Research Article

Psychological Science
2016, Vol. 27(2) 244–256

DOI: 10.1177/0956797615617897
pss.sagepub.com

Five-Month-Old Infants Have General Knowledge of How Nonsolid Substances Behave and Interact

Susan J. Hespos[1], Alissa L. Ferry[2], Erin M. Anderson[1], Emily N. Hollenbeck[1], and Lance J. Rips[1]
[1]Psychology Department, Northwestern University, and [2]Cognitive Neuroscience Sector, International School for Advanced Studies (SISSA)

Abstract
Experience puts people in touch with nonsolid substances, such as water, blood, and milk, which are crucial to survival. People must be able to understand the behavior of these substances and to differentiate their properties from those of solid objects. We investigated whether infants represent nonsolid substances as a conceptual category distinct from solid objects on the basis of differences in cohesiveness. Experiment 1 established that infants can distinguish water from a perceptually matched solid and can correctly predict whether the item will pass through or be trapped by a grid. Experiments 2 and 3 showed that infants extend this knowledge to less familiar granular substances. These experiments indicate that concepts of cohesive and noncohesive material appear early in development, apply across several types of nonsolid substances, and may serve as the basis of later knowledge of physical phases.

Keywords
cognitive development, infant development

Received 5/21/15; Revision accepted 10/28/15

Research on object knowledge in infancy has transformed the understanding of the origins of cognition. Traditionally, infants were believed to perceive a sensory flux of properties with no stable physical objects—shapes and colors, but no cats or cups. However, more recent research has revealed that infants have sophisticated expectations about the physical properties of objects early in development (Baillargeon et al., 2012; Spelke, Breinlinger, Macomber, & Jacobson, 1992; Wynn, 1992). What is missing from this picture is an understanding of infants' knowledge about nonobject kinds, like liquids or sand, whose physical properties are distinct from those of objects. Kinds like these play a key role in the lives of humans and other animals because of their importance in nutrition (e.g., water, milk, and juice), bodily functions (e.g., blood and cerebrospinal fluid), and transportation (e.g., in air and in water). Studies of infants' expectations about substances[1] could contribute to a more comprehensive theory of cognitive development that characterizes conceptual capacities common to everyone. Discovering the characteristics of these initial concepts will lead to a better understanding about how cultural and linguistic experiences change, and are changed by, the way people think (Li, Dunham, & Carey, 2009).

Adults react differently in encounters with fluid substances than in encounters with discrete objects. The consequences of dropping a bowl of soup on the floor are quite different from those of dropping a bowl of oranges. How and when do infants develop distinct expectations for the behavior of substances like liquid and sand and the behavior of objects? Previous research has revealed that initial concepts of objects are available in the first months of life, and the developmental trajectory underlying knowledge of physical objects is well documented (Baillargeon et al., 2012). But the trajectory of substance knowledge is not clear. To address this gap, we tested whether infants have principled knowledge

Corresponding Author:
Susan J. Hespos, Department of Psychology, Northwestern University, 2029 Sheridan Rd., Evanston, IL 60208
E-mail: hespos@northwestern.edu

about substances in general and can make predictions about the behavior of a range of different substances.

Infants have extensive experience with substances at mealtime, bath time, and other times, and this exposure begins early in development (Bourgeois, Khawar, Neal, & Lockman, 2005; Hespos, Dora, Rips, & Christie, 2012; Perry, Samuelson, & Burdinie, 2014; Rips & Hespos, 2015). But most research concerning infants' concepts of substances has focused on infants' success with objects and failures with substances in comparable situations (Cheries, Mitroff, Wynn, & Scholl, 2008; Chiang & Wynn, 2000; Huntley-Fenner, Carey, & Solimando, 2002; Rosenberg & Carey, 2009; Shutts, Condry, Santos, & Spelke, 2009). Together, these studies have been interpreted as providing evidence that infants' expectations about objects are principled in a way that their expectations about substances are not. We propose instead that infants have a set of principles attuned to substances that help them predict substances' distinctive properties and attendant behavior. Initial evidence supporting this view came from a study showing that 5-month-old infants used motion cues from a liquid or an object contained in a cup to predict whether the contents would pour or tumble when the cup was upended. The same motion cues also led infants to predict that the top surface of the liquid was penetrable but the top surface of the object was not (Hespos, Ferry, & Rips, 2009). Thus, infants appear to know some typical properties of liquids, including their flow and permeability.

The crucial structures underlying substances' distinctive properties are the loose physical bonds among their parts. Loose bonds allow substances to pass through barriers in a way that is impossible for cohesive objects, whose tight bonds keep their parts rigidly in place.[2] Most people probably do not know the physical chemistry responsible for these facts, but they may nevertheless have an intuitive notion of loose bonding that provides a general concept of what a substance is and allows them to describe the behavior of substances (Bates, Yildirim, Tenenbaum, & Battaglia, 2015). People understand, for example, that when a pan of boiling vegetables is poured into a colander, the water will flow through but leave the vegetables behind. In the experiments we report here, we tested whether an intuitive loose-bonding principle leads 5-month-old infants to have different expectations about substances and objects.

Earlier research on substances focused on one substance at a time—for example, water (e.g., Hespos, Ferry, & Rips, 2009) or Cheerios (vanMarle & Wynn, 2011). In the present research, we asked whether infants' expectations about substances generalize across very different types of nonsolids, not all of which were familiar. Prior results can be explained by the theory that infants recognize solid objects as a special class but treat substances merely as residual nonobjects. For example, infants might learn the properties of water as they encounter it in the bath and learn the properties of Cheerios as they encounter them at breakfast, without recognizing the commonalities of water and Cheerios. By looking at a range of substances that differ in their granularity and other properties, and by using the same tasks for all these substances, we investigated whether substance concepts are principled and organized as a domain, as is infants' knowledge about objects.

Experiment 1: Infants' Knowledge of Liquids

In Experiment 1, we tested whether 5-month-old infants have expectations about the loose-bondedness of liquids. Infants were habituated to motion events that revealed either that the contents of a cup were liquid (for half the infants) or that the contents were solid (for the other half; see the top panel in Fig. 1). After habituation, the infants saw two test events (one with the solid and one with the liquid) in alternation, and the time they spent looking at these events was the dependent measure.

Infants in the pouring condition saw two glasses, one with a grid glued inside. One test trial in this condition showed a liquid being transferred back and forth between the glasses, and the other test trial showed a solid being transferred between the glasses (see the bottom left panel in Fig. 1). In this condition, the motion cues of the liquid during habituation were perceptually similar to those of the liquid during the test. This similarity of motion could potentially affect looking times. Consequently, in the straw condition, we tested whether habituation would cause infants to form expectations about the permeability of the substance, as similarity of motion between the habituation and test trials was not a valid cue to permeability. During the test, infants in the straw condition saw a single glass and a straw with a grid on the end. The test trials alternated between (a) the straw with the grid being lowered inside the glass and through a liquid and (b) the straw with the grid being lowered inside the glass and coming to rest on top of a perceptually identical solid (see the bottom right panel in Fig. 1).

