Advanced Review

Physics for infants: characterizing the origins of knowledge about objects, substances, and number

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Adults possess a great deal of knowledge about how objects behave and interact in our every day environment, yet several puzzles remain unsolved regarding how we manage this ubiquitous skill. The notion of intuitive physics has been a central focus of research on cognitive development in infancy. This article focuses on the origins of knowledge about objects, substances, and number concepts in infancy. The article reviews common themes of solidity, continuity, cohesion, and property changes as they have been studied with regard to infants' knowledge about objects and more recently with regard to infants' knowledge about substances. In addition, we review how object and substance knowledge interfaces with number knowledge systems. The evidence supports the view that certain core principles about these domains are present as early as we can test for them and the nature of the underlying representation is best characterized as primitive initial concepts that are elaborated and refined through learning and experience.

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INTRODUCTION

We go beyond the information available in the environment, making inferences based on little or no experience. This is a captivating cognitive ability precisely because the achievement is both pervasive and illusive. We cannot build a robot that can navigate an everyday environment as well as a typical toddler because we have yet to fully understand the cognitive systems underlying even a 1- or 2-year olds' representation of spatial layouts. We never receive explicit lessons about how objects behave and interact, yet humans draw universally similar expectations. For example, we all expect unsupported objects to fall down. We also universally agree that hidden objects do not cease to exist when they are occluded from view. These expectations are not exclusive to humans but appear to be shared by many other species, from nonhuman primates[1] to chickens.[2]

These observations animate two important insights about object perception, both initially described by Spelke.[3] First, in situations where perception develops through experience but without instruction or reflection, the developmental changes tend to involve a process of continuity and elaboration. Second, studies of the origins and early development of these representation skills can lend insights to the mature ability. More recently, Baillargeon[4] has echoed these themes. Her theory of persistence states that infants possess impoverished representation systems early in development, but that as they gain experience, the developmental change is one of refinement and elaboration.

In this paper, we review some of the lessons learned in the last three decades about the nature and early development of object cognition and contrast this with infants' seemingly limited knowledge about an equally pervasive everyday entity, namely substances such as liquid and sand. The distinction between objects and substances is a fundamental category distinction required for many everyday actions that allow us to reach our goals. Unlike substances, objects can be held, thrown, or bitten.

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In contrast, substances can flow, often leak, and are drinkable. This ontological categorical distinction has captivated linguists who trace cross-linguistic differences in count/mass nouns.[5] In the philosophical domain of metaphysics, there are distinctions between entities that are separable or nonseparable.[6] In the field of psychology, there is 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. For example, unlike objects, substances deform to fit a container and can be penetrated by a solid object. Yet, like objects, substances are common and pervasive regardless of culture, socioeconomic status, or location. There is no explicit training in terms of how to handle substances or objects. Knowledge of how to interact with substances are not uniquely human, in that other species know how to swim, drink, and traverse layouts made of substances (e.g., a beach or gravel terrain). Given that there is evidence of sophisticated knowledge about objects early in development, we explore the nature of early knowledge about substances. In the first section, we review infant studies revealing expectations about the attributes of objects. Then, we review the infant studies revealing how there are different expectations about the same attributes when it comes to substances. In the second section, we focus on a commonality between objects and substances, which is that both entities are quantifiable.

OBJECTS—SOLIDITY AND CONTINUITY

The last 30 years has seen an explosion of research characterizing the nature of object representations in infancy. One of the early studies that used looking paradigms with infants provided evidence that infants do not expect two objects to occupy the same space at the same time.[7] Baillargeon[8] demonstrated that infants as young at 3.5 months of age look significantly longer at events where a rotating screen appears to pass through space occupied by a box (Figure 1). Further studies with infants as young as 2 months of age demonstrated that infants expect a ball to stop when it comes in contact with a solid wall (Figure 2).[9] One could argue whether this is a solidity violation (in that the ball appears to pass through the wall) or a continuity violation (in that the ball blinked in and out of existence).

