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Predicting the Outcomes of Physical Events: Two-Year-Olds Fail to Reveal Knowledge of Solidity and Support

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Two-year-olds' ($N = 153$) knowledge of solidity was tested in four search tasks adapted from infant looking-time experiments. In Experiment 1, 2-year-olds failed to search in the correct location for a falling ball after a hidden shelf that blocked its trajectory had been inserted in the apparatus. Experiment 2 extended this finding by showing that 2-year-olds failed to take into account the effects of either removing or inserting a shelf in their search for a toy dropped behind a screen. Experiment 3 examined sensitivity to the constraint provided by a solid barrier on horizontal motion. In all three experiments, 2-year-old children searched initially at the location where they saw the object during familiarization. Experiment 4, using multiple test trials but no familiarization to a pretest location, also showed that 2-year-olds failed to take the presence or absence of a barrier into account when planning where to search for a toy they had seen dropped behind a screen. In all of these studies, 2-year-olds showed no evidence of representing solidity and support constraints on the trajectories of falling objects. Experiments 1 and 3 also included 2½-year-olds ($N = 31$), who succeeded on these search tasks. The implications of the poor performance of 2-year-olds, in the face of success by very young infants on looking-time measures of sensitivity to similar constraints on object motion, are discussed.

INTRODUCTION

Infancy is a period of marked development of planning, memory, and action control (Diamond, 1985; Rovee-Collier, 1999; Spelke, Vishton, & von Hofsten, 1995). Because of these changes, a methodology that places relatively few demands on executive function has been developed to diagnose infants' representations of their world. This methodology is based on looking-time measures of violation of expectancy (see Baillargeon, 1995, for review). Put simply, infants often look significantly longer at the outcome of events that violate the physical laws of solidity, cohesiveness, and continuity of objects compared with those event sequences that do not involve such violations. In those studies where the critical event occurs behind an occluder, infants must be using some form of object representation to detect the violation. In the domain of object knowledge, the violation-of-expectancy studies seem to reveal much earlier competence than do those studies that depend upon search.

Such demonstrations of early competence led Spelke and colleagues (Spelke, Breinlinger, Macomber, & Jacobson, 1992) to articulate the core knowledge hypothesis (see also Baillargeon, 1995; Carey & Spelke, 1994). The core knowledge hypothesis is that some aspects of object knowledge are innate, or emerge very early in infancy, and continue to structure our representation of three-dimensional objects throughout life. The hypothesized components of core knowledge include the spatiotemporal specification of objects, such as cohesiveness (objects maintain their boundaries as they move through space), continuity (objects trace spatiotemporally continuous paths), and solidity (two objects cannot occupy the same space at the same time; Spelke et al., 1992). On the core knowledge hypothesis, other aspects of physical knowledge, not part of the core, are learned through extensive experience with the world. An example might be the knowledge that unsupported objects fall (Baillargeon, 1995; Spelke et al., 1992).

The core knowledge position predicts that 2-year-olds should reason in the same way as infants about event sequences that tap knowledge of solidity, cohesiveness, and continuity of objects. They should also show evidence of beginning to understand noncore principles. Methods, however, that involve responses appropriate for older children, such as reaching, also require executive control in addition to knowledge. The present studies set out to address the question of when object knowledge is available to executive function to guide search behavior in older children.

By the end of infancy, around 2 years of age, most of the impediments to planning and problem solving in the context of search for hidden objects seems to have been overcome: Children of this age will readily solve the most difficult Piagetian search tasks. Nonetheless, there are hints in the literature that 2-year-olds fail on some search tasks that may address core physical knowledge. For example, Hood (1995) found that 2-year-olds appeared to ignore the core principle that objects must move on continuous paths through space. When searching for a ball that was dropped into an opaque tube that formed an "S" bend, they repeatedly searched at the location directly below the bend even though the ball could not travel invisibly across this intervening space. When the object motion was reversed, so that the ball appeared to travel up the tube, performance was better, indicating that something about falling events overrides the deployment of physical knowledge in these search tasks (Hood, 1998).

Thus, searching for falling objects may be one situation that leads to responses that are inconsistent with the continuity principle at 2 years of age. The search task with the tubes may, however, be confounding several principles, such as solidity, gravity, and straight trajectories, which means that it is not directly comparable to the infant paradigms that first revealed core knowledge. With this in mind, we designed experiments to explore the emergence of understanding of solidity and support by using search tasks adapted from the infancy paradigms of Spelke et al. (1992).

The studies of solidity are based on Spelke et al.'s (1992) demonstration that young infants detect a violation when one object appears to pass through the space occupied by another. In one study, 4-month-old infants were familiarized with an object falling to a stage floor and then were shown a solid shelf that was placed above the stage. The stage and shelf were then partially occluded by a screen and the object dropped behind the screen. When screen was then removed, the object was revealed either resting on the shelf (possible outcome) or on the stage below the shelf (impossible outcome); infants looked significantly longer at the impossible outcome, despite the fact that the object occupied the same position as that during the familiarization phase. Furthermore, Spelke et al. demonstrated that even infants at 2½ months were sensitive to a difference between possible and impossible events in the case of objects traveling in the horizontal plane. This differentiation for vertical falling events is still present at 6 months and has been shown to operate in similar event circumstances up to 8 months (Huntley-Fenner, 1995).

