

## 13 Infant Physical Knowledge

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Physical reasoning is the ability to go beyond the information in the immediate perceptual array. For example, if I were to dangle my keys in front of me with the intention of letting go of them, everyone would predict that the moment I let go of the keys, they will fall towards the ground. Similarly, if I hide my keys behind my back, everyone has the expectation that the keys continue to exist and that the shape and size of the keys remain the same as they were before they were hidden from view. These two examples demonstrate that people share the same basic ideas about how objects behave and interact. These expectations may be universal across all humans, and they may even be shared by some other species. However, researchers are still puzzled by some aspects of these fundamental abilities. For instance, even though most people can effortlessly draw similar predictions about these events, we have yet to build a computer that can rival the physical reasoning abilities of a typically developing 1-year-old infant. In this chapter, we argue that one way to resolve some of the mysteries about physical reasoning is to look at the origins of the abilities and how they change over time. We start by reviewing the literature on the physical reasoning abilities of human infants. First, we present two case studies: knowledge about objects and knowledge about substances (e.g., liquid, sand, etc.). Each case begins by offering key distinctions that define physical reasoning abilities and then reviews the evidence that support these claims and how these findings provide information about the nature of the representation abilities. The final sections review how these findings relate to neuroscience, sociocultural, and policy perspectives.

The psychological theory of core knowledge has motivated a great deal of research on physical reasoning in infants. The key tenet of this approach is that underneath all the things that vary across humans, there exist a set of perceptual and conceptual capacities common to everyone. The research motivated by the core knowledge approach strives to characterize the nature of these abilities and how they develop. In particular, core knowledge abilities are evident early in development and they are used continuously throughout life.

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The abilities are universal across human cultures and shared among a variety of other species. A well-studied example of a core knowledge system is the ability to discriminate quantities. This system is called the approximate number system. We use the approximate number system to discriminate between a crowd with 200 people versus a crowd of 100 people and which pile of food is larger. The ability does not require counting; it is dependent on the ratio between the compared amounts. It does not require formal schooling: In fact, newborn infants can discriminate a 1:3 ratio (Izard, Sann, Spelke, & Streri, 2009). There is improvement in the precision of the ratio over development, in that 9-month-old infants can discriminate a 2:3 ratio and adults can do a 7:8 ratio (Lipton & Spelke, 2003). These findings provide evidence that quantity discrimination is continuous across ages and becomes refined through experience. The approximate number system is not unique to humans: A variety of foraging species have the same ratio-dependent discrimination ability (Jordan, Brannon, Logothetis, & Ghazanfar, 2005). Because of its focus on the aspects of development that are continuous, the core knowledge theoretical view is often portrayed as a contrast to Piaget's (1952, 1954) stage-like progression. The interesting questions moving forward are to use the comparisons between humans' core cognitive capacities and those of other animals to see where these paths diverge. The uniquely human cognitive abilities may be grounded in the core knowledge systems as a foundation for building new cognitive skills. Perhaps the reason humans seem so smart is that we can combine the core knowledge domains to create entirely new representation systems such as language and the natural numbers.

### 13.1 Case Study 1: Objects

We all have the expectation that an unsupported object should fall down and that an object that is under a cloth still continues to exist even if we can no longer see it. But, when did we acquire this information? There is no explicit training in terms of how to represent objects. The study of infants' expectations about objects provides evidence that the way a 3-month-old and an adult perceive the world is fundamentally similar. In infancy, early object concepts are primitive, but through experience in the environment, infants elaborate these initial concepts and identify increasingly refined variables that allow them to predict the outcomes of events with more accuracy (Baillargeon et al., 2012). Early research on this topic focused on mapping out the nature of these representations and detailing what infants know at different ages. More recently, this foundation has allowed us to focus on the process through which infants acquire this knowledge. Situations where knowledge develops through experience, but without instruction, tend to involve a process of continuity and elaboration. Therefore, studies of the origins and early development of physical reasoning abilities can lend insights to the mature ability (Spelke, 1990).

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The first challenge to understanding the development of physical reasoning is to figure out a way to ask preverbal infants what they know. One method that has been developed over the past 30 years is looking-time tasks (Baillargeon et al., 2012; Oakes, 2017). From an early age, infants have good control over their eyes. In addition, infants tend to look at things that they find novel and to look away from things when they get bored. In a typical experiment, an infant is seated on their parent's lap in front of a puppet stage. A curtain on the stage is raised and the experimenter manipulates objects on the stage. The dependent measure is the duration of an infant's looks at the events on stage across trials. To capture the looking duration there is a small video camera beneath the stage floor videotaping the infant's face when the curtain is up. The video image is viewed by two research assistants in a separate room. Their job is to press a button when the infant is attending to the events on the stage and to let go of the button when the infant looks away. If the infant looks away from the stage for two consecutive seconds, this is interpreted as the infant losing interest and the trial ends.

Using this method, Spelke, Breinlinger, Macomber, and Jacobson (1992) demonstrated that at 2 months, infants know that two objects should not pass through one another. In the experiment, the infants were shown an empty stage with a barrier wall on the right side (see Figure 13.1). A screen was put on stage covering the right side of the stage and the lower portion of the barrier. The experimenter brought out a ball and waved it to draw the infant's attention, then rolled the ball so that it went behind the screen and came to rest next to the barrier wall. The screen was then removed and looking time to the outcome was recorded. This trial type was repeated until infants showed a decline in looking. The decline in looking over repeated trials is called *habituation*. Habituation trials are designed to teach infants the contingency between their looking away and the trial ending, as well as to familiarize them to the objects in the events. After the habituation trials, infants were shown two types of test trials that alternated. In the *expected* test trials, a second barrier wall was introduced to the middle of the display. The same screen was placed on the stage, covering the lower portion of the barriers. The experimenter brought out a ball, waved it to call the infant's attention, then rolled the ball so that it went behind the screen and came to rest on the near side of the new barrier wall. The screen was removed and looking time to the outcome was recorded. The *unexpected* test trial was identical except that, when the screen was removed, the ball was against the far barrier wall (as if it had passed through the barrier). Looking time at the *expected* test trials was compared to looking time at an *unexpected* test trial. The results showed that infants looked significantly longer at the unexpected outcome revealing that infants expected the ball to be stopped by the barrier and looked longer at events that violated this expectation. More broadly, research using looking-time paradigms has revealed that infants have sophisticated expectations about how objects behave and interact. These findings provide evidence that Piaget may have underestimated infants' abilities because his methodology required complex motoric and cognitive abilities.