Regardless of whether it is a solidity or continuity violation, 2-month-old infants have demonstrated expectations about objects across a wide variety of contexts. Infants expect a container to have an opening in its top when an object is lowered inside it.[10] In addition, infants react when an object suddenly appears or disappears. For example, when there are two separate screens on a stage and an object disappears behind the far edge of one

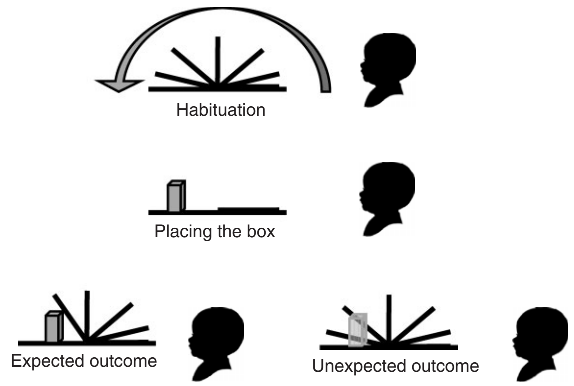

FIGURE 1 | Infants were habituated to a screen that rotated 180° back and forth. Next, a box was placed in the path of the rotating screen. There were two types of test trials. In the expected event, the screen rotated until it came in contact with the box then reversed direction. In the unexpected event, the screen rotated up hiding the box and then continued to pass through the space where the box was located. Infants looked longer at the unexpected compared to the expected events. Adapted from Refs 7 and 8.

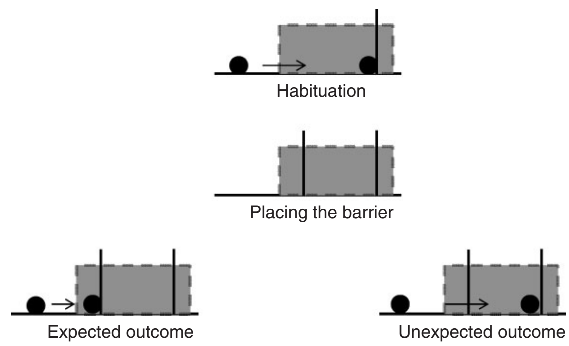

FIGURE 2 | Infants were habituated to an event where they were shown an empty stage with a barrier wall on the right side. A screen was lowered covering the right side of the stage and the lower portion of the barrier. The experimenter brought out a ball and waved it to call the infant's attention then rolled the ball so that it went behind the screen and came to rest next to the barrier wall. The screen was then raised and looking time at the outcome was recorded. Next, a second barrier wall was introduced to the display. There were two types of test trials. In the expected event, the screen was lowered 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 raised and looking time to the outcome was recorded. The unexpected event was identical except that when the screen went up the ball was against the far barrier wall. Infants looked significantly longer at the unexpected compared to the expected outcome. Adapted from Ref 9.

screen, infants expect the object to appear in the space between the screens before emerging from the far edge of the other screen.[11,12] When an object is placed inside a container and the container is moved to a new location, 2-month-old infants expect that the contained object will be displaced with the container.[10] Together, these findings demonstrate that from a very early age, infants know objects do not blink in and out of existence and they expect that two objects cannot occupy the same space at the same time.

OBJECTS AND COHESION

Infants also have expectations that objects are bounded and cohesive.[13] Evidence of this phenomenon was demonstrated by Kestenbaum et al.[12] Using a habituation task with 3-month olds, they demonstrated that infants detected the boundaries between adjacent objects even when the spatial separation was in depth. Similarly, at 4 months, Needham[14] demonstrated that infants expect separate objects when the boundary between the objects had a distinctly different shape. More recently, Cheries et al.[15] used a crawling task with 10-month-old infants and demonstrated that infants fail to track the cracker quantity when the cracker was broken into two pieces, suggesting that violations of cohesion disrupt infants' object tracking abilities. Together, these findings demonstrate some of the variables that infants use to determine the boundaries of objects. Infants expect single objects to move together, while relative motions specify distinct objects, and turning one object into two violates a fundamental object principle (cohesion), causing a failure in object tracking.

OBJECTS AND PROPERTY CHANGE

Infants also have expectations that objects should not surreptitiously change size, shape, pattern, or color.[4] For example, 6-month-old infants can detect a size change in a cartoon face.[16] In addition, Wilcox[17] has shown that 4.5-month-old infants use both shape and size features to individuate objects, but it is not until 7.5 months that infants use differing surface patterns to infer distinct objects, and not until 11.5 months that differences in color are used for individuation. Further studies have demonstrated that contextual cues can be manipulated to get infants to detect property changes. For example, priming trials where cups of one color are used for pounding and cups of a different color are used for scooping allowed infants to encode color information earlier than 11.5 months.[18] Together, these studies begin to reveal the nature of the mechanism that encodes property information. Through experience, the variables included in representations become elaborated over time. However, there is flexibility in the system demonstrated by how the developmental trajectory can be temporarily altered with priming examples that capture infants' attention and get them to encode specific properties relevant to a particular task.