This series of experiments began with 2- and 2½-year-olds because children at this age have the capacity to solve object permanence tasks in which the child must represent the invisible movement of the object through space. Had toddlers of this age succeeded in our tasks, which require sensitivity to solidity and support in the prediction of object location, we would have explored younger children's explicit knowledge of these same principles.

EXPERIMENT 1

Experiment 1 was based on Experiment 1 of Spelke et al. (1992). Two-year-olds were familiarized with three repetitions of a ball being dropped onto a stage, behind a screen, followed each time by the removal of the screen to reveal the ball lying on the stage floor. A shelf was then introduced and two cups placed in the apparatus, one on the stage floor and one directly above it on the shelf (see Figure 1). The screen was replaced and the ball dropped again. The screen was then removed, and the child's task was to retrieve the ball from the cup that it had fallen into. If children understood that the ball could not fall through the shelf, they should retrieve the ball from the cup resting on the shelf, not from the cup resting on the stage, below the shelf.

Method

Participants

Ninety 2-year-olds, *M* = 24 months, *range* = 23–25 months, and fifteen 2½-year-olds, *M* = 31 months,

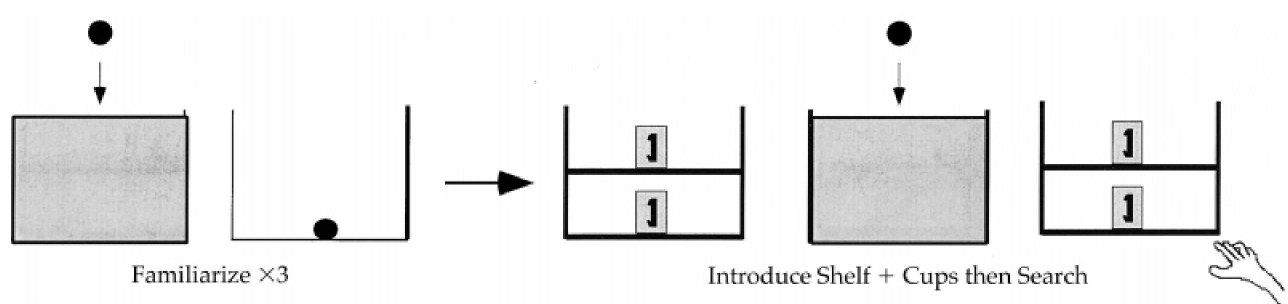

Figure 1 Diagram of the apparatus and testing sequence for Experiment 1. Participants were familiarized with the ball fall on to the stage for three trials. The shelf and cups were inserted and the falling sequence was repeated. Participants were then allowed to search.

range = 29–33 months, participated. There were approximately equal numbers of males and females at each age. The 2-year-olds were randomly assigned to one of three conditions (experimental, baseline, and control; 30 children each); the 2½-year-olds participated in the experimental condition only. The data from eleven 2-year-olds were discarded from the study: Six children would not remain seated and became upset; three removed both cups simultaneously; and two could not be persuaded to approach the apparatus to search. The data from one 2½-year-old were discarded because she searched both cups simultaneously.

Materials

The sequence of events was performed on a miniature stage that was supported on caster legs for mobility. The height of the base of the frame from the floor was 40 cm, and the rectangular front of the stage was 65×60 cm. The shelf was 7 mm thick and extended the width of the apparatus at a height of 15 cm above the base. The hiding containers were two identical bright red plastic coffee cups. The height of each cup was 10 cm. The occluder was a piece of gray cardboard that could be slotted into place. The ball was of bright multicolored rubber. Children were seated on a plastic child's chair at a distance of 1 m from the apparatus.

Procedure

Sixty 2-year-old children were randomly assigned to the experimental and baseline conditions. After the data had been acquired in these two conditions, a third control condition with 30 children was run to check that falling events did not bias children towards the bottom location. The fifteen 2½-year-olds participated in the experimental condition only. All children had the same warm-up trials.

Warm-up trials. Before testing, each child was given a warm-up. The child was handed the ball and then the experimenter produced two identical cups and held one in each hand. The child was asked to drop the ball into one cup and then retrieve it. This was repeated over three to four trials to acquaint the child with the cup as a thing that could hold the ball. The cups were then placed out of sight and the child was tested with one of three conditions.