Method

Participants. The participants in Experiment 1 were 62 healthy, full-term infants (27 female, 35 male), ranging in age from 4 months 7 days to 5 months 28 days (M = 5 months 1 day). Thirty-two infants were assigned to the pouring condition, and 30 were assigned to the straw condition. Within each of these conditions, half the infants were habituated to the liquid; the rest were habituated to the solid. Nine additional infants were tested but

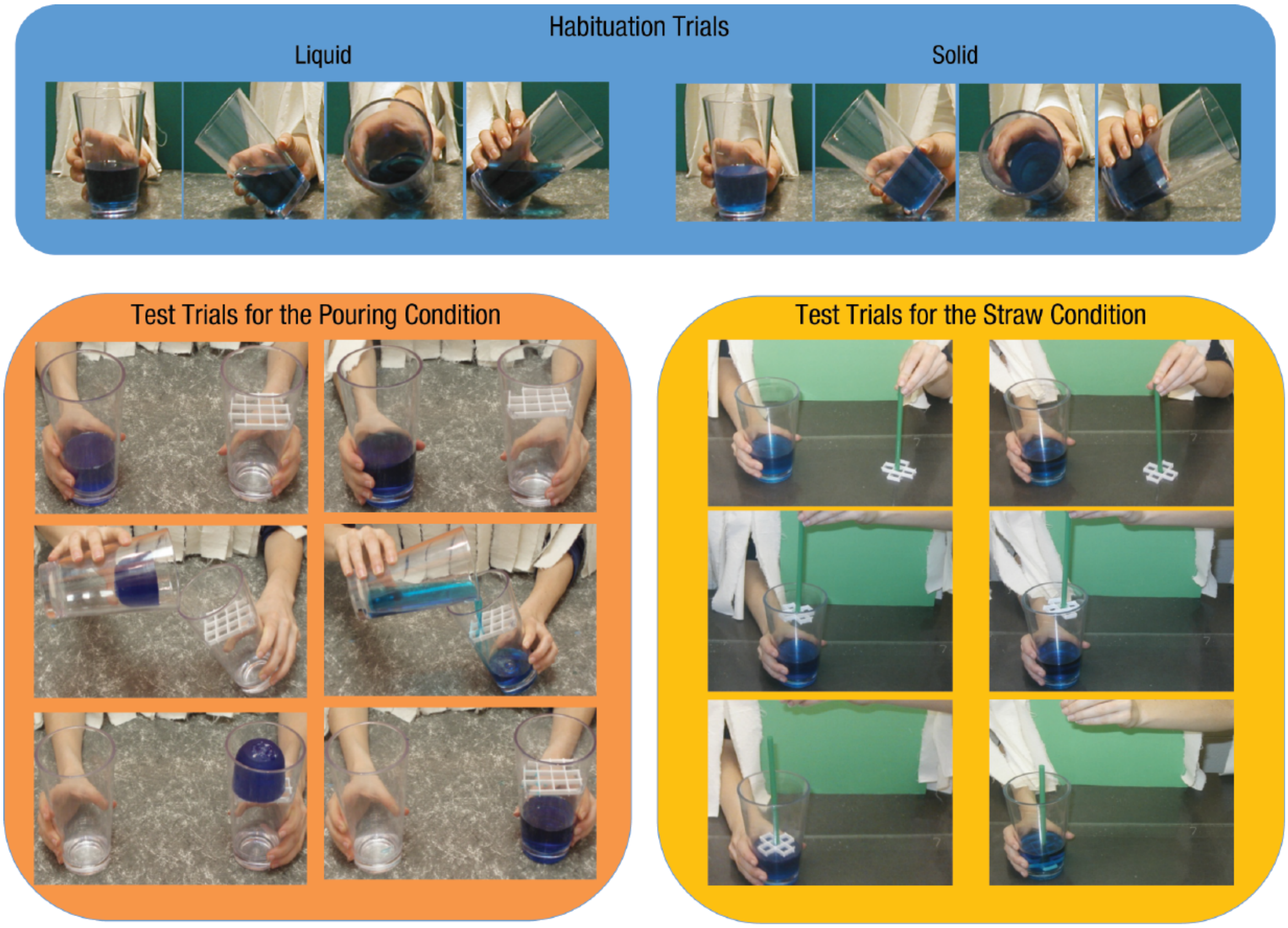

Fig. 1. Illustration of the habituation and test trials in Experiment 1. Each infant saw either the liquid or the solid habituation trials, during which the experimenter rotated a glass so that the movement of the contents could be observed (top panel). After habituation, infants who were in the pouring condition (bottom left panel) saw test trials in which the experimenter tipped a glass to pour its contents, either a liquid or a solid, into another glass containing a grid. Infants who were in the straw condition (bottom right panel) saw test trials in which a straw glued to a grid was placed inside a glass containing either a solid or a liquid. In both conditions, liquid and solid test trials were presented in alternation.

eliminated from the final analysis: 3 because they were fussy (i.e., two independent coders rated them as crying or fussy on more than four trials), 3 because they were inattentive during the test trials (i.e., at least half the test trials were less than 5 s long, which meant that the infants did not see the grid interact with the contents of the glass), 2 because they had bowel movements during the experiment, and 1 because he looked for the maximum amount of time allowed on every trial. We decided a priori to test 16 infants per condition-habituation combination, as in previous research investigating substance and object knowledge with the same methodology and age group (Hespos, Ferry, & Rips, 2009). (For further details about the participant population, stimuli, and apparatus, see the Supplemental Material available online.)

Events. During the habituation trials, infants viewed the experimenter rotating a glass that contained either liquid or solid contents (Fig. 1, top panel). In the pouring condition, when the screen went up at the start of a habituation trial, two glasses were on the stage: One was empty except for a grid, and the other had either blue liquid or a blue solid in it. The experimenter's hand grasped the glass with the blue liquid or solid, tilted it to the left (1 s), and in a smooth motion rolled the glass on the rim of its base over a 5-s count. Next, the glass was returned to the upright position (1 s); this action was followed by a pause (1 s). This 8-s cycle was repeated continuously until the trial ended (see the Procedure section). The glass containing the grid remained on the stage but was not used during the habituation phase. Infants who were habituated to a liquid saw trials in which the rotated glass contained blue liquid; hence they saw the corresponding motion of the liquid as the glass moved. Infants who were habituated to a solid saw trials in which the rotated glass contained the blue solid in the bottom and, consequently, saw no movement of the solid relative to the glass during the rotation. The habituation trials in the straw condition were identical to those in the pouring condition except that the glass with a grid was replaced with a green straw attached to a grid.

Solid and liquid test trials were presented in alternation to all participants. For infants in the pouring condition (Fig. 1, bottom left panel), the same two transparent glasses as in the habituation phase were on the stage when the screen went up. On solid trials, the experimenter grasped both glasses (1 s) and tilted them toward each other (1 s), until the solid tumbled from one glass to the grid in the other glass (6 s). The glasses were then returned to their initial positions (1 s), and there was a brief pause (1 s). The solid was transferred back and forth between the glasses until the trial ended (see the Procedure section). On liquid trials, the sequence of events was the same, but the solid was replaced by a liquid, which was poured back and forth between the glasses.

For infants in the straw condition (Fig. 1, bottom right panel), the transparent glass and the straw-grid combination from the habituation phase were on the stage when the screen went up in the test trials. The experimenter held the glass in one hand and the top of the straw in the other. The experimenter raised the straw vertically (1 s), moved it horizontally until it was over the glass (1 s), and then let go of the straw inside the glass. On solid trials, the straw and grid came in contact with the top surface of the solid, and on liquid trials, the bottom portion of the straw and grid became submerged in the liquid (3 s). Then the motions were reversed: The straw was lifted vertically until it was above the glass (2 s), moved horizontally until it was over the initial position (1 s), and lowered until its bottom rested on the stage floor (1 s), where it remained for a pause (1 s). The main difference between the solid and liquid test trials was that the grid came to rest on the top surface of the solid but passed through the liquid to reach the bottom of the glass (so that the straw was partially submerged in the liquid).

Procedure. During the experiment, infants sat on their parent's lap in front of the apparatus. Parents were asked to refrain from interacting with the infants during the experiment and to close their eyes during the test trials. A small hole in the front face of the stage contained a camera that captured a video image of the infant's face. Two research assistants in a separate room viewed this live recording. Each researcher depressed a computer button when the infant attended to the events on stage and released the button when the infant looked away. Each trial ended when the infant either looked away for 2 consecutive seconds after having looked for at least 2 s or looked for 60 cumulative seconds without looking away for 2 consecutive seconds. A computer determined the end of the trial and signaled the experimenter to lower the screen. Xhab software (Pinto, 1996) recorded looking times and calculated when the habituation criteria had been met.