The articles reviewed thus far converge on three points. First, from an early age infants expect that objects should not pass through one another. Second, infants expect objects should not blink in and out of existence. Third, over the course of development, infants learn to identify relevant properties of objects like shape, texture, and color. In summary, infants have principled expectations about how objects behave and interact.

SUBSTANCES—SOLIDITY AND CONTINUITY

Objects and substances are similar in that neither entity can blink in and out of existence—they both exist continuously through time. However, some of the early descriptions of the continuity principle included descriptions of solidity, in that objects cannot pass through one another.[9] The characteristic of being penetrable is not a violation when it comes to liquids and this constitutes an important distinction between objects and nonsolid substances. For example, if a straw is dropped into a glass containing liquid, the straw should penetrate the surface of the liquid and likely come to rest on the bottom of the glass. There is evidence that infants as young as 5 months of age possess this expectation about liquids[19] (Figure 3(a)). These findings suggest that infants use the movement cues in the initial trials to discriminate a liquid from an object of similar appearance and have different expectations about whether these entities are penetrable.

SUBSTANCES AND COHESION

A second characteristic that distinguishes objects and liquids is cohesion. It is perfectly normal for adjacent points of a liquid to separate and come back together. For example, when rinsing vegetables in a colander, the water comes out of the faucet together in a stream, separates as it goes over the vegetables (i.e., objects) and through the colander, and comes together again in the sink or drain. In contrast, the vegetables remain in the colander because they are cohesive objects and do not pass through the holes in the colander. There

