; Wilcox, this volume), the present results support the claim that, with experience, infants learn *what* information to attend to in events, not *how* to interpret this information. The single, static priming trial the infants received could not teach them that objects retain their colors when lowered into containers—it could only induce them to represent the color of the toy in the events.

In future research, we hope to modify the priming trial to determine what does and does not constitute an adequate priming experience for infants in this situation. For example, we suspect that showing four Boohbahs of one color (e.g., all purple), or showing four balls of the same colors as the different Boohbahs, would not constitute an adequate priming trial. Conversely, we suspect that showing four different Boohbahs whose colors do not match those in the test events (e.g., green, blue, white, and gray), would constitute an adequate priming trial. Investigating

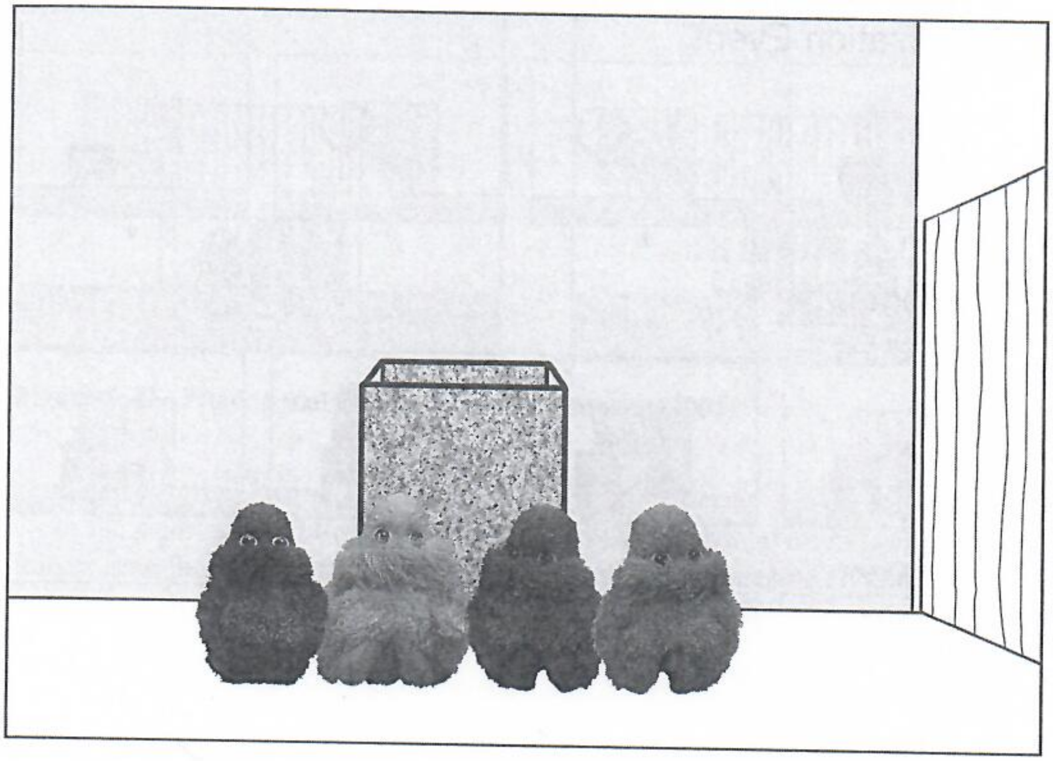


Figure 4–15. Priming trial used in Ng and Baillargeon (2006).

these various possibilities should help us better understand the mechanism that makes possible successful priming. Regardless of the outcomes of these experiments, however, the main thrust of the present research is the demonstration that infants who are induced to include information about a variable they have not yet identified in their physical representation of an event can then detect a change violation involving this variable.

Priming Infants to Attend to Height Information in a Tube Event

At 8 months of age, infants detect a surreptitious change to the height of an object in a containment but not a tube event; they are surprised when a tall cylindrical object lowered into a tall container is much smaller when removed from the container—but they are not surprised when the container is replaced with a tube (Li & Baillargeon, 2005). By this age, infants have identified height as a containment but not a tube variable; recall that height is identified at about 7.5 months in containment events but only at about 14 months in tube events (e.g., Hespos & Baillargeon, 2001a; Gertner et al., 2005; Hespos & Baillargeon, 2006; Wang & Baillargeon, 2006). In a recent experiment, we asked whether 8-month-old infants could be primed to attend to height information in a tube event (Li & Baillargeon, 2005).

The infants were assigned to a baseline or a priming condition. The infants in the baseline condition first received a familiarization trial in which they saw an