Infants first viewed a series of habituation trials until they met the habituation criterion, a decline of at least 50% in total looking duration from the first three to the last three habituation trials (or a maximum of nine trials). On average, the infants reached this criterion in seven trials. Each infant then viewed three liquid and three solid test trials, in alternation. The type of test event shown first was counterbalanced across infants.

Interobserver agreement was determined for looking durations for all infants and averaged 94%.

Results

Figures 2 and 3 summarize the looking times on the habituation and test trials for the pouring and straw conditions. For each infant, we calculated mean looking times for novel test events (solid test trials if the infant was habituated to the liquid, liquid test trials if the infant was habituated to the solid) and familiar test events (liquid test trials if the infant was habituated to the liquid, solid test trials if the infant was habituated to the solid). Fifty-four of the 62 infants looked longer at the novel test events than at the familiar test events ($p < .001$, binomial comparison). Across all participants, the average looking times were 36.36 s (SD = 17.84) for novel test events and 27.08 s (SD = 15.93) for familiar test events. Preliminary analysis revealed no significant effect of sex or test-trial order on the infants' looking times; we therefore collapsed across these variables in all further analyses.

A repeated measures analysis of variance (ANOVA) with between-subjects factors of condition (pouring vs. straw) and habituation (liquid vs. solid) and the within-subjects factor of test event (novel vs. familiar) revealed a significant main effect of test event, $F(1, 58) = 58.09$, $p < .001$, $\eta_p^2 = .50$, confirming that the infants looked longer at the novel than at the familiar test events. Across the experiment, the mean difference in looking time between the novel and familiar test events was 9.29 s (SD = 10.02), 95% confidence interval (CI) = [6.74, 11.80]. In addition, there was a significant interaction between test event and habituation, $F(1, 58) = 5.66$, $p = .021$, $\eta_p^2 = .09$: Both infants habituated to the liquid and those habituated to the solid looked longer at novel events than at familiar events, but this effect was larger for those who were habituated to the solid. Infants who were habituated to the liquid looked an average of 6.45 s (SD = 8.56), 95% CI = [3.42, 9.49] longer at the novel events than at the familiar events, whereas infants habituated to the solid looked an average of 12.51 s (SD = 10.71) longer at the novel events than at the familiar events, 95% CI = [8.44, 16.59]. Although we did not predict this effect, infants

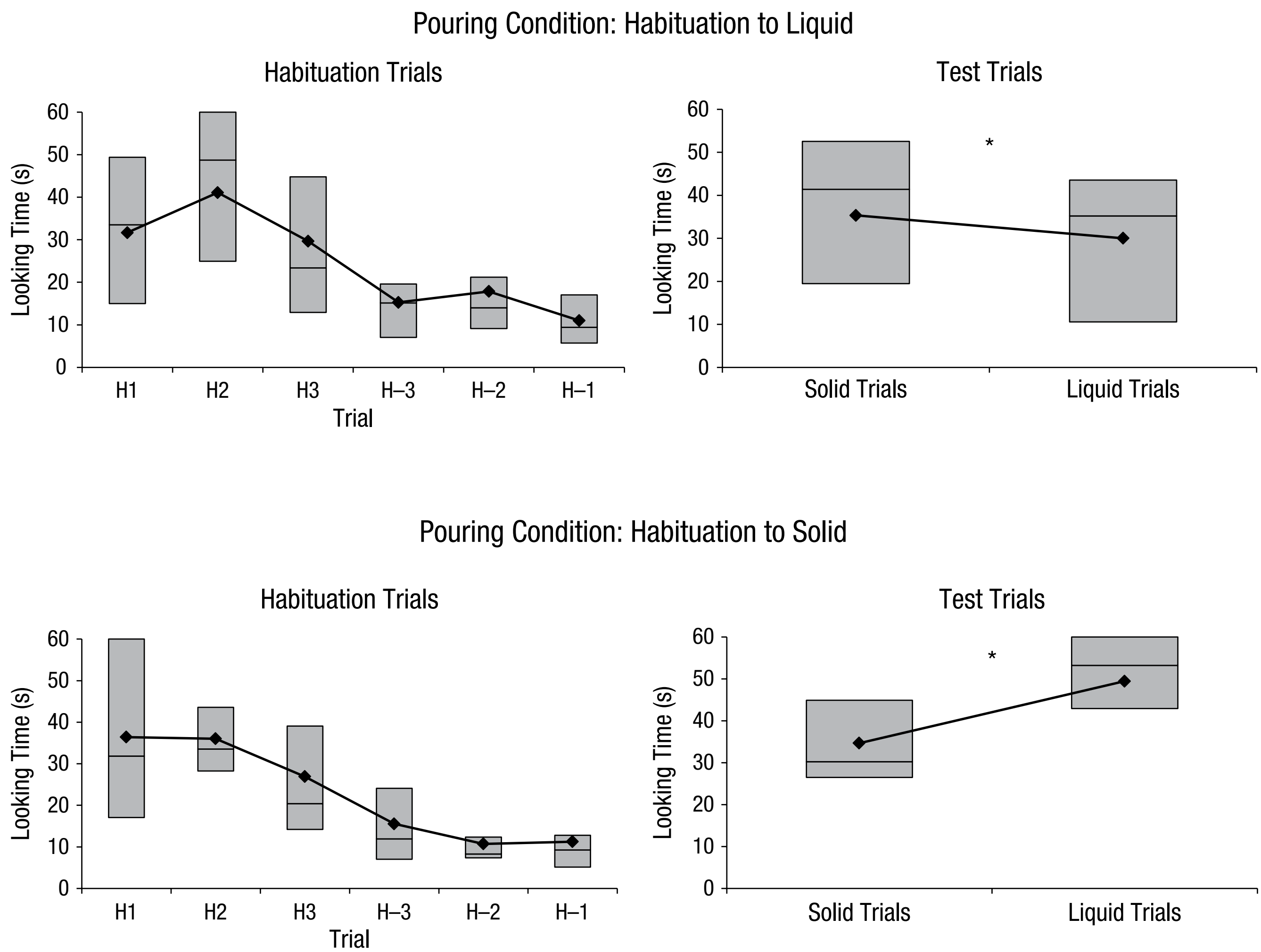

Fig. 2. Box plots of looking times during the habituation and test trials in the pouring condition in Experiment 1. Results are shown separately for infants habituated to the liquid and those habituated to the solid. For habituation, the graphs show results for the first three trials (H1, H2, H3) and the last three trials before the habituation criterion was met (H–3, H–2, H–1). Results for the liquid and solid test trials are shown separately. Black diamonds represent means, the central line in each box is the median, and the upper and lower portions of each box represent the third and first quartiles, respectively. Asterisks indicate significant differences between solid and liquid test trials ($p < .05$).

may have firmer expectations about a solid's behavior than about a liquid's behavior, and thus the infants in our experiment may have been more surprised by the solid-to-liquid shift than by the reverse shift. The analysis also revealed a significant main effect of condition, $F(1, 58) = 9.92$, $p < .003$, $\eta_p^2 = .15$; infants in the pouring condition looked longer at test trials overall than did infants in the straw condition. The transfer of the liquid or the solid between the glasses was apparently more interesting to the infants than was the movement of the straw into the glass, perhaps because of the broader spatial sweep of the transfer.