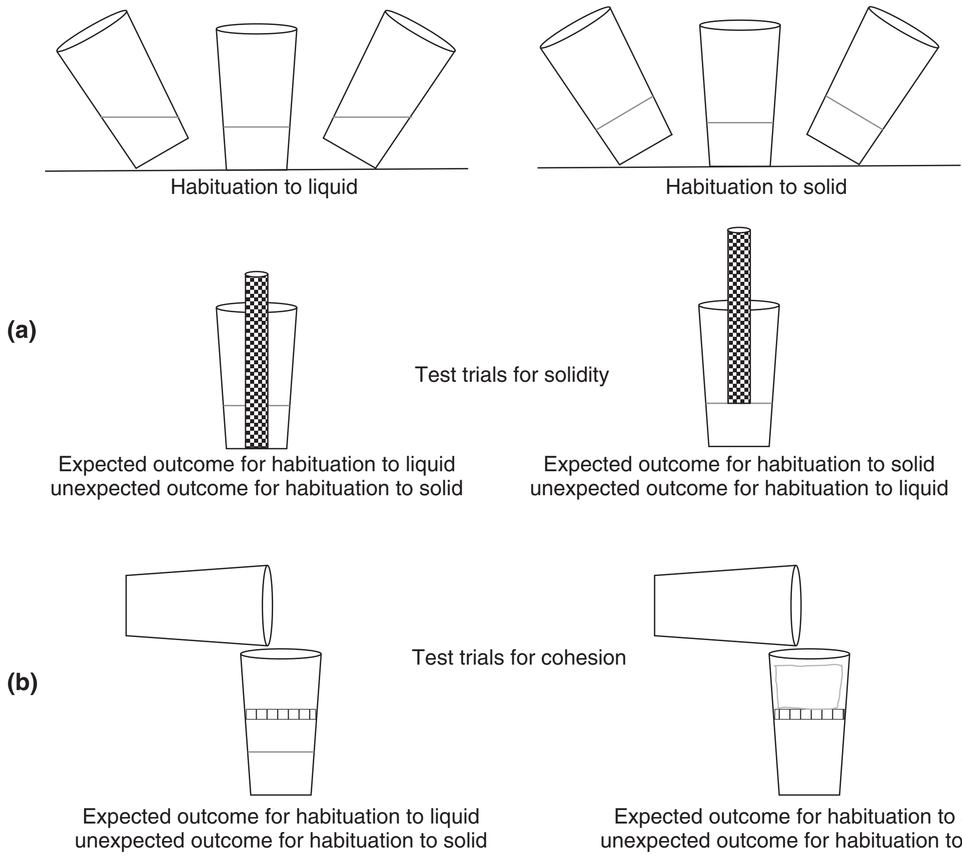

FIGURE 3 | Five-month-old infants were habituated to displays of tall glass containing either liquid or a perceptually identical solid. In both conditions, the glass was tipped back and forth to demonstrate the motion cues of its contents. (a) During the test trials for solidity, all infants received trials that alternated between a checkered pipe being lowered into a glass. On half the trials, the contents of the glass were liquid and the pipe 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 pipe stopped when it came in contact with the surface of the solid. Looking time was measured to the test displays. Infants habituated to the liquid trials looked longer at the solid test trials, while infants habituated to the solid trials looked longer at the liquid test trials. (b) During test trials for cohesion, all infants received trials where the contents transferred between two glasses and one of the glasses had a grid inside it. On half of the trials, the contents of the glass were liquid and it passed through the grid and collected in the bottom of the glass. On the other half of the trials, the contents of the glass were solid and came to rest on top of the grid inside the glass. Looking time was measured to the test displays. Infants habituated to the liquid trials looked longer at the solid test trials and the opposite pattern was found for infants habituated to the solid trials. Adapted from Refs 19 and 20.

is evidence that 5-month-old infants expect liquids to be noncohesive (Figure 3(b)).[20] Again, the infants used the motion cues in the initial trials to discriminate a liquid from an object of similar appearance and had expectations about the noncohesive qualities of liquids. Liquid is probably the most pervasive substance that infants encounter. Current experiments are testing whether these expectations about cohesion generalize to other substances, such as sand. These findings will lend insight into whether the representations are robust and generalize to other substances and viscosities as well as the role of experience in forming infants' expectations about these entities.

SUBSTANCES AND PROPERTY CHANGE

The previous two examples have focused on characteristics that define differences between objects and liquids. However, it remains unclear whether infants can detect property changes for substances in the same way that they do for objects. For example, substances rarely have a consistent shape since they tend to conform to fit their containers, so it is unlikely that infants would detect a shape change for a substance. To the best of our knowledge, there are no studies that examine infants' sensitivity to color or pattern changes for substances.

To summarize the results thus far, infants have principled expectations about objects in terms of solidity, continuity, cohesion, and property changes. Infants also have principled expectations about liquids in terms of penetration and cohesion. Questions remain about infants' expectations about substances and property changes. In addition, the earliest evidence of object knowledge is evident at 2 months of age but the youngest evidence for substance knowledge is 5 months. The studies up to this point have centered on characteristics that distinguish objects and substances. In the next section, we focus on an attribute that is similar for objects and substances, namely infants' ability to quantify objects and substances.

OBJECTS AND QUANTIFICATION

Although substances differ from objects in many ways, one commonality is that both types of entities are quantifiable. People can judge that there is more water in one cup than in another, just as they can judge that there are more cups on one table than on another. Indeed, we know a great deal about young infants' ability to quantify objects. For example, we know that they can represent both the *number* of individuals in a set[21–24] and also the *continuous extent* (temporal or spatial) of those individuals.[16,25–31] Infants can enumerate visual items,[24,32–34] auditory entities,[22,23,35,36] and even actions.[37] For continuous quantities, infants can discriminate visual items differing in surface area[16,30] and contour length,[27,28] as well as tones that differ in duration.[31,38] They are also sensitive to the spatial dimensions (e.g., height) of three-dimensional objects and can use this information to predict possible object relations.[25] In addition, infants utilize their numerical representations not just for discrimination, but also to make ordinal judgments,[39] to compute the results of addition and subtraction operations,[33,40] and to compute and compare the ratios of two numerical values.[41]

Recent research is beginning to shed light on just how infants may be representing number and other quantities. Although there is some debate about the nature of the underlying mechanism(s), there is strong empirical evidence to suggest the existence of two different systems that contribute to infants' ability to represent and compare quantities—an analog magnitude system and an object tracking system. The analog magnitude system is evolutionarily old and is shared by a wide variety of animal species, including human and nonhuman primates, rats, and pigeons, to name a few.[42] It represents quantities as continuous magnitudes, and variability in the representations increases in proportion to the represented quantity. The consequence of this is that discrimination based on analog magnitudes follows Weber's Law: it is the proportionate, rather than the absolute, difference between two values that determines their discriminability. For example, for both adults and infants, it is easier to discriminate 10 from 20 (1:2 ratio), than 20 from 30 (2:3 ratio), even though both pairs differ by exactly 10 units.