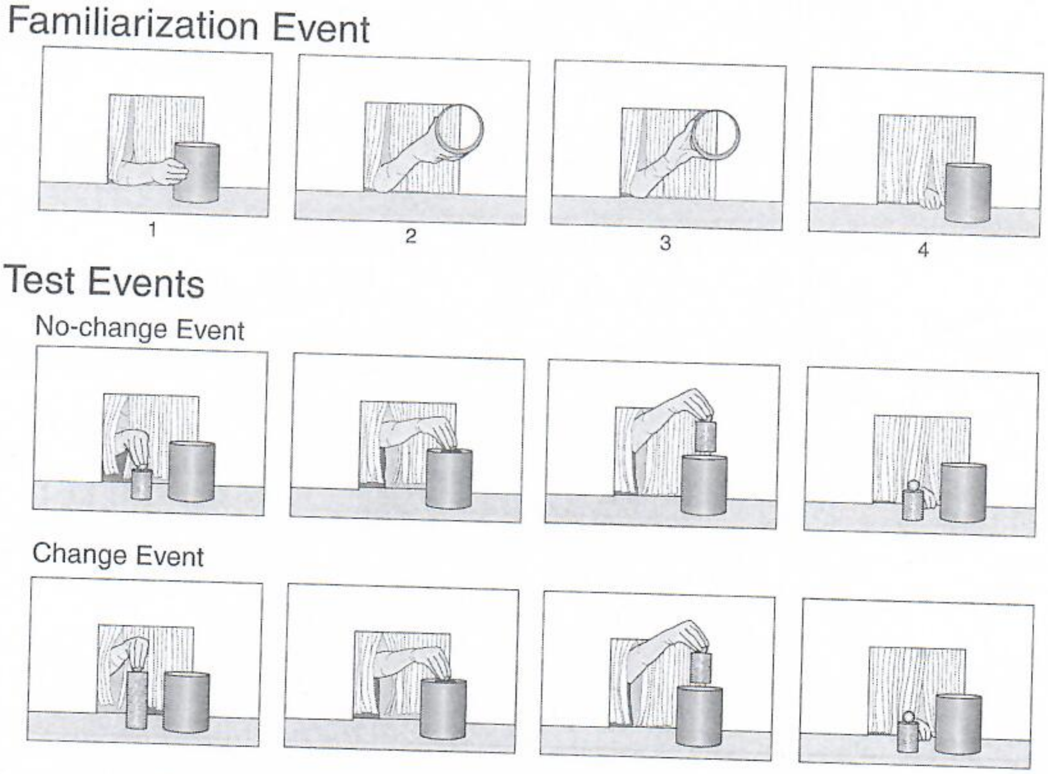


Figure 4–16. Familiarization and test events used in Li and Baillargeon (2005).

experimenter's gloved hand rotate a tall tube forward and backward (to show it was open at both top and bottom) and then place it upright on the apparatus floor (see Fig. 4–16). Next, the infants received a single test trial in which they saw either a change or a no-change test event. At the start of the change event, a tall cylindrical object with a red knob attached to its top stood to the left of the tube; the cylindrical portion of the object was the same height as the tube. The hand grasped the knob at the top of the object, lifted the object, and lowered it into the tube until only the knob and the very top of the object remained visible above the rim. The hand gently twisted the object back and forth for a few seconds and then returned it to its original position on the apparatus floor. When removed from the tube, the cylindrical portion of the object was only half as tall as previously. The no-change event was identical to the change event, except that the short object was used throughout the event. The infants in the priming condition were tested using the same procedure, with one exception: They received two static priming trials following the familiarization trial and prior to the test trial (see Fig. 4–17). In one trial, three cylindrical objects stood side by side on the apparatus floor: At one end was the tall object used at the start of the change event, at the other end was the short object used in the change and no-change events, and between them was a medium-sized object. The three objects were identical except for their heights; the cylindrical portion of the tall, medium, and short objects was 15, 11.3, and 7.5 centimeters, respectively. In the first priming trial, the objects were ordered from tall to short, from left to right; in the second trial, the objects were ordered from short to tall.

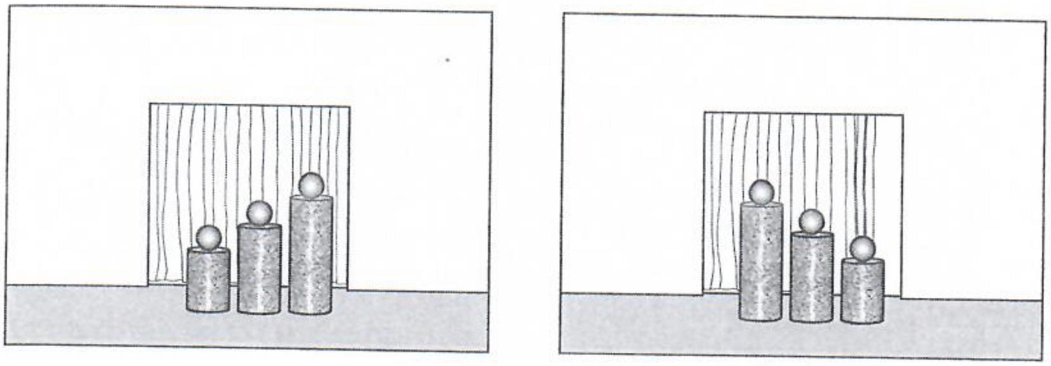


Figure 4–17. Priming trials used in Li and Baillargeon (2005).

In the priming condition, the infants who saw the change event looked reliably longer than those who saw the no-change event; in the baseline condition, in contrast, the infants looked about equally at the two events. These results suggested that the priming trials served to highlight height information for the infants in the priming condition; as a result, the infants were more likely to include height information in their physical representations of the test events. This height information then became subject to the infants' core knowledge, and the change event was flagged as a persistence violation; the infants realized that the tall object could not spontaneously change into a short object. The simple priming trials used here thus allowed infants to detect a height violation in a tube event 6 months before they typically do so. Such results provide strong evidence that the development of infants' physical reasoning involves primarily learning *what* information to attend to in each event category, and not learning *how* to interpret this information. The priming trials could not teach the infants that objects typically retain their heights when lowered into tubes—they could only make height information salient for the infants.

In future research, we hope once again to modify our priming trials to determine what constitutes an adequate height-priming experience for 8-month-old infants in this situation. For example, would infants be equally successful if shown only two cylindrical objects, the short and tall objects used in the change event? Or if shown short, medium, and tall cylindrical objects that differ in pattern and color from those used in the test events? Answers to these and related questions will help us gain a clearer understanding of the mechanisms that underlie successful priming.