Experimental condition. Parents were asked to seat their children on the chair in front of the stage and to gently restrain them to prevent approach to the apparatus during the three familiarization trials of the experimental condition. The experimenter showed the child an empty stage and then inserted the occluder. The child was asked to carefully watch the ball, now held in the experimenter's hand approximately 50 cm over the top of the occluder. When the child was watching the ball, it was released and fell behind the occluder on to the stage. The experimenter asked, "Where's the ball?" and then removed the occluder saying, "There's the ball!" The child was shown the ball on the base of the stage. This was repeated two more times. Following the three familiarization trials, a test trial was conducted. The shelf and cups were produced and the child was asked to watch as the shelf was inserted and the cups were placed on the shelf and below it in full view. The cups were aligned in the center of the stage with the handles turned toward the child. There was a 5-cm separation between the bottom cup and the underside of the shelf. The occluder was inserted and the falling sequence was repeated with the experimenter dropping the ball into the top cup. After the ball had landed in the cup, the experimenter removed the occluder and immediately asked the child to find the ball by looking in one of the cups. The location of the first cup to be grasped was the dependent measure.

Baseline condition. The baseline condition differed from the other two conditions in that there were no familiarization trials or test trials involving falling events. Instead the child was shown the stage with the shelf in place; the shelf was then covered with the occluder. After the warm-up with the ball and cups, the experimenter placed the ball in one cup in full view of the child and then placed the cups behind the occluder in the same locations as in other conditions. The cup with the ball was randomly assigned to each location. The experimenter then removed the occluder and asked the child to search for the ball in one of the cups. In this condition, the child had no basis for a response other than a guess, a preference due to ease of reaching, or some other unknown factor.

Control condition. As noted earlier, previous research with falling invisible displacements has indicated that preschoolers have naïve beliefs about object trajectories (Hood, 1995). To test whether all falling events lead to the expectation that objects land in the lowest container, data were collected from an additional 30 children. This control condition was identical to the experimental condition except that the child saw three familiarization trials with the shelf in place from the start. Therefore, during familiarization they saw the outcome of the ball landing on top of the shelf. The test trial was identical to that in the experimental condition.

Results

As Table 1 shows, the baseline preference was to search in the upper cup. When simply shown the out-

Table 1 Percentage of Toddlers Searching in the Upper Cup

Condition	Age 2 Years	Age 2½ Years
Experimental	40	93
Baseline	83	
Control	80	

come display with two cups and told that there was a ball in one of them, twenty-five of the thirty 2-year-olds searched in the cup on top of the shelf, more than would be expected by chance (83%, $p < .001$, binomial, two-tailed). This was probably because the top cup was easier to retrieve without a detour reach underneath the shelf.

The important result of Experiment 1 was the poor performance of the 2-year-olds in the experimental condition. Only 12 of the 30 searched correctly in the cup on top of the shelf, in spite of a baseline preference for this location. A χ^2 analysis revealed that the proportion of children who reached to the top cup in the two conditions (baseline versus experimental) was significantly different, $\chi^2(1, N = 60) = 24.8$, $p < .001$, two-tailed. To make the incorrect response of reaching for the lower cup, in violation of the principle that one object cannot pass through the space occupied by another, over half of the 2-year-olds overcame a baseline preference for reaching in the upper cup!

Although the baseline condition revealed that there was a location bias for the top cup in a nonfalling sequence, children may have been predisposed to infer that falling objects always land at the lowest surface. As noted earlier, Hood (1995) demonstrated a marked tendency for preschoolers to infer that objects always fall straight down even though there was an obvious solid mechanism constraining object motion. A similar tendency, difficult to overcome, may have been operating in the shelf task. The control condition (shelf always in place) was run to address the possibility that failure on the test of the experimental condition was attributable to naïve reasoning about falling objects, namely that objects always land at the bottom, straight down, irrespective of any intervening barrier.

In test trials of the control condition, children correctly reached for the cup on top of the shelf (80%, $p < .001$, binomial, two-tailed). The comparison of the experimental and control conditions with a χ^2 analysis revealed significantly different proportions of reaching to the top cup, $\chi^2(1, N = 60) = 10$, $p < .01$, two-tailed. Thus, the errors in the experimental condition of Experiment 1 did not reflect a tendency, difficult to correct, to predict that objects would land on the lowest surface directly below where they had been dropped. Taken together, the results from experimental and control conditions indicate that children's search on falling events seems to have been determined by where they saw the ball land during familiarization (on the shelf in the control condition, on the stage floor in the experimental condition) in spite of a baseline preference to reach to the top shelf in the absence of familiarization.

By age 2½ years, children succeeded robustly on this task; fourteen of the fifteen 2½-year-olds in the experimental condition correctly reached for the upper cup. Their preference was significantly above chance ($p < .001$, binomial, two-tailed) and significantly different from the behavior of the 2-year-olds in the same experimental condition, $\chi^2(1, N = 45) = 11.6$, $p < .001$, two-tailed.