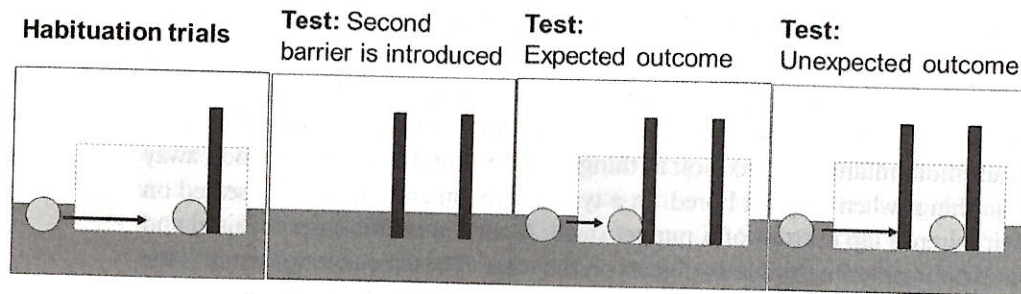


Figure 13.1. Schematic of the events used in Spelke et al. (1992).

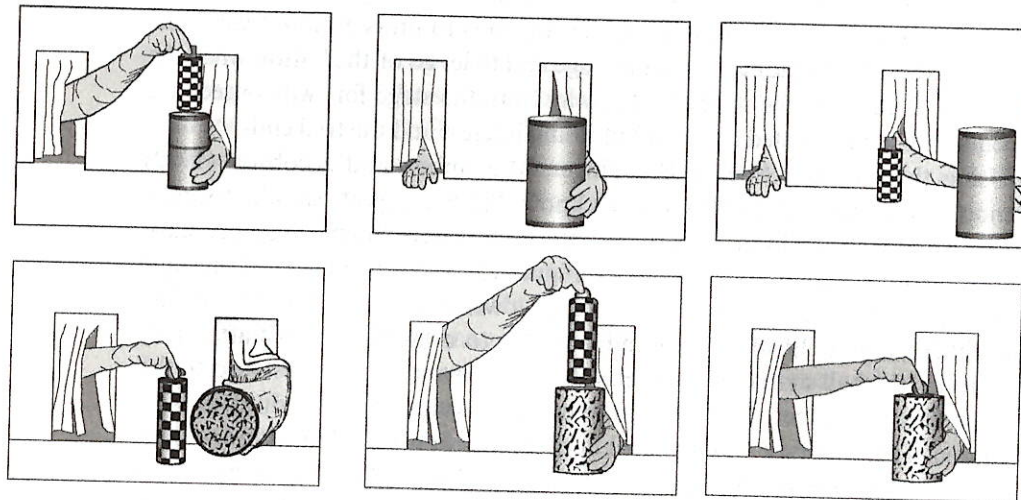


Figure 13.2. Schematic of the events used in the unexpected outcome trials for Hespos and Baillargeon (2001b).

The findings from looking-time experiments are interpreted as evidence that infants have core knowledge about objects. More specifically, infants expect objects to be *continuous* (e.g., they do not blink in and out of existence) and *solid* (e.g., two objects cannot occupy the same space at the same time). This initial finding has been replicated and extended in two ways. A study by Hespos and Baillargeon (2001b) found converging evidence for continuity and solidity using different events. In this study, 2-month-old infants expected that an object placed inside a container should travel with the container when the container was moved to a new location and looked significantly longer at an event that violated this expectation (see Figure 13.2, top row). In a different experiment, 2-month-old infants expected that two objects cannot pass through one another and they looked significantly longer at an event that violated this expectation (see Figure 13.2, bottom row). It is particularly striking that this knowledge is evident before infants have the manual dexterity to construct these expectations through interacting with the environment.

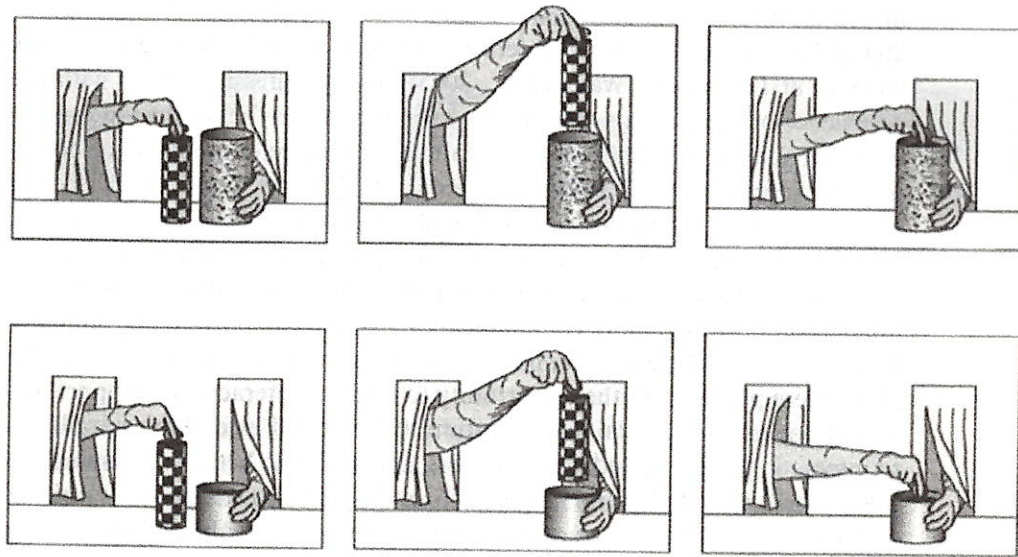


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**Figure 13.3.** *The expected (tall container event) and unexpected (short container event) from Hespos and Baillargeon (2001a).*

These initial concepts of continuity and solidity are primitive and leave many aspects of object knowledge undefined. What changes over the course of development is that, through an infant's experience interacting with the environment, these initial concepts are elaborated and refined. Over the course of several months, infants learn to identify variables that let them predict the outcomes of events more precisely. For example, 2-month-old infants have not yet identified how the height of an object determines how much of it will be hidden inside a container. Experiments with 5-month-old infants show that infants do not detect the violation if a very tall object is completely hidden in a short container because they look for equal durations at the events depicted in Figure 13.3 (Hespos & Baillargeon, 2001a). However, by 8 months of age, infants looked significantly longer at the short event compared to the tall event. These findings suggest that the infants gained more experience manipulating objects in their environment and now expect that a tall object would be only partially hidden if lowered into a short container. More broadly, these findings indicate that the change in physical reasoning is one of elaboration and refinement.