We also ran separate analyses to see whether the novelty preference occurred within each combination of condition (pouring vs. straw) and habituation (liquid vs. solid; see Figs. 2 and 3). In all four cases, the infants looked longer at the novel than at the familiar events ($p < .025$ for all binomial comparisons; $F(1, 15)$s > 7.5, ps $< .016$). Infants habituated to the liquid looked longer at the novel than at the familiar test events by an average of 5.48 s ($SD = 5.01$, 95% CI = [2.8, 8.15]) in the pouring condition and 7.37 s ($SD = 11.00$, 95% CI = [1.72, 13.03]) in the straw condition. Infants habituated to the solid looked longer at the novel than at the familiar test events by an average of 14.77 s ($SD = 8.68$, 95% CI = [10.15, 19.40]) in the pouring condition and 9.74 s ($SD = 12.58$, 95% CI = [2.13, 17.34]) in the straw condition.

Next, we compared the learning curves of the infants who were habituated to the liquid and those who were habituated to the solid (see Figs. 2 and 3). If infants had no knowledge of substances, these learning curves would likely differ. Analyses revealed, however, that there was no difference in the number of trials to meet the habituation criterion (habituation to liquid: $M = 7.34$; habituation

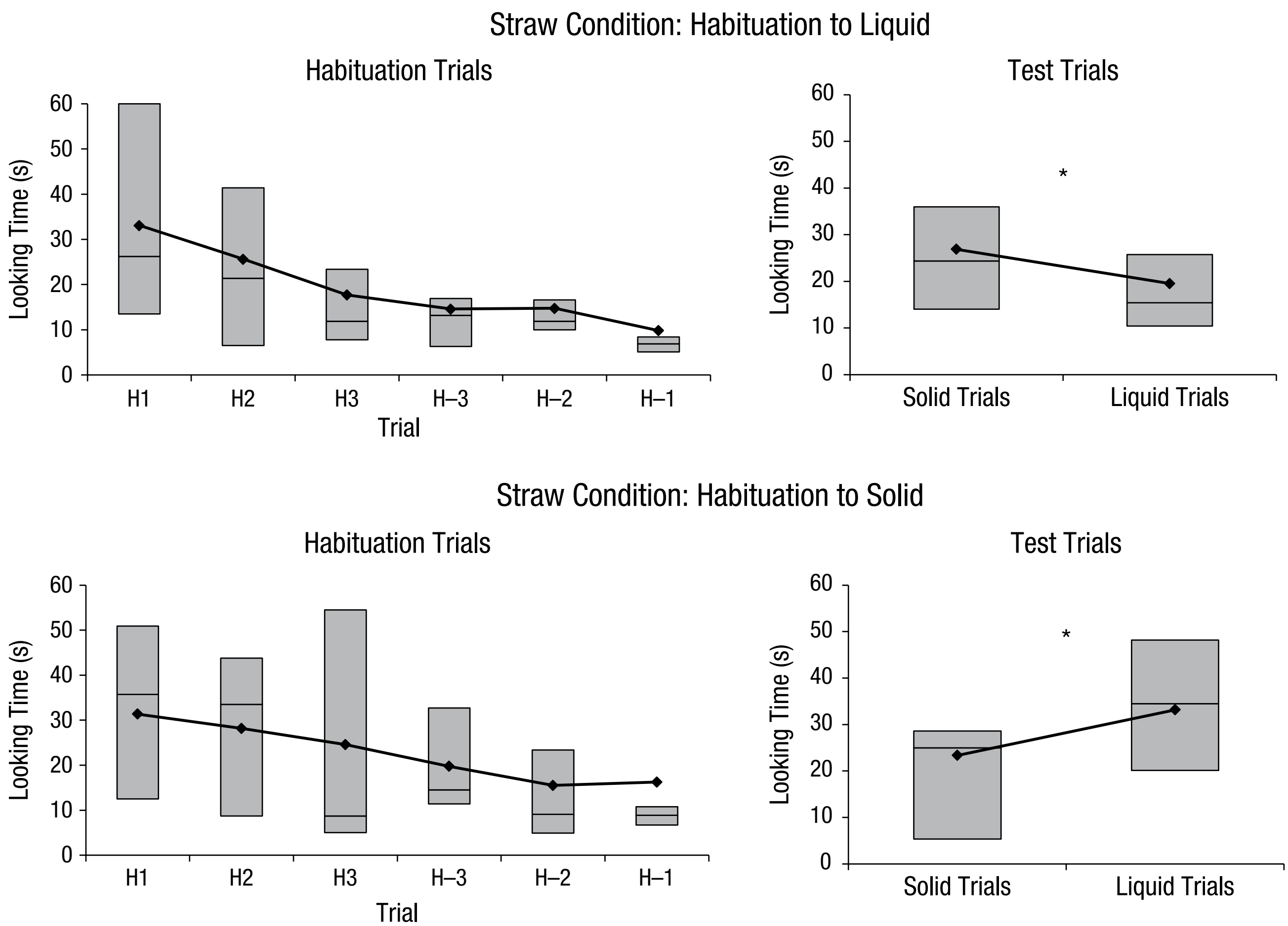

Fig. 3. Box plots of looking times during the habituation and test trials in the straw condition in Experiment 1. Results are shown separately for infants habituated to the liquid and those habituated to the solid. For habituation, the graphs show results for the first three trials (H1, H2, H3) and the last three trials before the habituation criterion was met (H–3, H–2, H–1). Results for the liquid and solid test trials are shown separately. Black diamonds represent means, the central line in each box is the median, and the upper and lower portions of each box represent the third and first quartiles, respectively. Asterisks indicate significant differences between solid and liquid test trials ($p < .05$).

to solid: $M = 7.27$; range = 6–9), $F(1, 60) < 1$, $p = .95$, or in the amount of looking time that the infants accumulated during habituation (habituation to liquid: $M = 157.44$ s, $SD = 63.75$; habituation to solid: $M = 175.77$ s, $SD = 94.13$), $F(1, 60) < 1$, $p = .37$. In sum, we found no evidence that there were any differences in the learning curves for habituation to the liquid and habituation to the solid. Although results for the test trials suggest that infants are more surprised when their expectations about solids are not met than when their expectations about liquids are not met, this is apparently not because of differences in their ability to encode these entities during habituation.

Discussion

These results provide clear evidence that the infants detected a state change from a solid to a liquid and from a liquid to a solid. We started our investigation by focusing on liquid because it is ubiquitous. It is as yet unclear whether infants' knowledge about substances is limited to those they have encountered, for example, in drinking and bathing. Of course, the infant participants in this study probably had not encountered the kind of blue water that we used as a stimulus, so our findings indicate that they were able to generalize beyond their immediate experience. But we wanted to know how far this generalization spreads. In the next experiment, we presented infants with a less common substance to test whether infants' expectations about liquids generalize to nonsolid substances generally.

Experiment 2: Infants' Knowledge of Granular Substances

In Experiment 2, we tested whether 5-month-old infants would understand the loose-bondedness of red sand.