Discussion

Two-year-olds failed to search correctly. They showed no sensitivity to the solidity principle when tested with the first trial with a shelf in place. Fully 60% of the 2-year-olds retrieved the cup on the bottom, below the shelf, even though there was a strong position bias to search in the top cup in a nonfalling situation. The control condition revealed that children could search correctly if they were familiarized to the ball landing on the shelf. Therefore, the failure in the experimental condition was not due to a bias toward lowest location. By age 2½ years, children succeeded at this task: they retrieved the ball from the cup on the shelf, rather than attempting to retrieve it from the cup under the shelf.

The failure of the 2-year-olds is striking, given the extensive evidence that young infants are sensitive to the solidity principle. If toddlers' representations of the locations of hidden objects embody the solidity principle, one might expect these representations to determine search. Surely one purpose of representations of object location is to guide retrieval of objects.

Because of our surprise at the failure of 2-year-olds in the present study, in each of the subsequent studies reported here, we sought to manipulate factors that might be making this task difficult or that might differentiate this task from the methods used with infants. For example, the physical arrangements in Experiment 1 present two sources of difficulty not found in the infant studies of solidity knowledge. First, there was the extra difficulty posed by the relation of containment; the child had to use the solidity principle to infer which cup the ball would be in, whereas the infants needed to infer only whether the object should be above or below the shelf. Containment may be a particularly difficult spatial relationship for children to understand (Dunst, Brooks, & Doxsey, 1982). Second, in the infant studies, the shelf was visible on either side of the occluder when the objects were dropped; in Experiment 1, the occluder completely covered the shelf. Perhaps the visual reminder of the barrier during the dropping of the object aided the infants' sensitivity to the solidity principle as has been demonstrated in other looking-time experiments (Baillargeon, 1993).

EXPERIMENT 2

Experiment 2 eliminates two major differences in apparatus between Experiment 1 and the infant studies. First, there was no cup. Second, a central column that had two vertical windows (see Figure 2) provided occlusion of the central falling event. This partial occlusion of the stage meant that that the shelf, protruding beyond the column, was visible during the test trials. By removing the need for cups and using two windows to occlude the ball, Experiment 2 allowed us to also test the children's understanding of support. If the shelf was in place during familiarization, the object (a toy frog) would be revealed at the upper location; subsequent removal of the shelf would constitute a test of support. If the child was familiarized without the shelf in place, then the ball would land at the lower location. The insertion of the shelf would now constitute a test of solidity. In the support condition, in which the child's attention was drawn to the *removal* of the shelf from the apparatus before the test trial, failure would be to search at the upper window for the frog, as if the frog could be suspended in midair. In the solidity condition, in which the child's attention was drawn to the *addition* of the shelf to the apparatus before the test trial, failure would be to search at the lower window for the toy, as if the toy could have passed through the shelf.

Method

Participants

Twenty-seven 2-year-olds, $M = 24$ months, *range* = 23–26 months, participated in Experiment 2. Fifteen were familiarized to the lower window and 12 were familiarized to the upper window. The data from 12 additional children were discarded from the study: of these, 3 would not search during the training trials; 6 reached during the familiarization despite gentle restraint; 1 would not search on the test trial; and 2 opened both windows simultaneously on the test trial.

Materials

The rectangular front of the stage was 61 × 51 cm and covered with a sheet of Plexiglas that was 1.2 cm

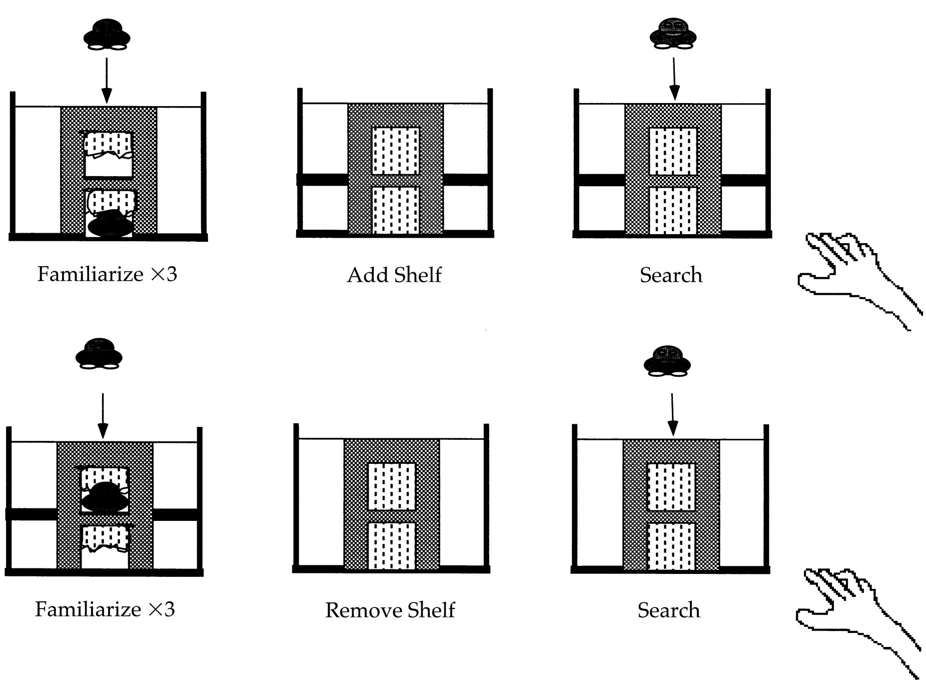

Figure 2 Diagram of the apparatus and testing sequence for Experiment 2. In the condition illustrated in the top sequence, participants were familiarized without the shelf and tested with the shelf inserted. The bottom sequence shows the reverse conditions.