INDUCING INFANTS TO SUCCEED OR FAIL AT DETECTING VARIABLE VIOLATIONS: CARRYOVER MANIPULATIONS

According to our account of infants' physical reasoning, infants who are induced, through some contextual manipulation, to include information about a variable they have not yet identified in their physical representation of an event should then be able to detect change and interaction violations involving the variable. In the

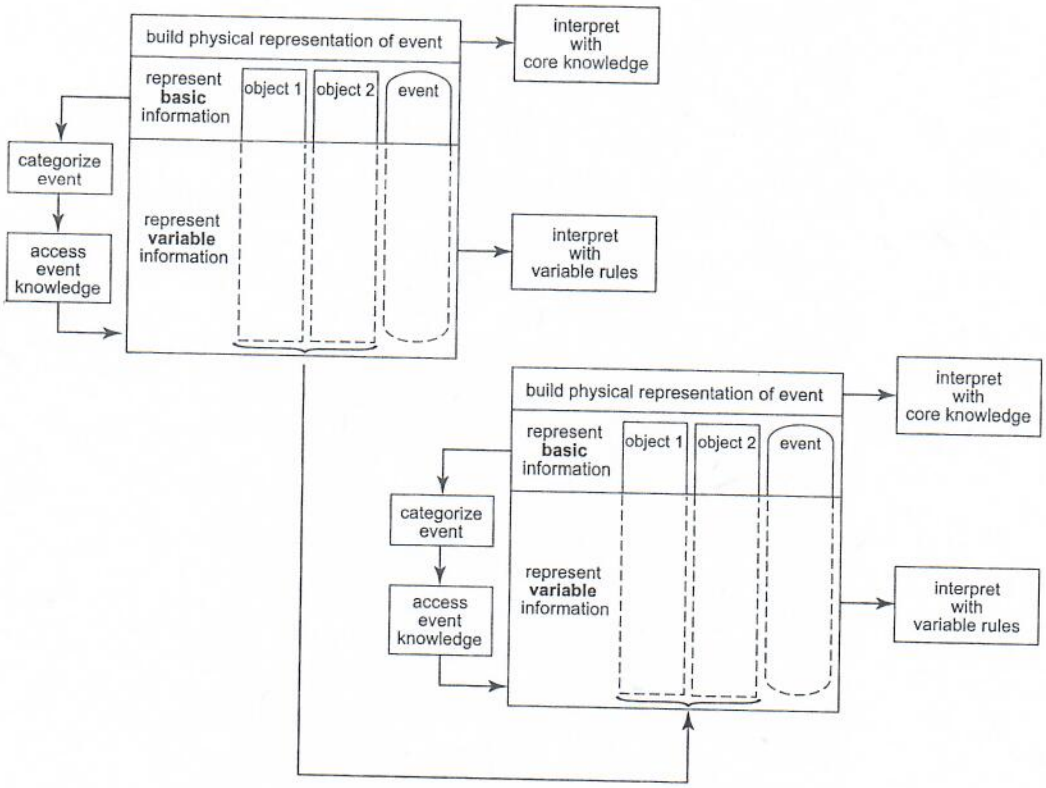


Figure 4–18. An account of infants' physical reasoning: How infants carry over variable information from one event representation to the next.

previous section, we discussed priming manipulations, which are designed to simply highlight a variable (or particular values of a variable). In this section, we discuss a very different sort of manipulation: carryover manipulations.

The point of departure for this research was the following question: What happens when infants see the same objects in two successive events from different event categories? Do they represent each event separately? Or do they carry over whatever variable information they included in their representation of the first event to their representation of the second event? The second alternative seemed to us more efficient, and hence more plausible (see Fig. 4–18). After all, why would infants represent the same information about the same objects over and over again as the objects move from one event to another? This would seem a waste of time and effort, and we already know from analyses of infants' perseverative errors in various tasks that infants attempt to be as efficient as possible (for reviews, see Aguiar & Baillargeon, 2000, 2003).