One may think that developmental changes such as the ability to detect a violation in the variable of height in a containment event at 8 months, but not at 5 months of age could be due to maturation alone. However, this interpretation is unlikely because expectations about the variable of height emerge at different times depending on the physical event. Infants have expectations about the variable of height in occlusion events as early as 3.5 months of age (Baillargeon & DeVos, 1991; Hespos & Baillargeon, 2001b), height

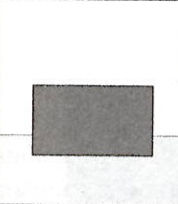


in containment events emerges at 8 months of age (Hespos & Baillargeon, 2001a; Wang, Baillargeon, & Paterson, 2005), and height in covering events emerges at 12 months (Wang et al., 2005). This progression aligns with the prevalence of these events in everyday environments in that occlusion is more common than containment and containment is more common than covering. We speculate that this developmental change may instead be based on experience. Recent evidence demonstrated a way to test these ideas. Casasola, Bhagwat, Doan, and Love (2017) provided parent-child dyads with nesting toys and recorded spontaneous interactions. They found that 18-month-old infants demonstrated more containment events than support events. Similarly their caretakers labeled containment more than support. However, in dyadic play, where parents had the opportunity to lead the interactions, support was more frequent than containment. Future studies could extend this paradigms to interactions with occluders, containers, and covers to better understand the roles of self-guided play and language in developing knowledge about objects.

Another factor that interacts with the development of object knowledge is individual differences in postural milestones like sitting, crawling, and walking. Various studies have shown that object manipulation and experience is rate limited by postural constraints (Higgins, Campos, & Kermoian, 1996; Rochat, 1992; Soska & Adolph, 2014). For example, self-sitting allows an infant to hold an object with one hand and probe its contours with the other hand and this has implications for their expectations about how objects behave and interact. A full account of physical knowledge will need to consider the interaction between cognitive, cultural, and motoric influences.

Infants' understanding of physical reasoning with regard to support events provides another example of initial knowledge that gets elaborated through identifying increasingly refined variables (see Figure 13.4). As early as 3 months of age, infants have the initial concept that unsupported objects should fall and they look significantly longer at an event that violates this expectation (Needham & Baillargeon, 1993). By 5 months of age, this initial concept becomes elaborated to discriminate the difference between the type of support, in that a box supported by being placed on top of a horizontal surface should provide support but a box placed against a vertical surface should not provide support. By 7 months infants identify a new variable, namely the amount of contact. Infants expect that 70% contact with the horizontal surface should provide support but only 15% contact with the horizontal surface (where the majority of the box is dangling over the edge) would not provide support (Baillargeon, Needham, & DeVos, 1993). Just after a year of age infants identify yet another variable about the shape of the supported object. Infants expect that an asymmetric object that is placed with the larger portion of the object on a box will be supported by the box. However, if the smaller portion of an asymmetric object is placed on the box so that that larger portion of the box is extended without support, then infants expect the box to fall. Together, these studies provide converging evidence for a developmental

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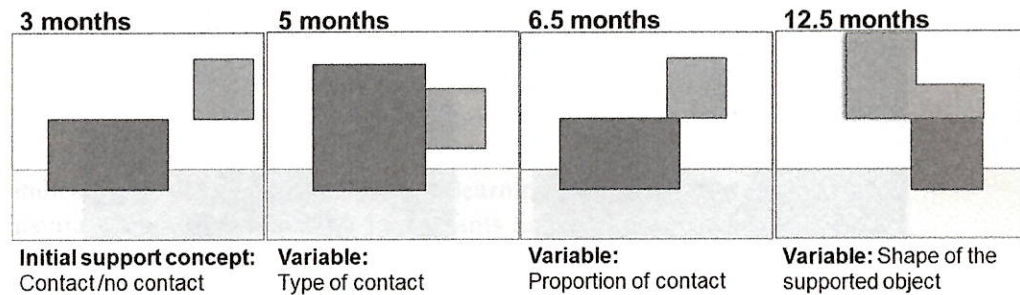
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progression of infant physical knowledge in their environment. Future studies could explore how these patterns exist across different environments. From Needham and Baillargeon (1993), active reaching and exploring objects before they fall (e.g., reaching for a block) leads to improved mental rotation (Needham, 2005). This knowledge can be used to disentangle the nature of physical knowledge.

All of the physical knowledge that infants have at looking-time tasks is based on their experience: would infants answer seems to be based on their motor skills, but the experiments allow infants to learn about one or another object. For example, a frog that was very close to the center took the first look at the screen revealed the frog's position (Figure 13.5). One possible explanation is that the entire container was one-third of the entire frog would be in the infant's attention. The edge of the frog was reached toward. The frog that was taken away from them they would reach toward what happened with the frog (Baillargeon, 2006).