thick. Two windows, 17.5 × 15 cm in dimension, were cut into the Plexiglas, one above the other and separated by 5 cm. The base of the lower window was aligned with the stage floor behind. Unlike Experiment 1, the shelf was much thicker at 2 cm and visibly protruded 16.5 cm at either side of the central occluding column, which was 28 × 51 cm. Each window was covered with a cloth cover. Instead of a rubber ball, a small beanbag frog was used because it was less likely to roll into view and more likely to remain at the point of landing on either the stage or shelf.

Procedure

Training trials. Before testing, each child was given training trials to teach them to reach through each window. The shelf was inserted and the child was shown the frog. The frog was then placed behind the occluder on either the shelf or stage for two trials at each location. Each pair of training trials alternated between the upper and lower window and the order was randomized across children. After the frog was in place, the experimenter lifted both curtains to reveal the frog at either the upper or lower window for approximately 3 s. The curtains were lowered and the child was encouraged to search at only one window. To be tested further, children had to pass three of four training trials.

Familiarization trials. Following the training trials, the child was seated directly in front of the apparatus on a toddler chair next to the parent or guardian at a distance of 1 m. The adult was asked to gently restrain the child during familiarization. For the lower window familiarization (see Figure 2), the shelf was taken out after the training trials, loudly tapped by the experimenter, and then placed against the laboratory wall in full view. In the upper window familiarization, the shelf remained in place following training. The frog was then dropped from a height of approximately 50 cm above the apparatus to fall behind the occluding column. Both curtains were raised simultaneously to show the location of the frog. This familiarization procedure was repeated three times. Fifteen children were familiarized to the frog landing on the base of the stage (lower window) and 12 children saw the frog on the shelf (upper window).

Test trial. Following familiarization, there was a single test trial. In the lower window familiarization condition, the shelf that had been resting against the laboratory wall was picked up, tapped, and then inserted behind the occluding column. In the upper window familiarization condition, the shelf was taken out, tapped by the experimenter and then placed up against the wall. In both conditions, the frog was again dropped behind the occluding column and the child was asked to search for the frog at only one window.

Table 2 Percentage of Toddlers Searching at Upper Window

Condition	% Search at Upper Window
Shelf removed on test trial (familiarized to upper window)	100
Shelf inserted on test trial (familiarized to lower window)	20

Results

As Table 2 shows, all 12 children (100%) who had been familiarized to the upper window searched at that location on the test trial whereas only 3 out of 15 (20%) who had been familiarized to the lower window searched in the upper position, $\chi^2(1, N = 27) = 17.3$, $p < .001$, two-tailed. The slight bias to searching at the upper window may reflect the same positional bias observed in Experiment 1.

Discussion

The data from Experiment 2 confirm the results of Experiment 1 in that 2-year-olds again failed to search correctly for hidden objects in the solidity condition. In the solidity condition, when the child's attention was drawn to the *addition* of the shelf to the apparatus before the test trial, they searched at the lower window for the toy, as if the toy could have passed through the shelf. The data extend this finding by showing that the children failed to search correctly in the support condition as well. In the support condition, when the child's attention was drawn to the *removal* of the shelf from the apparatus before the test trial, they searched at the upper window for the toy, as if the toy could be suspended in midair.

The failure in the solidity condition of Experiment 2 suggests that the search errors in Experiment 1 are not attributable either to the extra difficulty due to the containment relation posed by the cups or to the fact that the shelf was totally occluded. Furthermore, the reversal of the search error between the support violation and the solidity violation conditions of Experiment 2 indicates that the most likely explanation for the failure in Experiments 1 and 2 is that toddlers were searching at the location where they saw the object during the familiarization trials.

Why should the infant studies show sensitivity to the solidity principle in 3- to 8-month-olds, whereas these studies with 2-year-olds do not? One possibility is that the infant studies relied on what may be a statistically more sensitive measure of knowledge of solidity: a comparison between trials in which the principle was violated and trials in which it was not. In the search tasks of Experiments 1 and 2, in contrast, success was all or none; each child gave only one response: The child retrieved either the correct cup or the incorrect cup or chose one of the windows. Experiment 3 addresses this possibility by comparing children's search on trials when a barrier had been inserted with trials in which no barrier had been inserted.