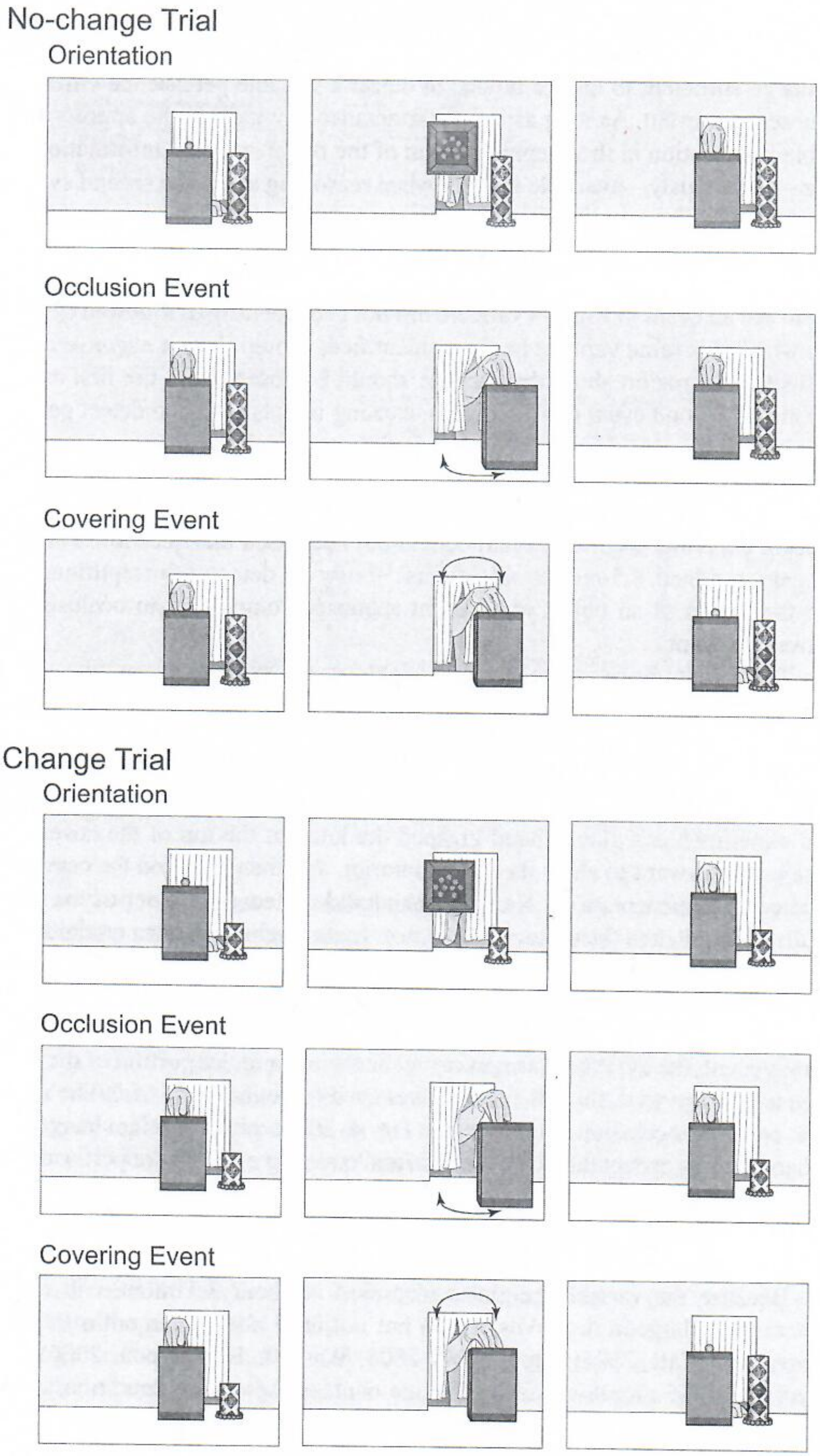
We reasoned that if infants carry over variable information from one event representation to the next, then infants who see an event in which a variable has been identified, followed by an event in which this same variable has not been identified, should show a *positive* carryover effect; the variable information included in the first event representation should be carried over to the second event representation, allowing infants to detect persistence violations involving the variable earlier than they otherwise would. Exposure to a single initial event would thus be sufficient to induce infants to detect a variable persistence violation in a subsequent event. As long as infants spontaneously include the appropriate variable information in their representation of the first event, this information should be—fortuitously—available to them when reasoning about the second event (e.g., Wang & Baillargeon, 2005).

At the same time, we realized that the converse should also be true: If variable information is carried over from one event representation to the next, then infants who see an event in which a variable has not been identified, followed by an event in which this same variable has been identified, should show a *negative* carryover effect; information about the variable should be absent from the first and hence from the second event representation, causing infants to fail to detect persistence violations they would have been able to detect otherwise.

Do infants show negative as well as positive carryover effects when they see the same objects involved in two successive events from different categories? A recent experiment (Li & Baillargeon, 2006) addressed this question. This experiment examined 8.5-month-old infants' ability to detect a surreptitious change to the height of an object in an event sequence comprising an occlusion and a covering event.

The infants were assigned to an occlusion-covering or a covering-occlusion condition. The infants in the occlusion-covering condition received either a change or a no-change test trial (see Fig. 4–19). At the beginning of the change trial, a short cylinder stood next to a tall rectangular cover with a knob attached to its top; the cylinder was half as tall as the rectangular portion of the cover. To start, an experimenter's gloved hand grasped the knob at the top of the cover, rotated the cover forward to show its hollow interior, and then replaced the cover next to the cylinder (orientation). Next, the hand slid the cover in front of the cylinder, fully hiding it, and then returned the cover to its original position on the apparatus floor (occlusion event). Finally, the hand lowered the cover over the cylinder, again fully hiding it, and then returned the cover to its initial position next to the cylinder (covering event). When the cover was removed from over the cylinder in the covering event, the cylinder was now as tall as the rectangular portion of the cover. In the no-change trial, the tall cylinder was used throughout the trial. The infants in the covering-occlusion condition (see Fig. 4–20) received similar change and no-change trials, except that the occlusion and covering events were performed in the reverse order: The cover was placed first over and then in front of the cylinder. The surreptitious change to the height of the cylinder in the change trial thus occurred in the occlusion rather than in the covering event.