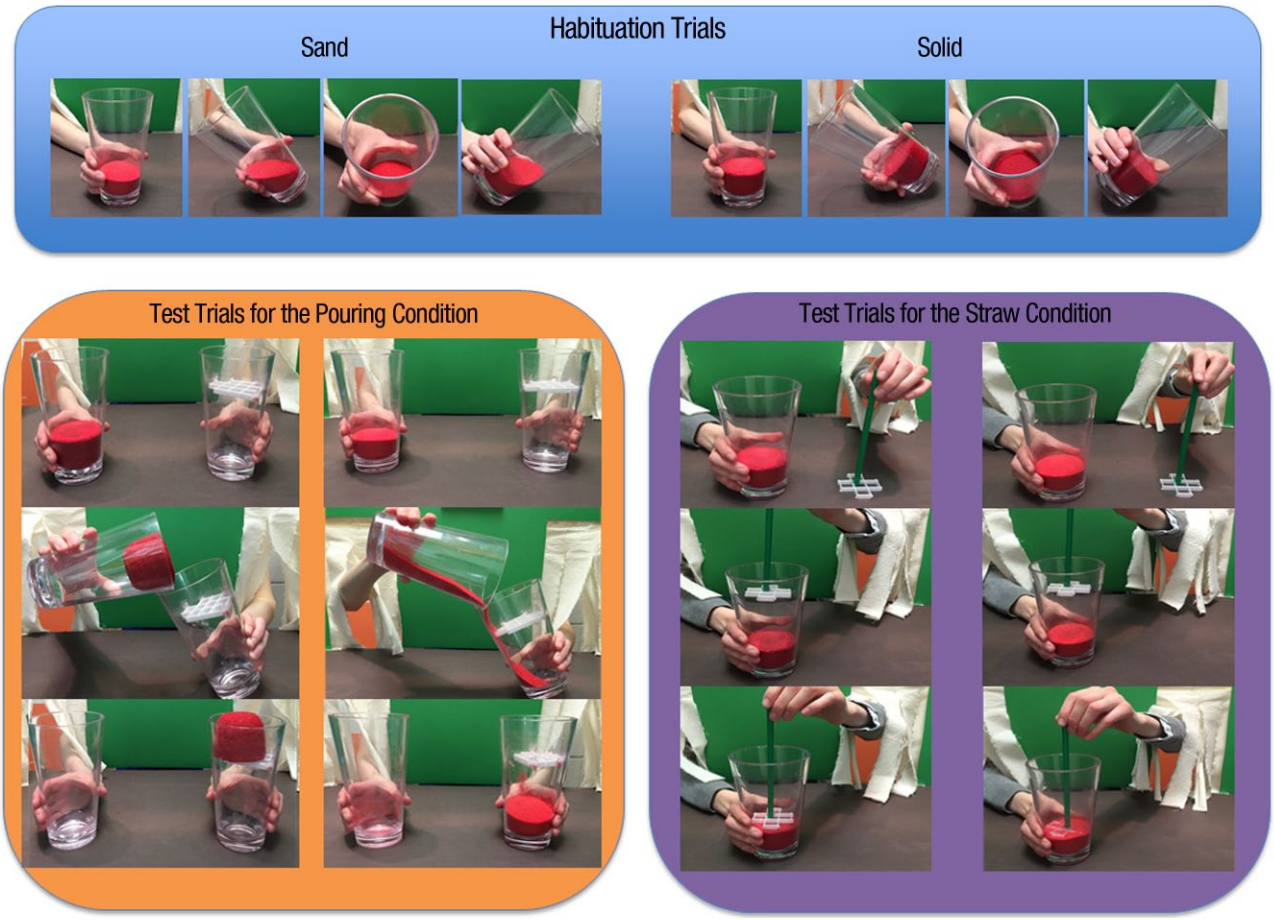

Fig. 4. Illustration of the habituation and test trials in Experiment 2. Each infant saw either the sand or the solid habituation trials, during which the experimenter rotated the glass so that the movement of the contents could be observed (top panel). After habituation, infants who were in the pouring condition (bottom left panel) saw test trials in which the experimenter tipped a glass to pour its contents, either sand or the sand solid, into another glass containing a grid. Infants who were in the straw condition (bottom right panel) saw test trials in which a straw glued to a grid was placed inside a glass containing either the solid or the sand. In both conditions, liquid and solid test trials were presented in alternation.

The conditions were identical to those in Experiment 1 except that we used this new substance and a new solid (see Fig. 4). Specifically, to control as far as possible for differences in properties other than those intrinsic to sand, we contrasted the sand with a solid "sand solid," created by gluing together sand of an equivalent quantity and quality. (For further details about the sand and sand solid, see the Supplemental Material.)

Method

Participants. The participants in Experiment 2 were 63 healthy, full-term infants (20 female, 43 male) ranging in age from 4 months 16 days to 5 months 24 days (M = 5 months 1 day). Thirty-two infants were assigned to the pouring condition, and 31 were assigned to the straw condition. Within each of these conditions, half the infants were habituated to the sand; the rest were habituated to the solid. Twelve additional infants were tested but eliminated from the final analysis: 6 became fussy, 1 was inattentive, and 5 had bowel movements during the experiment. As in Experiment 1, we decided a priori to test 16 infants per condition.

Procedure. The procedure was identical to that in Experiment 1. On average, the infants reached the habituation criterion in seven trials. Interobserver agreement was determined for all infants' looking durations and averaged 93%.

Results

Figures 5 and 6 summarize the looking times on the habituation and test trials for the pouring and straw conditions. Forty-three of the 63 infants looked longer at the novel test events (the sand solid for infants habituated to

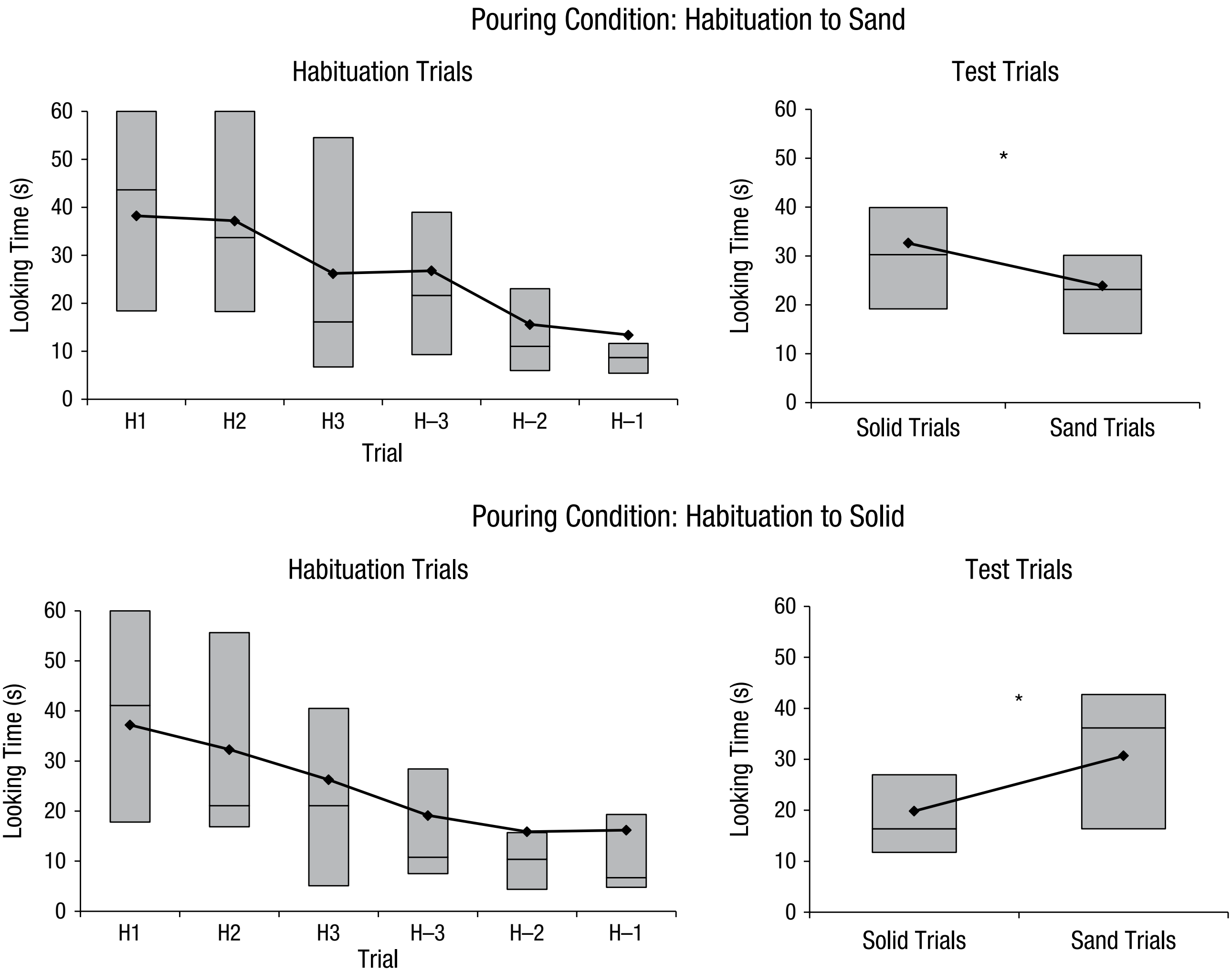

Fig. 5. Box plots of looking times during the habituation and test trials in the pouring condition in Experiment 2. Results are shown separately for infants habituated to the loose sand and those habituated to the sand solid. For habituation, the graphs show results for the first three trials (H1, H2, H3) and the last three trials before the habituation criterion was met (H–3, H–2, H–1). Results for the sand and solid test trials are shown separately. Black diamonds represent means, the central line in each box is the median, and the upper and lower portions of each box represent the third and first quartiles, respectively. Asterisks indicate significant differences between solid and sand test trials ($p < .05$).