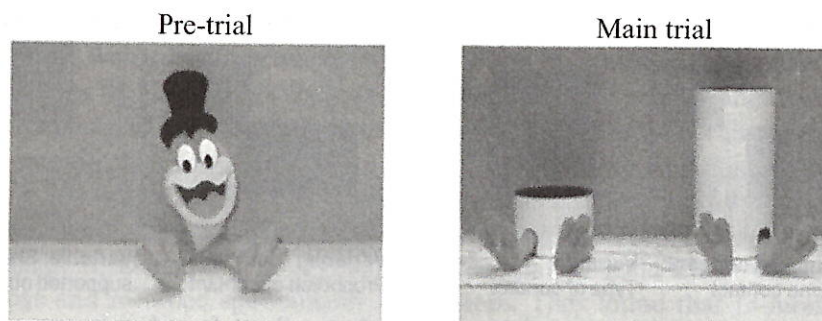


**Figure 13.4.** *Schematic of the support violations that infants detect at increasing ages.*

progression of initial knowledge that is elaborated through experience in the environment. Future studies could determine whether these developmental patterns exist across different exposure rates and cultures. Additionally, work from Needham and colleagues has shown that increasing 3- and 4-month-olds' active reaching experience by giving them sticky mittens (so they can pick up objects before they have the manual dexterity to grasp them with their own fingers) leads to improvements in parsing goal-directed actions with objects and mental rotation (Slone, Moore, & Johnson, 2018; Sommerville, Woodward, & Needham, 2005). Paradigms using interventions like the sticky mittens could be used to disentangle the roles of experience and maturation in the development of physical reasoning.

All of the physical reasoning evidence described thus far has relied on looking-time tasks to measure infants' knowledge. This raises the question: would infants demonstrate the same knowledge with action tasks? The answer seems to be yes. Infants in the first months of life do not have fine motor skills, but paradigms designed for infants to perform gross motor movements allow infants to execute choices based on their actions, like a swipe at one or another object. For example, infants were presented with a plush toy frog that was very tall. After playing with the frog for a little while, the experimenter took the frog from the infant and hid it behind a screen, then removed the screen revealing two containers that had frog feet sticking out of them (Figure 13.5). One of the containers was taller than the frog and it was feasible that the entire frog could be hidden inside the container. The other container was one-third the size of the toy frog and it was not feasible that the entire frog would fit inside the short container. The experimenter drew the infant's attention to each container and then pushed both containers to the edge of the infant's reaching space and recorded which container the infants reached toward. The rationale was that the infant wanted to recapture the toy that was taken away and if the infant remembered the height of the frog then they would reach for the tall instead of the short container. This is exactly what happened when we tested 8-month-old infants (Figure 13.5; Hespos & Baillargeon, 2006). In contrast, 5-month-old infants showed no preference





**Figure 13.5.** Pictures of the stimuli from Hespos and Baillargeon (2006).

between the tall and short containers. These findings align with the developmental changes in the looking-time tasks. Further studies that did action tasks testing the support variables of type of contact and amount of contact also revealed the same developmental changes at the same time providing converging evidence across looking and reaching paradigms for the development of physical reasoning abilities (Hespos & Baillargeon, 2008).

Together, these findings are important because they capture the interplay between two developmental trajectories. One is the core knowledge of continuity and solidity that is evident early and does not rely on experience. The other is a more protracted, experience-based trajectory that is characterized by identifying variables that allow infants to elaborate the initial concepts and become more precise. Together, looking-time paradigms provide considerable evidence that a 2-month-old and an adult perceive objects in fundamentally similar ways. The idea that infants have sophisticated expectations about how objects behave and interact is at odds with Piaget's notion of qualitative shifts in their object concept (Piaget, 1952).

This early work documented *what* infants understand about objects at certain ages. This sets the stage for investigating *how* infants' physical knowledge interacts with other cognitive abilities. One cognitive ability that comes into play is language. Human languages vary in meanings and children must learn which distinctions their languages use. For example, tight/loose fit is a spatial distinction that is marked linguistically in Korean but not English. Adult Korean speakers – but not adult English speakers – are sensitive to the conceptual distinction of tight and loose fit when they categorize spatial relations (Bowerman, 1996). As a matter of fact, language-specific differences in spatial categories are evident early in language acquisition. Korean children differ from English-speaking children on spatial category tasks in accord with their ambient languages (Choi & Bowerman, 1991). Is it possible that language specifies the spatial category boundaries, or do infants have expectations about spatial categories prior to language?

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Casasola and Cohen (2002) revealed that 10-month-old infants have expectations about containment and support prior to language production. Similarly, we found that 5-month-old infants in an English-speaking environment were sensitive to the Korean-marked tight-loose spatial category even though it was not marked in their ambient language (Hespos & Spelke, 2004). These findings indicate that the process that governs learning word meanings has a developmental trajectory where preverbal infants are sensitive to nonnative distinctions. Spatial language learning seems to develop by linking linguistic forms to universal, preexisting concepts. In these respects, the early development of spatial categories parallels the development of phonological perception. The infant's native language capitalizes on preexisting conceptual or acoustic distinctions and experience with a language influences the prominence of distinctions that are marked in the ambient language(s).

A second example of *how* physical knowledge interacts with other cognitive systems comes from studies on how infants allocate their attention to specific aspects of their environment. For example, infants who saw a solidity or no-contact support violation (similar to those described earlier) attend to that object more closely in subsequent interactions and learned to associate a novel sound with the object. In contrast, when the same teaching event was coupled with expected solidity or support events, infants failed to learn this new sound property (Stahl & Feigenson, 2015). Additionally, Stahl and Feigenson (2015) found that infants are active participants in their own knowledge acquisition. That is, infants who saw violations spent more time interacting with the object involved, compared to a distractor object. These infants also tested the objects in ways that suggested they were trying to replicate the unexpected behavior: Infants who saw a ball appear on the other side of a wall spent more time banging the ball against a high-chair tray, while infants who saw the ball float unsupported spent more time dropping the ball off the high-chair tray. This paradigm represents an exciting new approach to understanding how infants select what to learn.

To summarize the lessons from the first case study on objects, research using looking and reaching paradigms demonstrates that infants have expectations about how objects behave and interact. There is one early developing set of expectations about continuity and solidity that appear before infants have the opportunity to construct this knowledge through interacting with their environment. There is a second, experience-based trajectory characterized by identifying variables that allow infants to elaborate the initial concepts over the course of the first year. Together, these examples reveal that our knowledge about objects goes beyond the information available in the immediate environment. The expectations about how objects behave and interact is remarkably similar across humans in that these expectations require little experience and there may too be little variation across species.