This was demonstrated by Xu and Spelke[24] who tested 6-month-old infants' ability to discriminate between different numbers of dots. After being habituated to displays with either 8 or 16 dots, all infants received six test trials alternating between the habituated and the new number of dots (Figure 4). Infants who had been habituated to 8 dots looked longer at the 16-dot test displays, while infants habituated to 16 dots showed the opposite preference at test. However, when the habituation displays contained 8 and 12 dots, infants looked equally at the novel and familiar test displays. Thus, at 6 months of age, infants successfully discriminated sets of dots differing by a 1:2 ratio, but not by a 2:3 ratio. Further studies indicated that performance was indeed based on the ratio of the comparison quantities: infants successfully discriminated 4 from 8, and 16 from

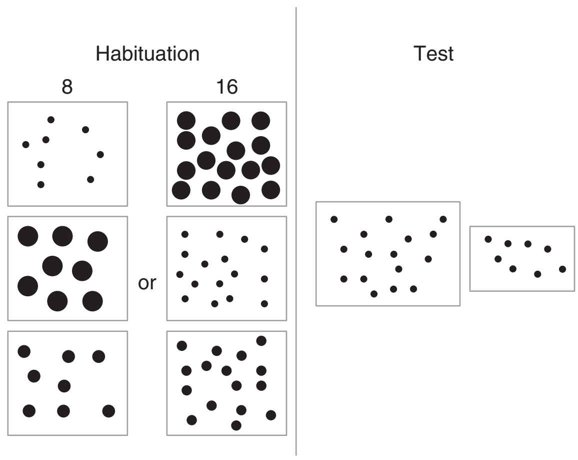

FIGURE 4 | Six-month-old infants were habituated to displays containing either 8 or 16 dots. At test, all infants received test trials in which they saw both 8- and 16-dot displays, on alternating trials. Looking time was measured to the test displays. Infants habituated to 8 dots looked longer on average at the 16-dot test displays, while infants habituated to 16 dots showed the opposite looking pattern. Thus, infants in both habituation groups reliably discriminated 8 from 16 dots (a 1:2 ratio). A separate group of infants tested in the same procedure failed to discriminate 8 from 12 dots (a 2:3 ratio). Note that the displays were controlled for nonnumerical cues that tend to covary with number, such as surface area and density, suggesting that infants' performance reflects genuine sensitivity to numerical quantities. Adapted from Ref 24.

32 dots, but failed to discriminate 4 from 6 and 16 from 24 dots.[24,34,43] The *Weber fraction signature* governs not just infants' discrimination of visual sets, but also auditory sets and continuous quantity dimensions. At 6–7 months of age, infants successfully discriminate numbers of tones that differ by a 1:2 ratio, but not by a 2:3 ratio.[22,23] Importantly, the precision of the representations increases with development such that by 9–10 months of age, infants can discriminate quantities that differ by a 2:3 ratio.[22,44] Such development continues, with precision increasing further during childhood, and finally reaching adult levels where values as near as 9:10 can be discriminated.[45]

A second mechanism, the object tracking system, is also present in young infants and is believed to underlie their ability to track and compare small sets of visual objects.[46,47] The system was originally described in the adult literature on visual attention to explain adults' ability to track a limited number of objects as they move around the world and undergo occlusion.[48,49] (For a video demonstration of this phenomena see http://www.yale.edu/perception/Brian/demos/MOT.html). The mechanism consists of a limited set of indexes that 'point' to objects in the world, and that stick to the objects as they move through space. The signature property of this system is its limited capacity—it can track only as many objects as it has indexes, which in adults seems to be about four.[49] Another signature property of the object tracking system is that the ability to track objects breaks down when there are violations to the continuity or cohesion of objects, but not when objects change their shape or other properties.[15,50–53]