the loose sand and the loose sand for infants habituated to the sand solid) than at the familiar test events ($p = .005$, binomial comparison). Across all participants, the average looking times were 29.27 s (SD = 15.97) for novel events and 23.44 s (SD = 13.72) for familiar events. An ANOVA with between-subjects factors of condition (pouring vs. straw) and habituation (sand vs. solid) and the within-subjects factor of test event (novel vs. familiar) revealed a significant main effect of test event, $F(1, 59) = 12.99$, $p = .001$, $\eta_p^2 = .18$, confirming that the infants looked longer at the novel than at the familiar events. Across the experiment, the mean difference in looking time between the novel and familiar events was 5.83 s (SD = 13.09, 95% CI = [2.54, 9.13]). In addition, there was a significant interaction between test event and condition, $F(1, 59) = 6.21$, $p = .015$, $\eta_p^2 = .10$. The difference between looking times for novel and familiar test events was larger for infants in the pouring condition than for infants in the straw condition. Preliminary analysis revealed no significant effect of sex or test-trial order on the infants' looking times; we therefore collapsed across these variables in subsequent analyses.

To parse this interaction, we ran a separate analysis for each condition. In the pouring condition, there was a significant main effect of test event, $F(1, 31) = 17.68$, $p < .001$, $\eta_p^2 = .36$. Infants in this condition looked 9.74 s longer at the novel test events than at the familiar test events (SD = 13.11, 95% CI = [5.02, 14.47]). However, the main effect of test event was not significant in the straw condition, $F(1, 30) < 1$. Infants in this condition looked an average of 1.80 s longer at the novel events than at the familiar events (SD = 11.98, 95% CI = [−2.60, 6.19]).

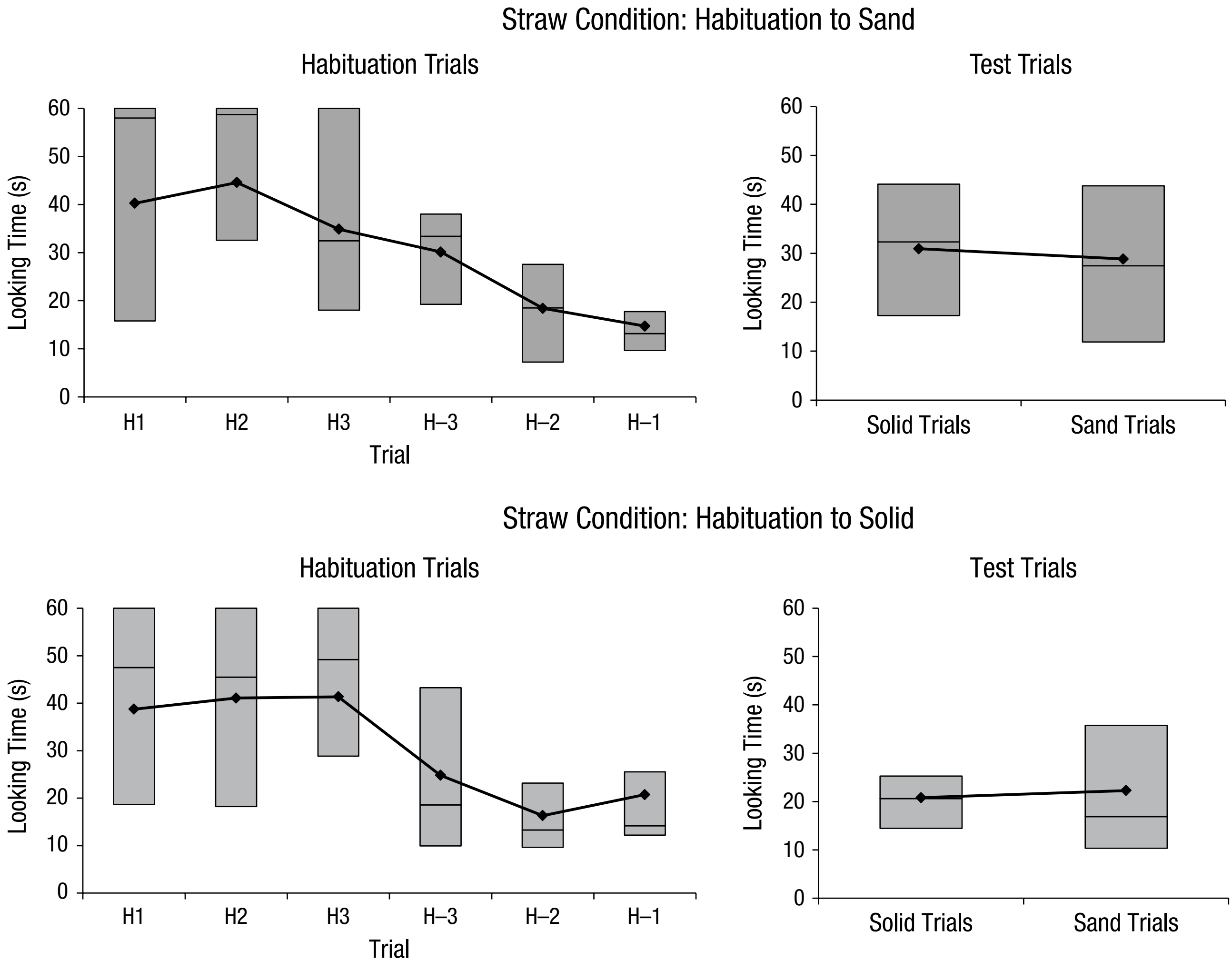

Fig. 6. Box plots of looking times during the habituation and test trials in the straw condition in Experiment 2. Results are shown separately for infants habituated to the loose sand and those habituated to the sand solid. For habituation, the graphs show results for the first three trials (H1, H2, H3) and the last three trials before the habituation criterion was met (H–3, H–2, H–1). Results for the sand and solid test trials are shown separately. Black diamonds represent means, the central line in each box is the median, and the upper and lower portions of each box represent the third and first quartiles, respectively.

Finally, we compared the learning curves in for habituation to the loose sand and habituation to the sand solid. There was no difference in the number of trials to meet the habituation criterion (habituation to loose sand: M = 7.64; habituation to sand solid: M = 7.13; range = 6–9), $F(1, 61) = 2.07$, $p = .16$, or in the amount of looking time that the infants accumulated during habituation (habituation to loose sand: M = 222.72 s, SD = 120.31; habituation to sand solid: M = 206.53 s, SD = 122.27), $F(1, 60) < 1$, $p = .60$.