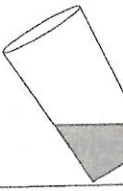


### 13.2 Case Study 2: Substances

When a cup containing pencils is tipped over, not much happens. However, when a cup containing coffee is tipped over, panic can ensue as one tries to catch the cup before too much coffee spills. These reactions to spills are the result of understanding that objects and liquids have different physical properties and therefore behave differently. These reactions may seem obvious, but when do we develop the expectation that liquids deform to fill the space? This ontological categorical distinction has captivated linguists who trace cross-linguistic differences in count/mass nouns (Imai & Mazuka, 2007). In the philosophical domain of metaphysics, there are distinctions between entities that are separable or nonseparable (Rips & Hespos, 2015). In the field of psychology, there is a growing interest in looking at the origins and development of knowledge about substances and how it compares to the representations that guide expectations about objects (Hespos & vanMarle, 2012). For example, unlike objects, liquids deform to fit a container and a solid object can pass through them. Yet, like objects, liquids are common and some expectations about how they behave are probably universal across cultures and species. Given that there is evidence of sophisticated knowledge about objects early in development, the question we tackle in case study 2 is whether there is sophisticated knowledge about substances early in development.

Early evidence suggested that the answer was no: infants did not have principled expectations for substances (Cherries, Mitroff, Wynn, & Scholl, 2008; Chiang & Wynn, 2000; Huntley-Fenner, Carey, & Solimando, 2002; Rosenberg & Carey, 2009). In one study, Huntley-Fenner et al. (2002) showed 8-month-old infants a pile of sand, then concealed the pile behind a screen and poured a second pile of sand behind a nearby but spatially separated screen. The test trials alternated between expected and unexpected outcomes, and looking time was the dependent measure. The expected outcome was to reveal two piles of sand – one behind each screen when the screens were removed. The unexpected outcome was to reveal only a single pile behind one of the screens and nothing behind the other screen. The infants' looking times did not differ between the expected and unexpected events, providing evidence that they did not detect the violation when one sand pile disappeared. In contrast, when the sand substance was replaced with solid objects that were shaped like sand piles, then the infants looked significantly longer at the unexpected test trials. Infants' difficulties in tracking sand extended to collections of objects, like a pile of Legos (Chiang & Wynn, 2000). Together, these findings were interpreted as evidence that infants have principled expectations for objects but not for substances (Spelke & Kinzler, 2007).

Bourgeois, Khawar, Neal, and Lockman (2005) introduced a different approach to ask whether infants had any expectations about substances. They presented infants with stimuli that varied in qualities of hard versus soft versus liquid versus netting and found that 6- to 10-month-old infants adjust their



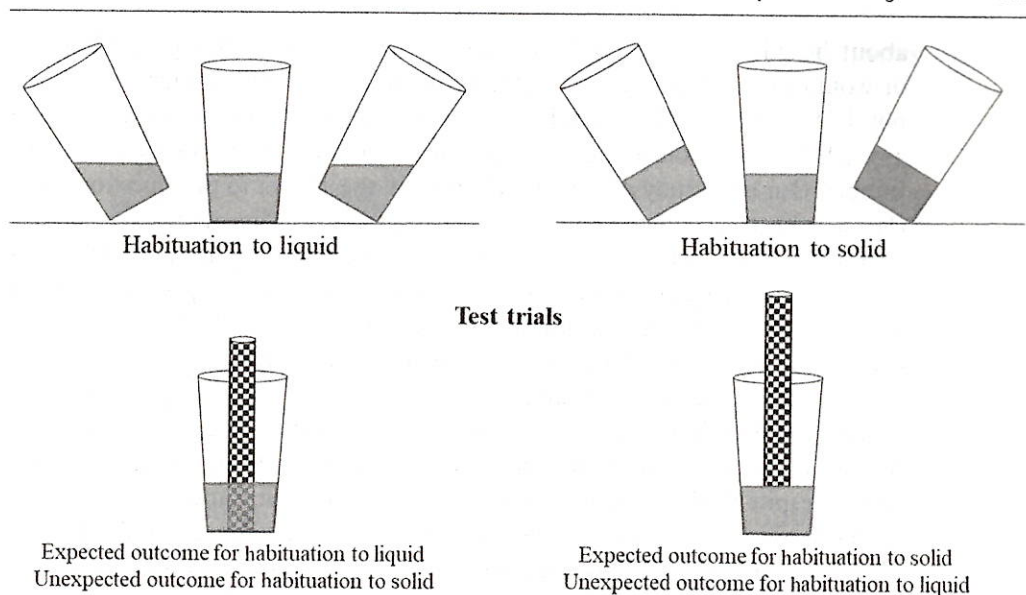
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**Figure 13.6.** A schematic of the habituation and test trials used in Hespos et al. (2009).

actions towards objects based on the material-specific qualities of the stimuli. This finding was important because it demonstrated that infants approach objects and liquids with different behaviors. In turn, the starting point for our research was to focus on the different ways that objects and substances behave. For example, objects tend to be solid such that two objects cannot pass through one another, but liquids are loosely bonded so a straw can penetrate the surface of the liquid and come to rest on the bottom of the glass. Using a looking paradigm, 5-month-old infants were habituated to either a glass that contained liquid or a perceptually similar looking solid (see Figure 13.6). The glass was tipped back and forth and the motion cues specified whether the contents were liquid or solid. Next, in test trials, all infants saw trials of a straw being lowered into a glass. On half the trials, the contents of the glass were liquid and the straw penetrated the surface of the liquid and came to rest on the bottom of the glass. On the other half of the trials, the contents of the glass were solid and the straw stopped when it came in contact with the surface of the solid. Infants dishabituated (i.e., showed a significant increase in looking time compared to their last habituation trials) when there was a state change from liquid to solid or from solid to liquid. This suggests that infants have different expectations for the ways that solids and liquids behave (Hespos, Ferry, & Rips, 2009). These findings begin to clarify how 5-month-old infants comprehend the physical properties of substances.