Because the variable height is identified at about 3.5 months in occlusion events (Baillargeon & DeVos, 1991) but not until about 12 months in covering events (McCall, 2001; Wang et al., 2005; Wang & Baillargeon, 2006), we expected the 8.5-month-old infants in the occlusion-covering condition to show a positive carryover effect. When watching the occlusion event, the infants would categorize the event, access their knowledge of occlusion events, and include information about the relative heights of the cover and cylinder in their physical representation of the event. When the infants next saw the covering event, this height information would be carried over into this new physical representation;



No-change Trial

Orientation

Occlusion Event

Covering Event

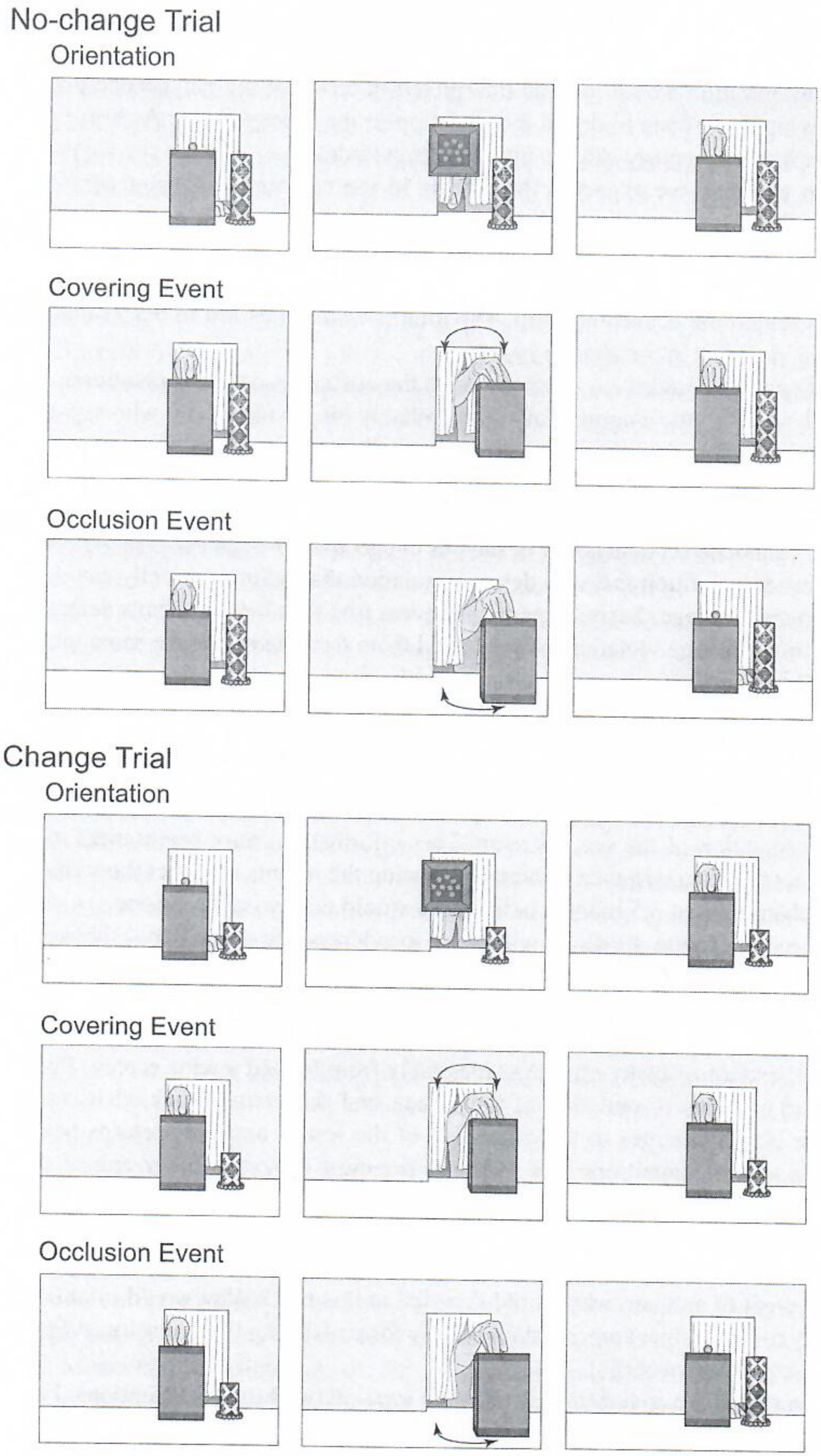
Change Trial

Orientation

Occlusion Event

Covering Event

Figure 4–19. Test events used in the occlusion-covering condition of Li and Baillargeon (2006).



No-change Trial

Orientation

Covering Event

Occlusion Event

Change Trial

Orientation

Covering Event

Occlusion Event

Figure 4–20. Test events used in the covering-occlusion condition of Li and Baillargeon (2006).

the information would then be interpreted in terms of the persistence principle, allowing the infants to detect the violation in the change event: A short cylinder cannot spontaneously change into a taller cylinder.

In contrast, we expected the infants in the covering-occlusion condition to show a negative carryover effect. When watching the covering event, the infants would include no height information in their physical representation of the event. As a result, no height information would be carried over when the infants next represented the occlusion event. The infants would thus fail to detect the persistence violation in the change event.

Results supported our predictions. In the occlusion-covering condition, the infants who saw the change trial looked reliably longer than those who saw the no-change trial; in the covering-occlusion condition, in contrast, the infants looked about equally during the two trials. Thus, whereas the 8.5-month-olds in the occlusion-covering condition *succeeded* in detecting a violation that infants typically cannot detect until about 12 months of age, the 8.5-month-olds in the covering-occlusion condition *failed* to detect a violation that infants typically can detect at 3.5 months of age. Seeing a particular event first thus helped infants detect a surreptitious change violation, or prevented them from detecting the same violation.

These results are interesting for several reasons. First, they provide strong support for the notion that infants detect variable persistence violations when they include information about the relevant variables in their physical representations of the events. The infants in the occlusion-covering condition carried over the height information from their physical representation of the first event to their physical representation of the second event. This information, once represented, became subject to the persistence principle, allowing the infants to detect the violation in the change event 3.5 months before they would otherwise have done.