Evidence for the object tracking system in infants comes from work by Feigenson and colleagues in which they hid crackers, one at a time, in two different opaque cups and then let infants choose one of the two cups. If infants could keep track of how many crackers went into each cup, and compare the quantities, they were expected to select the cup with the larger amount. This is exactly what infants did. In this *ordinal choice task*, 10- to 12-month-old infants reliably chose two crackers over one, and three crackers over two, but chose randomly whenever there were more than three crackers in either cup. Thus, they were at chance when the comparison quantities were two versus four and three versus six, and even one versus four, despite the extremely favorable ratio between the quantities.[30,54] This pattern of performance—failure with quantities beyond three—was termed the *set size signature*, and was taken as evidence that infants use a capacity-limited object tracking mechanism to represent and compare the quantities in this task. A similar pattern is also seen in a manual choice task, where 12- and 14-month-old infants watched an experimenter hide some number of objects in an opaque box, watched her retrieve either all or just a subset of the objects, and then were allowed to reach into the box. Whenever the initial set was three or fewer, infants would reach reliably longer when they believed objects remained in the box than when they had seen the experimenter remove the entire set. However, there was no difference in search times when four items had been hidden, regardless of how many the experimenter had retrieved.[47] This set size limit on infants' performance suggests that the object tracking mechanism is limited to representing only sets of three or fewer in infancy.

SUBSTANCES AND QUANTIFICATION

On the basis of this body of findings, infants' quantification abilities appear to be quite broad. They apply to objects, sounds, and events, items presented sequentially and items presented simultaneously, as well as stationary items and moving items. However, in all of these cases, the entities quantified are discrete individuals. Even when representing continuous quantities, such as surface area or duration, the stimuli themselves were individual objects, sounds, or events. But what about substances? Can either of the two mechanisms be used to quantify entities that are inherently nonindividuated? Early research into substance quantification was mixed showing success with liquids and failure with other substances (e.g., sand and Legos). Gao et al.[55] showed 9-month-old infants a transparent container that was one-fourth full of red liquid. The experimenter then hid the container behind a screen and, as the infant watched, poured more liquid into the hidden container. The infants looked significantly longer when the screen was removed if the level of liquid in the original container did not change (i.e., if the container was still one-fourth full) than if it appeared three-fourths full. These findings suggest that infants can detect the change in amount/size of the substance (although vanMarle and Wynn[56] offer an alternative interpretation of these results that does not require knowledge of substances.)

In contrast to Gao et al.[55], there are several studies showing that infants fail to track changes in the size/amount of substances. For example, Huntley-Fenner et al.[57] showed 8-month-old infants a pile of sand, then the pile was concealed behind a screen. Next, they poured a second pile of sand behind a nearby but spatially separated screen. In this situation, adults would expect to see two distinct piles of sand if the screens were taken away. However, infants spent no more time looking at a display containing