EXPERIMENT 3

By coincidence, most of Experiment 3 was conducted simultaneously and independently of Experiments 1 and 2 by the second and third authors, who wanted to conduct a toddler version of the horizontal infant experiment reported in Spelke et al. (1992). Therefore, there were a number of procedural differences from Experiments 1 and 2. Most importantly, each toddler was given two trials of *both* types (barrier trials and no barrier trials) in a horizontal version of the search task. Instead of search, pointing to the correct location was the response required of the child. Also, unlike falling events, the horizontal arrangement of locations of Experiment 3 allowed the object to be rolled from two directions. This enabled a much stronger test of an understanding of solidity because the direction was reversed between the first and second trial of each barrier and no-barrier condition, thus ensuring that the toddler could not simply rely on the memory of the outcome from the first trial.

Two-year-olds were familiarized to an object rolling onto a stage, behind a curtain, coming to rest at the far edge of the stage (see Figure 3). Then, on some trials, we inserted a barrier, which protruded visibly above the curtain, between the two halves of the stage; the object was then rolled in again. The dependent measure was which side of the stage the child pointed to when asked where the object was. Preliminary studies (Prasada, Carey, & Welch, 1993) showed that even children as old as 2½ to 3 years of age developed position biases in similar situations, so several precautions were taken to minimize position biases and to ensure that the toddlers understood how to point to the location of the hidden object. Following a period of warm-up, there were four training trials; participants watched the object being lowered slowly from above into one side of the apparatus or the other and were asked to point to where it was. To be tested further, the child had to point correctly on three of the four training trials.

The first barrier trial corresponded to the single test

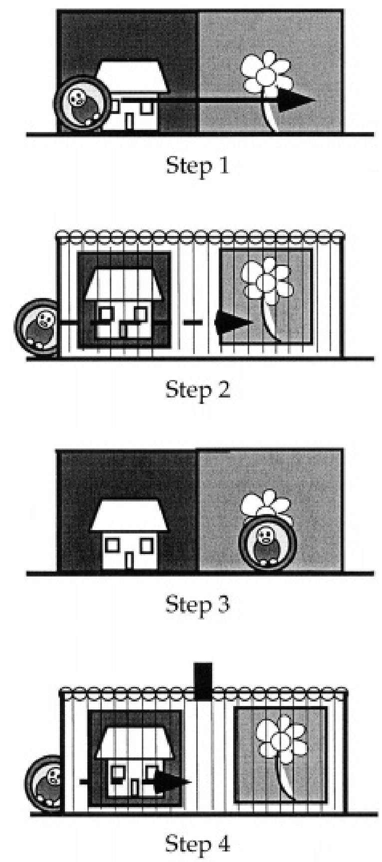

Figure 3 **Diagram of the apparatus and testing sequence for Experiment 3. Steps 1–4 represent the sequence for a single test trial. In Step 1, the participants see the movement of the can (with toy inside) across the stage with no curtains. In Step 2, the curtains are lowered and the can is again rolled across the stage. In Step 3, the curtain is raised to show the location of the can. Step 4 is the test sequence where the barrier is inserted (on barrier trials) and the can is again rolled behind the curtains.**

trials of Experiments 1 and 2. The no-barrier trials allowed us to see whether individuals differentiated barrier from no-barrier trials. Thus, the data from Experiment 3 would be directly comparable to those from the infant studies, where two outcomes were presented.

Method

Participants

Participants were sixteen 2-year-olds, $M = 24$ months, *range* = 23–27, and sixteen 2½-year-olds, $M = 30$ months, *range* = 29–32. Half of the participants at each age were girls and half boys.

The data from 18 other 2-year-olds were excluded from the final analysis: Nine did not pass the training trials; three showed strong side biases on the test trials;

and six did not complete the four test trials. An additional eight 2½-year-olds were tested and excluded from the final analysis: Five did not pass the training trials; two showed side biases on the test trials; and one did not complete the four test trials.

Materials

The events took place on a puppet stage diagrammed in Figure 3. The left side of the stage was red and had a picture of a house on the back wall. The right side was green and had a picture of a flower on the back wall. The stage was covered by curtains that matched the color of the back of the stage and also had the corresponding pictures on them. A slot in the floor of the stage allowed the rolling of objects from outside the curtain across the stage. Objects were placed in a can with a ridge that fitted in the slot; this allowed the objects to be rolled. The objects were colorful soft toys (animals, vehicles, blocks, etc.) that could be wedged inside the can. The open side of the can faced the child, so the child could see the objects being rolled and would see them when the curtains were opened after the child pointed. Small slots on the floor and back wall allowed a barrier to be inserted in the middle of the stage. When in place, with the curtains closed, the barrier protruded above the top of the curtains.

The stage was placed on a table that was at eye level for the children, and the children sat on a seat 1 m from the stage. The child's parent was seated next to and slightly behind the child and was asked not to interact with the child during the experiment. One experimenter was behind the stage to roll the objects and to ensure that the can stopped in the correct place. This stopping was achieved by reaching through the slot in the floor of the stage; the experimenter's hand was never visible. This experimenter recorded where the child pointed. Another experimenter stood in front of the stage and off to the side and interacted with the child.