Discussion

These results indicate that the infants detected the state change from a solid to sand or from sand to a solid. This effect was strong in the pouring condition but not in the straw condition. One methodological explanation for the small novelty preference in the straw condition is that when the grid was below the surface of the sand, it was hidden from the participants' view because of the sand's opacity. In contrast, the grid submerged in water was still visible in Experiment 1, and in fact was even magnified. For infants, tests of the same capacity often yield different results depending on whether the procedure demands memory for something that has been occluded (Hespos, Gredeback, von Hofsten, & Spelke, 2009; Munakata, McClelland, Johnson, & Siegler, 1997; Shinskey, Bogartz, & Poirier, 2000; Shinskey & Munakata, 2001); infants show increased difficulty when tasks require them to maintain representations of occluded items.

Experiment 3: Infants' Knowledge of Transparent Granules

Infants in Experiment 1 reacted differently when a grid attached to a straw was submerged in liquid than when it remained on top of a solid, but infants in Experiment 2 showed no such difference when we substituted sand for the liquid. To test the hypothesis that this difference in performance was due to the sand occluding the straw, we ran an additional straw condition in which the red sand was replaced with small glass spheres. This had the advantage of maintaining the granular qualities of sand but conferred the perceptual advantage of transparency that was present in Experiment 1.

Method

Participants. The participants were 16 healthy, full-term infants (8 female, 8 male) ranging in age from 4 months 15 days to 5 months 19 days (*M* = 5 months 3 days). Nine infants were habituated to the loose glass balls, and 7 infants were habituated to a solid (see the next section). Three additional infants were tested but eliminated from the final analysis: 1 became fussy, 1 had a bowel movement during the experiment, and 1 looked the maximum amount of time on every trial. We decided a priori to test a total of 16 infants because the point of this last experiment was to focus on the straw condition and use a transparent granular substance.

Procedure. The procedure was identical to that of the straw condition in Experiment 2 except that the red sand was replaced with 5-mm glass balls, the solid (taking the place of the sand solid of Experiment 2) was made by gluing together the same volume of glass balls, and the grid was painted red to enhance its visibility when submerged in the loose balls. On average, the infants reached the habituation criterion in seven trials. Interobserver agreement for looking times was 94%.

Results

Figure 7 summarizes the looking times on the habituation and test trials. Twelve of the 16 infants looked longer at the novel test events than at the familiar ones (p = .035, binomial comparison, one-tailed). The average looking times were 37.85 s (SD = 20.79) for novel test events and 29.98 s (SD = 19.67) for familiar test events. Preliminary analysis revealed no significant effect of test-trial order on the infants' looking times. However, there was a main effect of sex, $F(1, 12) = 5.87$, $p = .032$; on average, females looked longer at the test events than males did. Given that sex did not interact with test event, we collapsed across test-trial order and sex in subsequent analyses. An ANOVA with the between-subjects factor of habituation (balls vs. solid) and the within-subjects factor of test event (novel vs. familiar) revealed a significant main effect of test event, $F(1, 14) = 6.19$, $p = .026$, $\eta_p^2 = .31$. Across the experiment, the mean difference in looking time between the novel and familiar events was 7.87 s (SD = 13.91, 95% CI = [0.456, 15.28]).

Finally, we compared the learning curves for habituation to the loose glass balls and habituation to the glass-ball solid. There was no difference in the number of trials to meet the habituation criterion (habituation to loose glass balls: M = 6.89; habituation to glass-ball solid: M = 7.85; range = 6–9), $F(1, 14) = 1.86$, p = .19, or in the amount of looking time that the infants accumulated during habituation (habituation to loose glass balls: M = 196.39 s, SD = 119.83; habituation to glass-ball solid: M = 240.65 s, SD = 171.65), $F(1, 14) < 1$, p = .55. In sum, we found no evidence that there were any differences in the

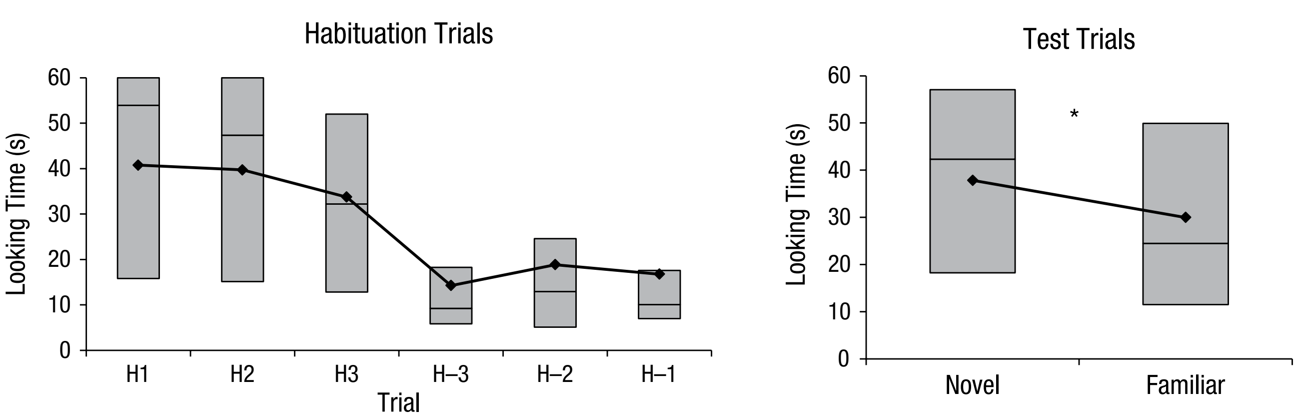

Fig. 7. Box plots of looking times during the habituation and test trials in Experiment 3. For habituation, the graphs show results for the first three trials (H1, H2, H3) and the last three trials before the habituation criterion was met (H–3, H–2, H–1). Black diamonds represent means, the central line in each box is the median, and the upper and lower portions of each box represent the third and first quartiles, respectively. The asterisk indicates a significant difference between novel and familiar test trials ($p < .05$).

learning curves between the loose and solid habituation trials.

Discussion

These results indicate that the infants detected the state change from a solid to a granular substance when the substance was transparent instead of opaque. We interpret these results as evidence that infants have broad expectations about substances that generalize across very different types of nonsolids.

General Discussion

The results of these three experiments confirm that infants can anticipate how substances and objects behave. Specifically, the results suggest that 5-month-old infants have general beliefs about the loose-bonding properties of substances: The motion cues that participants detected in the glass during the habituation trials led them to make distinct predictions about whether the contents of the glass would pass through the grid or come to rest against it. These expectations were evident for a liquid, as well as for two less familiar substances, sand and glass balls. Our findings support the possibility that infants' knowledge of substances may be principled and organized, as is their object knowledge.

The findings from these experiments also cast doubt on the possibility that infants have expectations about objects but not substances and that the observed effects were entirely based on deviations from object principles. This possibility is unlikely for three reasons. First, the habituation curves for the solid and substance conditions were identical. If the infants had expectations about how objects, but not substances, behave, the habituation curves for solids would have decreased faster than the curves for substances, and the number of trials to habituation would have been fewer for solids than for substances. Second, the infants reacted in opposite ways to the same test trials depending on what they had seen during habituation (substance vs. solid): What was a novel event for infants habituated to a substance was a familiar event for infants habituated to a solid. If the infants' expectations had been guided by object knowledge alone, looking times in the habituation-to-solid condition would have been identical to those found here. However, for infants habituated to substances, both test events would have been novel, and we would therefore expect equal and long looking times for solid and substance test trials, contrary to what we actually found (see Figs. 2, 3, and 5). Third, the difference between the straw conditions in Experiments 2 and 3 was a difference only within the domain of substances; therefore, if object knowledge alone had guided the infant's behavior, it should not have differed between these conditions. Consequently, the most parsimonious account of these data is that infants have expectations about substances as well as about objects.