Second, future research will need to address the discrepancy between the present results and those in the object-individuation literature (e.g., Xu & Carey, 1996; Wilcox & Baillargeon, 1998a; Wilcox & Chapa, 2002; Xu, 2002, 2003). In a seminal task designed by Xu and Carey (1996), two distinct objects (e.g., a ball and a toy duck) emerge successively from behind a wide screen. First, one object emerges to one side of the screen and then returns behind it; next, the other object emerges to the other side of the screen and then returns behind it. After several repetitions, the screen is removed to reveal either one of the objects (one-object outcome) or both objects (two-object outcome). In this task, 10-month-olds typically give no evidence that they expect two objects to be present when the screen is removed. But if infants carry over object representations from one event to another, why would they fail at this task? Why would infants fail to carry over the object representations they formed during the occlusion event to the post-occlusion event?

Our tentative answer to this question rests on two broad assumptions. The first is that infants carry over object representations from one event to another only when the available spatiotemporal information makes it possible to unambiguously *track* the objects from the first to the second event (e.g., Baillargeon, 2008; Wang & Baillargeon, 2008). In our carryover task, infants can establish continuous traces for the cover and cylinder from the first to the second event; at all times, infants know where each object is located, even when the cylinder is hidden (e.g., Leslie, Xu, Tremoulet, & Scholl, 1998; Scholl & Leslie, 1999). In the task of Xu and Carey (1996), in contrast, the available spatiotemporal information is not sufficient to determine that two objects are present behind the screen in the first event, or (a fortiori) to track the objects across the two events.

Our second assumption is that, when objects cannot unambiguously be tracked from one event to another, as in the task of Xu and Carey (1996), infants use a different strategy to determine how many objects should be present in the second event. Specifically, infants (1) retrieve their physical representation of the first event, (2) examine the basic spatiotemporal and identity information included in the representation to determine how many distinct objects emerged on either side of the screen, and (3) expect at least the same number of objects to be present in the second event (because the screen is wide, additional objects could also be present). We have referred to this strategy as involving the *mapping* of object representations from event to event (e.g., Wilcox & Baillargeon, 1998a, 1998b).

To see why a mapping strategy would lead infants to fail at the task of Xu and Carey (1996), consider what basic spatiotemporal and identity information infants represent when watching a ball and a toy duck emerge successively from behind a screen. The basic spatiotemporal information specifies the visible path that the ball and the duck follow on either side of the screen but is insufficient to establish whether they are the same object or different objects. The basic identity information for the ball and the duck is actually the same information, because both objects are closed and self-propelled. In terms of the basic information represented, there is thus nothing to suggest that there is more than one closed, self-propelled object emerging alternately on either side of the screen (recall that size, shape, pattern, and color information is variable information and is not included at the basic level). As a result, when the screen is removed and infants examine the basic information in their physical representation of the occlusion event, this information specifies that one closed, self-propelled object emerged from behind the screen. Infants thus form an expectation that at least one closed, self-propelled object should be present in the new, post-occlusion event. Because both the one- and the two-object outcomes are consistent with this expectation, neither outcome appears unexpected.

The preceding analysis makes a number of interesting predictions. For example, it suggests that infants should succeed at the task of Xu and Carey (1996) if the occlusion event involves two objects that receive different identity descriptions at the basic level: not two closed, self-propelled objects, as above, but instead a closed and an open object, or an inert and a self-propelled-object. Experiments are under way in different laboratories to test these predictions, with promising results. Meanwhile, possible support for the present analysis comes from recent experiments (e.g., Bonatti, Frot, Zangl, & Mehler, 2002; Wu & Baillargeon, 2008) showing that 10-month-old infants succeed at the task of Xu and Carey if the two objects that emerge successively from behind the screen are a human-like object (e.g., a self-propelled human doll) and a non-human-like object (e.g., a self-propelled toy animal), but not two human-like objects (e.g., two distinct self-propelled human dolls) or two non-human-like objects (e.g., two distinct self-propelled toy animals).

These results suggest that by 10 months of age, if not before, the basic identity information infants represent about objects includes whether they are human-like or not. Additional experiments are testing these speculations.

CONCLUSIONS

The account of infants' physical reasoning presented in this chapter rests on two central claims. One is that infants' physical representations of events initially include only basic information and become increasingly richer and more detailed as infants gradually identify relevant variables. The other claim is that infants primarily learn *what* information to include in their physical representations, not *how* to interpret this information once represented. Infants' core knowledge provides a causal framework for interpreting both the basic and the variable information infants include in their physical representations.

According to our account, the primary task of development, with respect to infants' physical reasoning, thus consists in the gradual identification of variables. Over the course of the first year or so, infants identify dozens and dozens of variables; event category by event category, vector by vector, variable by variable, infants learn what information to pay attention to when watching events. One analogy for this developmental process might be the following: Infants' physical-reasoning system can at first draw no more than rough blueprints of events, containing only a few key pieces of information; over time, these blueprints become increasingly detailed as infants learn what additional pieces of information should be included to better predict events' outcomes.

The Persistence Principle Revisited

As was mentioned earlier, Spelke and her colleagues (e.g., Spelke et al., 1992; Carey & Spelke, 1994; Spelke, 1994; Spelke et al., 1995b) have suggested that principles of continuity (objects exist and move continuously in time and space) and cohesion (objects are connected and bounded entities) guide infants' interpretation of physical events from birth. According to these principles, infants should be surprised if an object disappears into thin air or breaks apart—but they should not be surprised if an object surreptitiously changes size, shape, pattern, or color. And, indeed, we have seen that infants often fail to detect such violations.