We started with a solid object and a water-like liquid because they are the clearest examples of their kinds. However, this initial finding raises questions about how far infants' knowledge extends. Do infants develop expectations



about liquids because they have extensive experience drinking and bathing or would they generalize such expectations to any event that shared the same physical attributes? More specifically, would an infant who has never been to a beach have expectations that a cup containing sand should pour out and not tumble? Our next study provided evidence that the answer to this question is yes (Hespos, Ferry, Anderson, Hollenbeck, & Rips, 2016). The events were similar to those depicted in Figure 13.6, but we replaced the liquid with sand and found similar results. Together, these findings provide evidence that expectations about substances emerge early and these inferences are based on little or no experience. A remaining question is whether violations of substance properties would lead to increased exploration and learning, such as Stahl and Feigenson (2015) found with violations of object knowledge. Answering this question would help reveal whether expectations for substances are treated as having consistent principles, despite the less constrained nature of nonsolid substances.

The results we have presented suggest that infants can grasp simple physical properties that apply to nonsolid substances. However, the previous research showing success with objects and failure with substances in otherwise identical paradigms raises questions about the extent of their knowledge (Chiang & Wynn, 2000; Huntley-Fenner et al., 2002; Rosenberg & Carey, 2009). Infants are apparently unable to predict the number of piles that result from pouring sand behind adjacent screens. But it is possible that this is due more to the working memory demands of the pouring event than a lack of expectations for substances. In a recent study, we tested infants' expectations about the mechanical properties of sand in a simplified pouring event. Although nonsolid substances can sometimes spread to fit the space allotted, constraints particular to sand limit its ability to do so. If infants see two cups of sand poured at opposite ends of a tray behind a screen, would it violate their expectations to reveal a single pile? What if just one cup was poured behind the screen? Would it be surprising if a single pour resulted in two separate piles? Our findings show that the answers are yes (see Figure 13.7). We found that 5-month-old infants look longer at events in which pours from two separate cups result in a single pile. In a separate condition, we found infants look longer if a single pour of sand results in two sand piles. The picture that is emerging is that infants have core principles for substances that are distinct from their expectations about objects.

To summarize the lessons from the second case study on substances, research using looking paradigms demonstrates that infants have expectations about how substances behave and interact. More specifically, the motion cues that specify that the contents of a glass are a substance lead infants to have expectations about how substances can divide and accumulate. In contrast to the vast literature on object knowledge, the study of substance knowledge in infants is new and there are only a handful of studies. Future research will need to test the youngest age groups to find out whether 2-month-olds have expectations about how liquids and sand divide and accumulate. In addition, mapping out

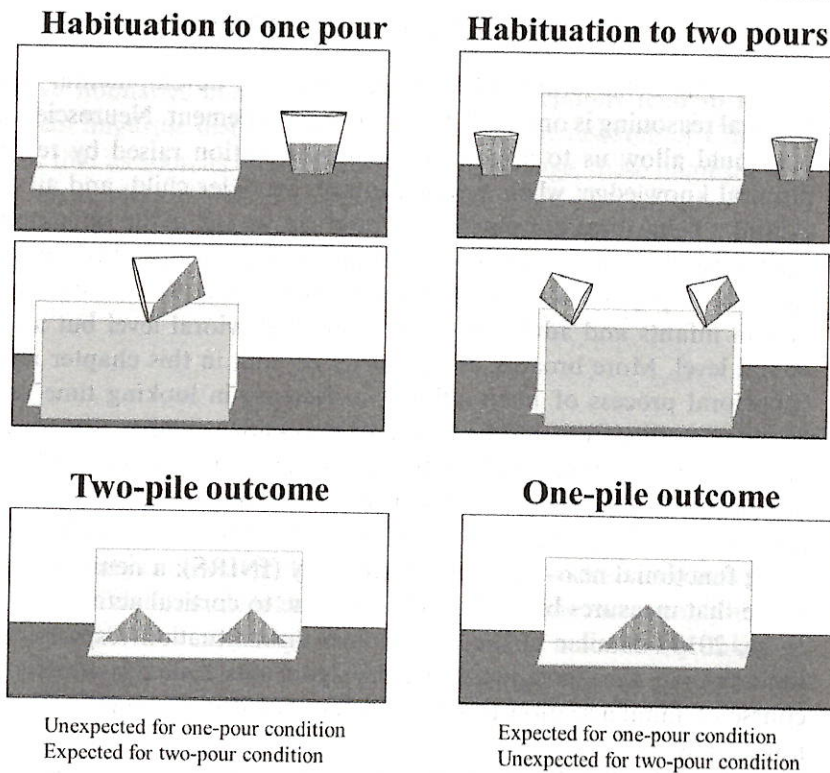


**Figure 13.7**  
Anderson et al. (2016)

the development of expectations about substances, such as water versus sand, is an important area for future research.

To consider the implications of these findings for the development of substance knowledge, we note that there are two distinct types of knowledge about substances: one that is based on direct experience and another that is based on other cognitive abilities that are developed simultaneously (Hespos, 2015). The findings presented here support the idea that infants have a core understanding of the properties of substances, such as the fact that sand can be poured and will accumulate in a single pile, but they also show that infants have expectations about the behavior of substances that are distinct from their expectations about objects.





**Figure 13.7.** A schematic of the habituation and test trials used in Anderson, Hespos, and Rips (2018).

the developmental trajectory of this knowledge will be important. Do infants have expectations about the viscosity of liquids like the difference between water versus honey? If so, is this elaboration of knowledge about substances experience-based and when does it come into play?

To consider object and substance case studies together could shed new light on the nature of our representational systems. Object and substance knowledge may develop in parallel and it is an empirical question about whether there are two distinct domains of core knowledge that become connected through other cognitive systems, or whether there is one physical reasoning domain where distinctions between object and substances are situation-specific variables that are identified through experience. For example, as adults we can simultaneously construe a single entity as an object and a substance (Rips & Hespos, 2015). That is, I am seated at an object that I consider a table because it supports my computer while I write. However, if I were cold and in need of warmth I might also consider that the table is made of wood and I could burn it for warmth. A question for future research is: when does this flexibility between object and substance construal develop?