However, the details of the structure of infants' substance knowledge remain to be explored. It is likely that these initial concepts about substances at 5 months of age form the basis of later knowledge about physical phases. Currently, it is unknown whether infants discern rigid subcategories of substances and, if so, whether the boundaries between substance categories are malleable (as they can be for objects; see Hespos & Piccin, 2009; Hespos & Spelke, 2004). For example, it is an open question whether infants recognize separate natural subcategories of substances (e.g., powder vs. sand vs. Cheerios), or whether these entities fall along a continuous dimension of granularity (like variations in height; Hespos & Baillargeon, 2001, 2006). Research on these questions should have implications for philosophical theories about ontological kinds and individuals (e.g., Cartwright, 1965). Future studies will also need to test how closely infants' intuitive ideas about substances match those of adults (e.g., Hayes, 1988)—for example, whether infants understand how substances operate under laws governing flow or how substances interact with solids (for some recent results on adults' knowledge of these topics, see Bates et al., 2015).

In conclusion, these experiments contribute two new findings about infants' knowledge of the physical world. First, we have shown that 5-month-old infants have expectations that substances are loosely bonded and objects are cohesive. Motion cues lead infants to recognize an entity's loose- or tight-bondedness and to make appropriate predictions about its later behavior. Second, infants' substance knowledge is not limited to those substances with which they are familiar. In Experiments 2 and 3, infants' ideas about substances generalized to sand and glass balls, which the infants were unlikely to have encountered previously. Infants' understanding of substances appears early in development, perhaps as early as their understanding of objects. We propose that in addition to the core domains of objects, actions, number, and space, there is room for one more—substances.

Author Contributions

S. J. Hespos and L. J. Rips developed the study concept. All authors contributed to the study design. Testing and data collection were performed by S. J. Hespos, A. L. Ferry, E. M. Anderson, and E. N. Hollenbeck. S. J. Hespos drafted the manuscript. All authors provided critical revisions and approved the final version of the manuscript for submission.

Acknowledgments

We thank the members of the Infant Cognition Lab at Northwestern University, and in particular Stephanie Morris and Jeron Rowland, for their help with data collection and coding.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Funding

This work was supported by National Science Foundation Grant BCS-0718513, awarded to S. J. Hespos.

Supplemental Material

Additional supporting information can be found at http://pss.sagepub.com/content/by/supplemental-data

Open Practices

Anyone wishing to obtain a copy of the raw data should contact the corresponding author directly (Susan J. Hespos, hespos@northwestern.edu). The codebook for these data is extensive, and researchers may find it helpful to specify the aspect of the data that they would like to reproduce. The complete Open Practices Disclosure for this article can be found at http://pss.sagepub.com/content/by/supplemental-data.

Notes

1. In this article, we use the term *substance* to refer to nonsolid matter generally, and we provide data on infants' expectations regarding liquid, sand, and glass balls specifically. The divisions of the physical world in terms of concepts about objects and substances is an interdisciplinary topic drawing on cognition, linguistics, and metaphysics. A more detailed account of our views on the ontological category of substance knowledge is available in Rips and Hespos (2015) and Hespos and vanMarle (2012).
2. This quality is related to Spelke's (1990) core object principle of "cohesion": A cohesive entity is defined as one on which any two surface points are linked by a path of connected surface points. Because the focus of our investigation was on nonsolid matter, we framed our experiments to emphasize the noncohesive nature of loose bonds (see also Cacchione, 2013).

References

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.

Bates, C. J., Yildirim, I., Tenenbaum, J. B., & Battaglia, P. W. (2015). Humans predict liquid dynamics using probabilistic simulation. In R. Dale, C. Jennings, P. Maglio, T. Matlock, D. Noelle, A. Warlaumont, & J. Yoshimi (Eds.), *Proceedings of the 37th Annual Meeting of the Cognitive Science Society*. Retrieved from https://mindmodeling.org/cogsci2015/

Bourgeois, K. S., Khawar, A. W., Neal, A. S., & Lockman, J. J. (2005). Infant manual exploration of objects, surfaces, and their interrelations. *Infancy*, *8*, 233–252.

Cacchione, T. (2013). The foundations of object permanence: Does perceived cohesion determine infants' appreciation of the continuous existence of material objects? *Cognition*, *128*, 397–406. doi:10.1016/j.cognition.2013.05.006

Cartwright, H. M. (1965). Heraclitus and the bath water. *Philosophical Review*, *74*, 466–485. doi:10.2307/2183124

Cheries, 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.

Hayes, P. J. (1988). Naive physics I: Ontology for liquids. In A. M. Collins & E. E. Smith (Eds.), *Readings in cognitive science: A perspective from psychology and artificial intelligence* (pp. 251–269). San Mateo, CA: Morgan Kaufmann.

Hespos, S. J., & Baillargeon, R. (2001). Infants' knowledge about occlusion and containment: A surprising discrepancy. *Psychological Science*, *12*, 141–147.

Hespos, S. J., & Baillargeon, R. (2006). Decalage in infants' reasoning about occlusion and containment events: Converging evidence from action tasks. *Cognition*, *99*, B31–B41.

Hespos, S. J., Dora, B., Rips, L., & Christie, S. (2012). Infants make quantity discriminations for substances. *Child Development*, *83*, 554–567.

Hespos, S. J., Ferry, A. L., & Rips, L. J. (2009). Five-month-old infants have different expectations for solids and liquids. *Psychological Science*, *20*, 603–611. doi:10.1111/j.1467-9280.2009.02331.x

Hespos, S. J., Gredeback, G., von Hofsten, C., & Spelke, E. S. (2009). Occlusion is hard: Comparing predictive reaching for visible and hidden objects in infants and adults. *Cognitive Science*, *33*, 1483–1502. doi:10.1111/j.1551-6709.2009.01051.x

Hespos, S. J., & Piccin, T. (2009). To generalize or not to generalize: Spatial categories are influenced by physical attributes and language. *Developmental Science*, *12*, 88–95.

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*, 19–27.

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.

Li, P., Dunham, Y., & Carey, S. (2009). Of substance: The nature of language effects on entity construal. *Cognitive Psychology*, *58*, 487–524. doi:10.1016/j.cogpsych.2008.12.001

Munakata, Y., McClelland, J. L., Johnson, M. H., & Siegler, R. S. (1997). Rethinking infant knowledge: Toward an adaptive process account of successes and failures in object permanence tasks. *Psychological Review*, *104*, 686–713.

Perry, L. K., Samuelson, L. K., & Burdinie, J. B. (2014). Highchair philosophers: The impact of seating context-dependent exploration on children's naming biases. *Developmental Science*, *17*, 757–765.

Pinto, J. P. (1996). Xhab [Computer software]. (Available from J. P. Pinto, pinto@psych.stanford.edu)

Rips, L. J., & Hespos, S. J. (2015). Divisions of the physical world: Concepts of objects and substances. *Psychological Bulletin*, *141*, 786–811.

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). London, England: Oxford University Press.

Shinskey, J. L., Bogartz, R. S., & Poirier, C. R. (2000). The effects of graded occlusion on manual search and visual attention in 5- to 8-month-old infants. *Infancy*, *1*, 323–346. doi:10.1207/S15327078IN0103_3

Shinskey, J. L., & Munakata, Y. (2001). Detecting transparent barriers: Clear evidence against the means-end deficit account of search failures. *Infancy*, *2*, 395–404. doi:10.1207/S15327078IN0203_7

Shutts, K., Condry, K. F., Santos, L. R., & Spelke, E. S. (2009). Core knowledge and its limits: The domain of food. *Cognition*, *112*, 120–140.

Spelke, E. S. (1990). Principles of object perception. *Cognitive Science*, *14*, 29–56.

Spelke, E. S., Breinlinger, K., Macomber, J., & Jacobson, K. (1992). Origins of knowledge. *Psychological Review*, *99*, 605–632.

vanMarle, K., & Wynn, K. (2011). Tracking and quantifying objects and non-cohesive substances. *Developmental Science*, *14*, 502–515. doi:10.1111/j.1467-7687.2010.00998.x

Wynn, K. (1992). Addition and subtraction by human infants. *Nature*, *358*, 749–750.