Procedure

Warm-up trials. The child was seated in front of the stage with the curtains closed and asked to point to the flower and house on the curtains. The curtains were then opened, and the child was asked to point to the flower and the house on the back of the stage. This encouraged the child to differentiate the two sides and to point.

Training trials. The can was not used in the four training trials. In the first trial, the curtains were opened and a toy was placed, in full view of the child, on the stage to one side. The curtains were then closed, and the child was asked to point to where the toy was located. The curtains were then opened and the toy was revealed. This was repeated for the other side. In the third trial, the child was shown the empty stage, the curtains were closed, and the toy was then lowered from above onto one side of the stage while the child watched. The child was then asked to point to the location of the toy and was given feedback by the curtains being opened. This procedure was repeated for the other side. The objects were placed on different sides of the stage for different trials. For half of the participants, the order of sides was right, left, left, right and for the other half it was left, right, right, left. The training trials introduced the child to pointing at the hidden toy and ensured that the child had pointed to both sides of the stage. The criterion for passing this phase was correct pointing on all four training trials.

Familiarization and test trials. Immediately after the training trials, four test trials that included familiarization and test followed. Each trial had four parts, which are illustrated in Figure 3. After the child had handled the toy for a brief period of time, it was placed in the can. In Step 1, the curtains were open and the object was rolled from outside the curtain on one side (say the left) to the middle of the curtain on the opposite (the right) side, while the child watched. In Step 2, the curtains were closed, and the object was rolled from outside the left curtain to the middle of the right side of the stage again. In Step 3, the curtains were opened to reveal the can. Steps 2 and 3 were then repeated two more times. These steps (2 and 3) are exactly the same as the familiarization trials in Spelke et al.'s (1992) Experiment 3. In Step 4, on half the trials, a barrier was placed in the middle of the stage (barrier trials). The child was shown the barrier, shown that it was solid, and watched it put in place. The curtains were then closed, and the object was once again rolled from the same position outside of the left side of the stage toward the right side. The child was asked to point to the location of the object. After responding, the child was shown the location of the object. On the other half of the trials, no barrier was put in place (no barrier trials). The correct response on the no-barrier trials is the far (right, in this example) side of the stage; the correct response on the barrier trials is the near (left, in this example) side of the stage.

Each child received two barrier trials and two no-barrier trials, blocked. Half were given the two barrier trials first, and half the two no-barrier trials first. The object was alternately rolled in from opposite sides of the stage (i.e., if the movement in the first trial was from left to right, the movement in the second trial was from right to left). This ensured that if a child pointed to the wrong location on the first barrier trial, the mistake could not be corrected simply by pointing on the second barrier trial to where the object was on the previous barrier test trial. Half of the participants saw the objects rolled in from the left, the right, the right, and the left, whereas the other half saw them rolled in from the right, the left, the left, and the right. On each trial, a different object was placed in the can.

Results

Table 3 shows the percentage of choices of the near side of the stage on the first test of each type for both age groups. Adult performance would be 100% on the barrier trials, 0% on the no-barrier trials. Consider first the performance on the first barrier trial, the trial that corresponds to the single trial of Experiments 1 and 2. The data from Experiment 1 are closely replicated; in Experiment 1, 40% of the 2-year-olds' choices were correct; in Experiment 3, 47% of the 2-year-olds pointed correctly to the near side. Again, fewer than half of the 2-year-olds drew on knowledge of solidity to predict that the object would stop on the near side of the inserted barrier. In both experiments 2-year-olds are at chance. Firthermore, as in Experiment 1, the 2½-year-olds succeeded on the first barrier trial. They correctly indicated the near side of the stage on 75% of first barrier trials (Table 3; $p < .05$, sign test). In sum, in Experiment 3, as in Experiment 2, making the barrier visible when objects were rolled into the display and removing the possible extra difficulty of reasoning about containment did not change the pattern of results from Experiment 1. Nor did changing the motion from vertical to horizontal change the pattern of results.

Experiment 3 adds a second measure of success. Are the barrier and no-barrier trials differentiated from each other? As can be seen in Table 3, toddlers of both ages succeeded at the first no-barrier trials; they pointed correctly to the far side. For each child, at each age, the percent choice of the near side on the two no-barrier trials was subtracted from the percent choice of the near side on the two barrier trials. A positive difference score reflects the correct differentiation of the two types of trials. For 2½-year-olds, there were 4 children with difference scores of 0, and all other scores were in the positive direction (Wilcoxon $T = 0$, $N = 12$, $p < .01$). Thus, older children successfully differentiated the two types of trials. For 2-year-olds, there were 3 children with difference scores of 0, 3 with difference scores in the negative direction, and 10 with difference scores in the positive direction (Wilcoxon $T = 18$, $n = 13$, $p < .10$). Thus, 2-year-olds, as a group, were close to differentiating the two types of trials. Thus, it possible that one reason that infants show knowledge of solidity whereas children at 2 years tend to fail in these experiments is that the infant measures rely on a statistically more sensitive comparison of responses to two types of trials, whereas the toddler measures in Experiments 1 and 2 involved a single trial.