### 13.3 Implications for Neuroscience/Psychophysiology

The behavioral studies suggest that the developmental change in physical reasoning is one of elaboration and refinement. Neuroscience methods could allow us to approach a central question raised by research on physical knowledge: when a young infant, an older child, and an adult all exhibit a behavioral discrimination, how can we tell if the same underlying mechanism leads to behavioral discrimination across ages? If true continuity exists in physical knowledge, then we may expect to see convergent findings in infants and adults not only at the behavioral level but also at the neural level. More broadly, the majority of data in this chapter relies on a behavioral process of habituation – a decrease in looking time as stimuli become familiar. It would be fascinating to know whether there is converging evidence for infants' habituation at the neural level indicated by changes in blood flow due to functional activation or changes in electrophysiological response over time. Initial evidence for exactly this pattern has been reported using functional near-infrared spectroscopy (fNIRS), a neuroimaging technique that measures blood flow changes due to cortical activity (Lloyd-Fox et al., 2019). Similar to the habituation–dishabituation response found in looking time, neuroimaging revealed a significant decline in activity over the course of familiarization trials and a significant increase in activity during novel trials.

We have divided this chapter into reasoning about objects and reasoning about substances, but neuroscience could offer clues into how distinct these processes are and whether they diverge over the course of development. Evidence from adults suggests that representations of objects are associated with activation in the lateral occipital complex (Kourtzi & Kanwisher, 2001). It would be interesting to learn whether, in infancy, these areas are activated by looking-time displays featuring only objects or by those featuring substances as well. This could tell us whether object and substance representations are linked in infants' physical reasoning or whether these are separate domains.

### 13.4 Implications for Sociocultural Perspectives

The lack of variance in physical reasoning abilities across ontogeny and phylogeny suggests that there may be little variance across culture in these abilities as well. However, languages vary in how they describe space. While English differentiates containment (in) and support (on), and Korean distinguishes between a tight fit and a loose fit, languages like Dutch make even further distinctions for different types of contact (Bowerman, 1996; Gentner & Bowerman, 2009). As described above, Hespos and Spelke (2004) provides evidence that we start with a universal set of concepts about how entities in

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our world interact, and then language enhances or diminishes specific spatial relations. Though Hespos and Spelke (2004) showed that 5-month-old infants have nonnative concepts where adults' perceptions tend to mirror their ambient linguistic distinctions, it is clear from the research of Choi and Bowerman that as soon as children start using language, these linguistic distinctions are in place (Bowerman & Choi, 2003; Choi & Bowerman, 1991; Choi, McDonough, Bowerman & Mander, 1999). It would be interesting to map out these developmental changes for a variety of languages and spatial categories.

### 13.5 Conclusions and Policy Implications

Together, this chapter has argued that core concepts critical to early physical reasoning – such as object and substance knowledge – are likely a part of our evolutionary endowment. In addition, we have also described how these concepts become elaborated and refined as infants become increasingly able to explore the world. Because this process of elaboration is so closely linked to experience in the environment, it has clear policy implications. The research described above touches on the ways in which core knowledge interacts with other systems. These insights can provide valuable guidelines to practitioners and educators about the flexibility in our learning systems. There is evidence that language may capitalize on preexisting spatial concepts and change the way that adults perceive spatial events, so understanding whether a person speaks multiple languages and how these languages align or contrast in spatial terms could aid acquisition of a second language. There is also evidence that postural milestones like the onset of sitting, crawling, and walking can influence how infants interact with objects in their environment. This, in turn, influences when infants identify variables that allow them to predict the outcome of events with more accuracy. For children with developmental delays in reaching postural milestones, it may facilitate cognitive development to provide artificial postural support so that infants can manipulate objects and gain experience that might be rate limited by delayed postural milestones. Previously mentioned work from Casasola et al. (2017) shows how infant play tends to focus on containment while dyadic play with parents leads to a greater mix of support and containment. This example highlights how parents or older peers can scaffold infants' interaction with objects, giving them the opportunity to consider new variables sooner. As our field begins to incorporate large datasets, such as videos over the first year of life, we can use these data to better understand the role of play in constructing this knowledge and how the trajectory varies across cultures. This in turn will allow us to pinpoint the most fruitful times and methods for intervention.



## References

- Anderson, E., Hespos, S. J., & Rips, L. (2018). Five-month-old infants have expectations for the accumulation of nonsolid substances. *Cognition*, 175, 1–10. <https://doi.org/10.1016/j.cognition.2018.02.009>
- Baillargeon, R., & DeVos, J. (1991). Object permanence in young infants: Further evidence. *Child Development*, 62(6), 1227–1246.
- Baillargeon, R., Needham, A., & DeVos, J. (1993). The development of young infants' intuitions about support. *Infant and Child Development*, 1(2), 69–78.
- Baillargeon, R., Stavans, M., Wu, D., Gertner, R., Setoh, P., Kittredge, A. K., & Bernard, A. (2012). Object individuation and physical reasoning in infancy: An integrative account. *Language Learning and Development*, 8, 4–46.
- Bourgeois, K. S., Khawar, A. W., Neal, A., & Lockman J. (2005). Infant manual exploration of objects, surfaces, and their interrelations. *Infancy*, 8, 233–252.
- Bowerman, M. (1996). Learning how to structure space for language: A crosslinguistic perspective. In P. Bloom, M. A. Peterson, L. Nadel, & M. F. Garrett (Eds.), *Language and space* (pp. 385–436). Cambridge, MA: MIT Press.
- Bowerman, M., & Choi, S. (2003). Space under construction: Language-specific spatial categorization in first language acquisition. In D. Gentner & S. Goldin-Meadow (Eds.), *Language in mind* (pp. 387–428). Cambridge, MA: MIT Press.
- Casasola, M., Bhagwat, J., Doan, S. N., & Love, H. (2017). Getting some space: Infants' and caregivers' containment and support spatial constructions during play. *Journal of Experimental Child Psychology*, 159, 110–128.
- Casasola, M., & Cohen, L. (2002). Infant categorization of containment, support, and tight-fit spatial relationships. *Developmental Science*, 5(2), 247–264.
- Cherries, E. W., Mitroff, S. R., Wynn, K., & Scholl, B. J. (2008). Cohesion as a constraint on object persistence in infancy. *Developmental Science*, 11, 427–432.
- Chiang, W. C., & Wynn, K. (2000). Infants' tracking of objects and collections. *Cognition*, 77, 169–195.
- Choi, S., & Bowerman, M. (1991). Learning to express motion events in English and Korean: The influence of language-specific lexicalization patterns. *Cognition*, 41(1–3), 83–121.
- Choi, S., McDonough, L., Bowerman, M., & Mandler, J. M. (1999). Early sensitivity to language-specific spatial categories in English and Korean. *Cognitive Development*, 14(2), 241–268.
- Gentner, D., & Bowerman, M. (2009). Why some spatial semantic categories are harder to learn than others: The typological prevalence hypothesis. In J. Guo, E. Lieven, S. Ervin-Tripp, N. Budwig, S. Özçaliskan, & K. Nakamura (Eds.), *Crosslinguistic approaches to the psychology of language: Research in the tradition of Dan Isaac Slobin* (pp. 465–480). New York, NY: Lawrence Erlbaum Associates.
- Hespos, S. J., & Baillargeon, R. (2001a). Infants' knowledge about occlusion and containment: A surprising discrepancy. *Psychological Science*, 12(2), 141–147.
- (2001b). Reasoning about containment events in very young infants. *Cognition*, 78, 207–245.
- (2006). Decalage in infants' reasoning about occlusion and containment events: Converging evidence from action tasks. *Cognition*, 99, B31–B41.