However, we have offered an alternative interpretation for these failures. This interpretation rests on three main points. First, we have proposed that, instead of the separate principles of continuity and cohesion, infants possess a single, stronger principle of persistence, which states that objects exist and move continuously in time and space, retaining their physical properties as they do so (Baillargeon, 2008). From this perspective, a cohesion violation is only an extreme shape or size violation.

Second, the persistence principle can be applied only to the information infants include in their physical representations of events. Because infants initially include relatively little information in these representations, they often fail to detect persistence violations. Infants cannot be surprised when a tall object becomes shorter when briefly lowered into a tall tube, or when a purple toy becomes orange when briefly lowered into a container, if they did not include height and color information in their representations of the events.

Third, infants who are induced, through priming, carryover, or other contextual manipulations (e.g., Wilcox & Chapa, 2004; Gertner et al., 2005; Li & Baillargeon, 2005, 2006; Ng & Baillargeon, 2006; Wilcox, this volume), to include information about a variable they have not yet identified in their physical representation of an event can immediately detect persistence violations involving the variable.

The persistence principle states, in essence, that objects persist as they are in time and space. Why would such a constraint be helpful to infants? In this chapter, we have discussed several answers to this question. One is that the persistence principle helps young infants interpret the limited, basic information they represent about events (e.g., "object continues to exist under cover") and thus gets the task of learning about physical events off to a rapid start. Another is that the persistence principle helps infants identify relevant variables by supplying causal explanations for these variables. But a simpler way to think about the persistence principle might be to consider how infants would fare when watching, say, a ball roll along a surface toward a box some distance away if they had to check back and forth every second that the ball and box had not morphed into different objects or disappeared altogether. A notion of persistence means that the objects that are included in an event representation are expected to persist as they are within the representation, giving infants the opportunity to reason and learn about their interactions.

Future Directions

There are several directions in which our account of infants' physical reasoning needs to be extended. Three are mentioned briefly here.

A first direction concerns the links between infants' object-representation and physical-reasoning systems. We assume that, when shown two objects standing side by side at the start of an event, infants store information about the objects in their object-representation system; how detailed these representations are depends in part on how long the objects are available for examination (e.g., Hunter, Ross, & Ames, 1982; Rose, Gottfried, Melloy-Carminar, & Bridger, 1982; Hunter, Ames, & Koopman, 1983; Wagner & Sakovits, 1986; Hunter & Ames, 1988; Roder, Bushnell, & Sasseville, 2000). As the event unfolds, infants' physical-reasoning system may need to query the object-representation system for variable information. For example, if (1) infants realize they must include information about a variable in their physical representation of an event and (2) this information is no longer perceptually available (e.g., the object is now hidden), they may then access their object-representation system to retrieve the necessary information. In this view, infants who have not yet identified a variable as relevant to an event category might have encoded information about it in their object-representation system but might fail to retrieve this information to include it in their physical-reasoning system. These speculations suggest that infants who have not yet identified a variable as relevant to an event category might still demonstrate knowledge of the variable if tested in a task that taps their object-representation rather than their physical-reasoning system. Experiments are under way to investigate these and related possibilities (Li et al., 2006b).

A second direction concerns what might be called quantitative extensions of our account. Throughout this chapter, we have considered simple events involving two or three objects; for example, events in which an object is lowered into and then retrieved from a container. What would happen if infants were shown events involving multiple objects? Consider infants who have identified size, shape, and pattern as containment variables. If these infants saw containment events in which two, three, or four objects were lowered into a container, rather than only one, would they still encode the same variable information about each object? Similarly, what if infants were shown multiple events simultaneously; for example, if they saw two or more events in which one object was lowered into a container? Would infants include as much variable information about each event as if they saw a single event, or would they include less? Given infants' limited information-processing resources, we might expect them to encode less variable information with either multiple objects or multiple events, and recent evidence suggests that this is indeed the case (e.g., Mareschal & Johnson, 2003; Káldy & Leslie, 2005).

A final research direction, which we have been pursuing for some time (e.g., Baillargeon, Needham, & DeVos 1992; Needham & Baillargeon, 1993; Kotovsky & Baillargeon, 1994, 1998; Wang, Kaufman, & Baillargeon, 2003; Yuan & Baillargeon, 2005; Li, Baillargeon, & Needham, 2006a; Hespos & Baillargeon, 2008; Yuan & Baillargeon, 2008), involves extending our account to events other than those discussed in the present chapter; namely, support and collision events. So far, our results suggest that the account presented here applies equally well to these events. In all cases, infants begin with limited representations, which become richer as they identify relevant variables; core knowledge guides from birth the interpretation of the basic and variable information infants include in their event representations; and priming manipulations that highlight particular variables help infants detect violations earlier than they would otherwise have done.

Is the present account a nativist account? Yes, certainly; core knowledge is assumed to play a key role in infants' interpretation of physical events. Does the present account also emphasize learning? Here again, our answer is a resounding yes; much of what happens in the development of infants' physical reasoning is the gradual identification of variables, event category by event category, vector by vector, and variable by variable, as a result of infants' daily experiences. Core knowledge and experience are thus both necessary to explain the complex and protracted history of infants' acquisition of their physical knowledge.

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Notes

1. Of course, the principle of persistence will apply somewhat differently to inert and self-propelled objects. For example, a cat can spontaneously alter its shape to some extent but a spoon cannot. Recent evidence suggests that, by 2.5 to 6 months of age, infants already recognize that some physical events may be possible for self-propelled but not inert objects (e.g., Wu & Baillargeon, 2006; Wu, Luo, & Baillargeon, 2006; Yuan & Baillargeon, 2008; Luo, Kaufman, & Baillargeon, in press).