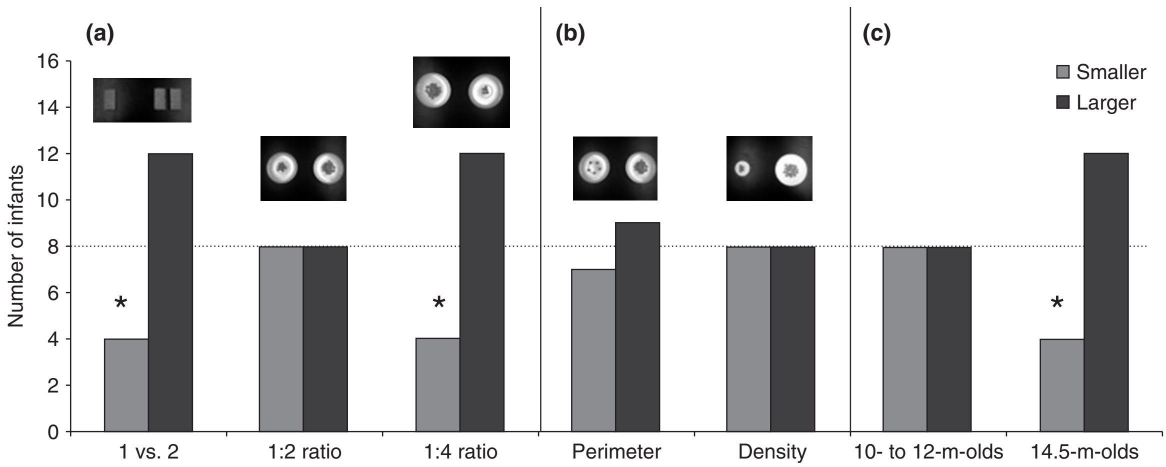

FIGURE 5 | Bars depict the number of infants choosing the larger or smaller amount. Note that all amounts were hidden in cups during the choice period. (a) 10- to 12-month-old infants reliably chose two crackers over one in an object condition, but required a 1:4 ratio in order to choose the greater of two quantities of substance. (b) Infants performed at chance with substance quantities differing by a 1:4 ratio when either perimeter or density was removed as a cue to amount. (c) In a sequential version of the task where the quantities differed by a 1:4 ratio, and in which infants only saw one amount at a time before being hidden, 14.5-month-old infants reliably chose the greater quantity but 10- to 12-month-old infants chose randomly. Adapted from Ref 56.

just one pile (as if one of the piles had magically disappeared), than they did at a display containing two. With similar-looking solid objects, though, infants performed as expected in this paradigm, spending more time looking at the one-object than the two-object display. Similar results were found with piles made up of individual Lego blocks. Infants were able to track cohesive Lego piles in which the whole pile was moved behind the screen at once, but not noncohesive piles in which the pile was decomposed and moved one-block-at-a-time behind the screen. In the former case, they performed the same as with solid objects, in the latter, they failed to discriminate between the one and two pile outcomes.[58] For the sand and Lego studies, continuous quantity (e.g., the summed volume of the objects or sand piles) was a reliable cue in both the object and sand conditions, but apparently, 8-month-old infants did not detect changes in this attribute for substances. Nonetheless, recent research has shown success in infants' quantification of substances.

Research by vanMarle and Wynn[56] using the ordinal choice paradigm showed that by 10 months of age, infants can choose the greater of two quantities of substance. However, their ability to do so was limited compared to their abilities with objects. Whereas infants at 10 months succeeded with quantities of objects differing by a 1:2 ratio, they required a 1:4 ratio to succeed with substances. In addition, they required redundant cues to amount (i.e., perimeter and density) to succeed with substances, and performed at chance when either of these cues was unavailable. Finally, it was not until 14 months of age that infants were able to mentally compare substance quantities. At 12 months, their success was limited to situations in which they could see both quantities simultaneously before they were hidden in the cups (Figure 5).

More recently, there has been converging evidence for substance quantification from younger infants using a looking paradigm. Hespos et al.[59] used a habituation paradigm to test whether infants could discriminate between a single pile of sand poured on a plate from one that was either four times bigger or four times smaller than the quantity that they saw during habituation trials. They found that 3-, 7-, and 10-month-old infants were capable of making the 1:4 ratio distinction. Further experiments using the same setup tested whether infants could discriminate a 1:2 ratio difference in quantity of sand. They revealed that girls detected the change in quantity but boys did not. This sex difference was persistent from 7 to 13 months of age. Taken together with the findings on object quantification, such results suggest that infants can indeed quantify substances, but that doing so taxes the representational mechanism to a greater degree than quantifying objects.

CONCLUSIONS

Infants have detailed knowledge about how objects behave and interact from the first weeks of life. As early as 2 months of age, they have initial concepts about continuity, cohesion, and change properties. While these initial concepts are primitive, there is a wealth of evidence depicting how and when infants elaborate this knowledge through experience with objects in their everyday environment. Recent research also indicates that from at least 5 months of age, infants hold expectations about substances that are distinct from solid objects on key attributes of motion cues, penetration, and cohesion. These findings suggest that infants' knowledge of substances is principled in the same way that their knowledge of objects appears to be. Finally, there is a large literature (only briefly reviewed here) suggesting that from an early age, infants possess quite sophisticated quantity representation abilities. Infants are able to discriminate both discrete and continuous quantities over a wide range of entities, including both objects and substances. The evidence to date demonstrates the existence of two representational mechanisms (the analog magnitude system and the object tracking system), each with different performance signatures, and whose properties echo the themes of ontogenetic continuity and refinement found for object knowledge. By studying the nature of early ontological distinctions we hope to better understand the initial concepts that over time become enriched through experience, and how such knowledge underlies our understanding of everyday physics.

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