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- (2008). Young infants' actions reveal their developing knowledge of support variables: Converging evidence for violation-of-expectation findings. *Cognition*, 107(1), 304–316.
- Hespos, S. J., Ferry, A., Anderson, E., Hollenbeck, E., & Rips, L. (2016). Five-month-old infants have expectations about how substances behave and interact. *Psychological Science*, 27(2), 244–256. <https://doi.org/10.1177/0956797615617897>
- Hespos, S. J., Ferry, A., & Rips, L. (2009). Five-month-old infants have different expectations for solids and liquids. *Psychological Science*, 20(5), 603–611.
- Hespos, S. J., & Spelke, E. S. (2004). Conceptual precursors to spatial language. *Nature*, 430, 453–456.
- Hespos, S. J., & vanMarle, K. (2012). Physics for infants: Characterizing the origins of knowledge about objects, substances, and number. *Wiley Interdisciplinary Reviews: Cognitive Science*, 3(1), 19–27.
- Higgins, C., Campos, J., & Kermoian, R. (1996). Effects of self-produced locomotion on infant postural compensation to optic flow. *Developmental Psychology*, 32, 836–841.
- Huntley-Fenner, G., Carey, S., & Solimando, A. (2002). Objects are individuals but stuff doesn't count: Perceived rigidity and cohesiveness influence infants' representations of small groups of discrete entities. *Cognition*, 85, 203–221.
- Imai, M., & Mazuka, R. (2007). Language-relative construal of individuation constrained by universal ontology: Revisiting language universals and linguistic relativity. *Cognitive Science: A Multidisciplinary Journal*, 31(3), 385–413.
- Izard, V., Sann, C., Spelke, E. S., & Streri, A. (2009). Newborn infants perceive abstract numbers. *Proceedings of the National Academy of Sciences of the United States of America*, 106(25), 10382–10385.
- Jordan, K. E., Brannon, E. M., Logothetis, N. K., & Ghazanfar, A. A. (2005). Monkeys match the number of voices they hear to the number of faces they see. *Current Biology*, 15(11), 1034–1038.
- Kourtzi, Z., & Kanwisher, N. (2001). Representation of the perceived object shape by the human lateral occipital complex. *Science*, 293(5534), 1506–1509.
- Lipton, J. S., & Spelke, E. S. (2003). Origins of number sense. Large-number discrimination in human infants. *Psychological Science*, 14, 396–401.
- Lloyd-Fox, S., Blasi, A., McCann, S., Rozhiko, M., Katus, L., Mason, L., ... Elwell, C. E. (2019). Habituation and novelty detection fNIRS brain responses in 5- and 8-month-old infants: The Gambia and UK. *Developmental Science*, 22(5), e12817. doi: 10.1111/desc.12817
- Needham, A., & Baillargeon, R. (1993). Intuitions about support in 4.5-month-old infants. *Cognition*, 47, 121–148.
- Oakes, L. M., (2017). Sample size, statistical power, and false conclusions in infant looking-time research. *Infancy*, 22, 436–469.
- Piaget, J. (1952). *The origins of intelligence in children*. New York, NY: W. W Norton & Co.
- (1954). *The construction of reality in the child*. New York, NY: Basic Books.
- Rips, L. J., & Hespos, S. J. (2015). Mental divisions of the physical world: Objects and substances. *Psychological Bulletin*, 141(4), 786–811.
- Rochat, P. (1992). Self-sitting and reaching in 5- to 8-month-old infants: The impact of posture and its development on early eye-hand coordination. *Journal of Motor Behavior*, 24(2), 210–220.



- Rosenberg, R. D., & Carey, S. (2009). Infants' representations of material entities. In B. M. Hood & L. R. Santos (Eds.), *The origins of object knowledge* (pp. 165–188). Oxford: Oxford University Press.
- Slone, L. K., Moore D. S., & Johnson S. P. (2018) Object exploration facilitates 4-month-olds' mental rotation performance. *PLoS ONE* 13(8), e0200468.
- Sommerville, J. A., Woodward, A. L., & Needham, A. (2005). Action experience alters 3-month-old infants' perception of others' actions. *Cognition*, 96(1), B1–B11.
- Soska, K. C., & Adolph, K. E. (2014). Postural position constrains multimodal object exploration in infants. *Infancy*, 19(2), 138–161.
- Spelke, E. S. (1990). Principles of object perception. *Cognitive Science*, 14(1), 29–56.
- Spelke, E. S., Breinlinger, K., Macomber, J., & Jacobson, K. (1992). Origins of knowledge. *Psychological Review*, 99(4), 605–632.
- Spelke, E. S., & Kinzler, K. D. (2007). Core knowledge. *Developmental Science*, 10(1), 89–96. doi: 10.1111/j.1467-7687.2007.00569.x
- Stahl, A. E., & Feigenson, L. (2015). Observing the unexpected enhances infants' learning and exploration. *Science*, 348(6230), 91–94.
- Wang, S., Baillargeon, B., & Paterson, S. (2005). Detecting continuity violations in infancy: a new account and new evidence from covering and tube events. *Cognition*, 95(2), 129–173.

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