2. One interesting question for future research is whether all rules begin as discrete functions, and then become continuous functions as needed. For example, do infants initially learn simply that objects protrude above containers when taller, but not shorter, than the containers? With such a rule, infants would be able to predict that a tall object should protrude above a short container—but not how much it should protrude.

3. We are not entirely certain which variable(s) infants attend to before 3 months of age and, thus, which variable(s) might precede lower-edge-discontinuity in the decision tree in Figure 4–5. Our working hypothesis is that there is at least one such variable, having to do with the presence of internal openings. We suspect that, by 2.5 months, infants expect an object to remain partly visible when behind an occluder with an internal opening—for example, an O-shaped screen, with a large central window. At this stage, infants would still expect an object to be hidden behind a screen shaped like an inverted U because such a screen does not present an internal opening; rather, an external opening is created when the screen is placed upright on a surface. In this manner, infants would attend first to internal and later to external openings in predicting when objects behind occluders should be visible or hidden. Experiments are planned to test these possibilities.

4. Because 3.5-month-old infants have been tested with height violations (Baillargeon & DeVos, 1991) but not yet width violations, it is unknown whether 3.5-month-old infants can in fact detect both height and width violations. If they can, then it is possible that infants represent height and width in terms of a more general size variable. In addition, to return to the issue raised in footnote 2, there is evidence that 5.5-month-olds not only can predict that a tall object should appear above a short occluder, but also can judge by how much it should protrude (Luo, Baillargeon, & Lécuyer, 2008). By 5.5 months of age, infants' rule for height in occlusion events thus appears to be a continuous rather than a discrete function.

5. Readers may wonder why variable transparency is such a late acquisition. Work by Johnson and Aslin (2000) suggests that infants do not begin to detect clear, transparent surfaces until about 7 months of age, as a result of developments in their contrast sensitivity, which might in turn be tied to the maturation of the magnocellular system.

6. Experiments with infants younger than 4.5 months are necessary to determine precisely when size and shape are identified as relevant variables and whether one variable is in fact typically identified before the other. We saw earlier that by 3.5 months, infants can reason about height and perhaps width in occlusion events (Baillargeon & DeVos, 1991; Wang et al., 2004). By 4 months, infants attend to shape information to organize static, partly occluded displays (e.g., Needham, 1998), so it may be that this variable is present by 4 months.

7. We are not claiming that all infants will show the same décalages; for example, not all infants will identify the variable height first as a containment and only later as a covering variable. Some infants may well identify the two variables at about the same time, or in the reverse order. When we say that infants identify height as a containment variable at about 7.5 months of age, what we are really saying is that 7.5-month-old infants as a group look reliably longer at a containment event that presents a height violation than at an event that presents no such violation; as a rule, about 75% of the infants show the effect. It is likely

that a few infants identify the variable earlier and that others do so later. As we make clear in the next section, the ages at which infants identify variables depend to a large extent on the ages at which they are exposed to appropriate observations from which to extract the variables. Thus, although most infants with similar day-to-day experiences may identify a variable at a certain age, infants with different experiences may identify it earlier or later.

8. Readers may wonder why we are describing this vector as "when does an object inside a container protrude above it?" as opposed to "when is an object inside a container hidden?" as with the occlusion vector in Figure 4–5. Our reason is empirical and comes from experiments on infants' responses to events involving transparent containers. In containment events, height is identified at about 7.5 months (e.g., Hespos & Baillargeon, 2001a; Li & Baillargeon, 2005; Hespos & Baillargeon, 2006) and transparency at about 9.5 months (Luo & Baillargeon, 2008). If these variables belonged to a single vector specifying when objects inside containers should be hidden, then we would expect 8.5-month-old infants to be surprised when a short object placed inside a tall, transparent container remains visible through the container; because the object is shorter than the container, infants should expect the object to be hidden, and they should be surprised when it is not (an error of commission). However, 8.5-month-old infants, in fact, are not surprised when an object placed inside a transparent container is either visible or not visible through the container (an error of omission) (Luo & Baillargeon 2008). These results suggest that, in containment events, height and transparency belong to separate vectors; whereas height belongs to a vector specifying when an object inside a container should protrude above it, transparency belongs to a vector having to do with when an object inside a container should be hidden. Thus, when a short object is lowered inside a tall transparent container, 8.5-month-old infants bring to bear their knowledge of height to predict that no portion of the object will be visible above the container. However, they cannot make a prediction as to whether the portion of the object inside the container should be hidden or visible. Apparently, it is not until infants are about 9.5 months that they form a vector specifying when objects inside containers should be hidden. This analysis leads to striking predictions concerning 7.5- and 8.5-month-old infants' responses to events involving transparent containers. When a tall object is lowered inside a short transparent container, infants should look reliably longer at the event if the top of the object is not visible above the container. However, as long as the top of the object protrudes above the container, infants should look about equally whether or not the bottom of the object is visible through the container. Experiments are planned to test these predictions.

9. We are suggesting that 4.5-month-old infants detect a change violation when a large ball disappears behind a narrow screen and a small ball reappears from behind it—but it could be argued that infants view this event as an interaction violation instead, or alternate between these two interpretations. Do infants reason that (1) because the large ball fills most of the space behind the narrow screen, it must be the only object present, and (2) the large ball cannot spontaneously become smaller (change violation)? Or do infants reason that (1) the large and small balls must be different objects and (2) the two cannot hide simultaneously behind the narrow screen (interaction violation)? We adopt the first interpretation in this chapter but recognize that further research is needed to establish which is in fact correct.

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