Table 3 Percentage of Responses to Near Side

Condition	Age 2 Years	Age 2½ Years
1st wall trials	47	75
2nd wall trials	67	60
1st no wall trials	25	25
2nd no wall trials	27	27

Discussion

Experiment 3 was very difficult for 2-year-olds. Thirty-four toddlers at 2 years of age were presented the task before we identified 16 who could finish it without side biases, and 24 at 2½ years of age were required to complete a sample of 16. The prevalence of side biases underscores the role of perseveration in these tasks. Nonetheless, the results from the first barrier trials of Experiment 3 closely matched those of Experiments 1 and 2, in spite of extensive procedural differences among the three experiments. Overall, 2-year-olds failed to search in accordance with the solidity constraint; their failure is underlined by the statistically more sensitive comparison of the barrier and no barrier trials in which they did not clearly respond differently in these two types of trials. In line with the results of Experiment 1, 2½-year-olds succeeded on the first barrier trial, and they also robustly differentiated the barrier and the no-barrier trials.

EXPERIMENT 4

Experiments 1–3 suggest that if 2-year-olds are familiarized to the outcome of an object moving to a particular location over a number of trials, they do not search appropriately on a test trial when a barrier alters the final position of the object. This suggests that familiarization introduces a position bias that determines search (Experiment 2) or reduces responding to chance levels (Experiments 1 and 3). Note that the infant studies that were the model for these studies also familiarized infants with the same type of outcomes. Apparently, perseveration affects action planning (search or pointing) more than attention to outcomes in the looking-time studies. Thus, the question remains: If perseveration were removed, would toddlers exhibit knowledge of solidity and support in a search situation? Experiment 4 was designed to answer this question and to pursue the suggestion in Experiment 3 that a within-child comparison of two types of events might yield evidence of sensitivity to solidity and support.

In Experiment 4, we adapted the windows paradigm of Experiment 2 to address whether 2-year-olds would search successfully if we removed the perseveration introduced by familiarization and presented the children with multiple trials with feedback. In the windows paradigm, two sources of perseveration could disrupt search at the alternate locations. The first of these was the position bias, which was most commonly observed in the upper location for Experiments 1 and 2. The second source of perseveration was the familiarization of seeing the frog at one location before search. To address the position bias, four control trials were inserted after the training trials and before the test trials to identify those children who were predisposed to search at one position. To address the second source of perseveration, we eliminated the familiarization phase of seeing the frog land at one of the locations before the removal or insertion of the shelf on the test trial.

Method

Participants

Thirty-three 2-year-olds were initially recruited (22 females and 11 males). One child refused to participate at all and another did not complete the test trials. Six additional children provided invalid data because they ran around the side of the apparatus on the test trials to see where the frog was. Of the 25 children, only those who demonstrated the capacity to switch their search behavior at least once during the control trials were included for further analysis. The data from five children were dropped from the analysis because three children always searched at the top window during the control trials and two children always searched at the bottom window. Therefore data for twenty 2-year-olds, $M = 24.8$ months, *range* = 23–27, were analyzed. There were 13 girls and 7 boys in the final group.

Procedure

There were three sets of trials in Experiment 4. In the training and control trials, the shelf was always in place so that the frog could be located at the top window or the bottom window. In the test trials, which involved the falling events, the presence of the shelf (top window) or absence of the shelf (bottom window) determined the location of the frog. In each set of trials, the location of the frog was predetermined by a pseudorandom sequence in which the first two trials always differed. This produced four possible sequences where T = top and B = bottom; BTBT, BTTB, TBTB, and TBBT. These sequences were equally distributed among the children and conditions so that no child encountered the same sequence in any two sets of trials.

Training trials. Children were shown the shelf inserted into the apparatus. The frog was placed at either the top or bottom window depending on the sequence selected beforehand. Both curtains were briefly lifted to reveal the frog and then lowered simultaneously to occlude the toy again. The child was then asked to find the frog. If the child initially selected the correct window on at least three out of four trials, then that child progressed to the control trials.

Control trials. Children where told that they now had to guess where the frog would be hiding. The experimenter clenched both fists so that the frog was hidden from view in one of them and then simultaneously placed one hand at the top location and one at the bottom. The position of the frog was predetermined by the pseudorandom sequence. The child was asked to choose one window to find the frog. All children subsequently progressed to the test condition, although only those children who had demonstrated the capacity to switch search between the top and bottom window on the control trials were included in the final analysis of searching for the falling frogs.

Test trials. Children were instructed to pay close attention because the shelf would sometimes be in and sometimes out. When appropriate, they were also told to keep their eyes on the frog. With each insertion or removal, the experimenter tapped on the shelf to enhance attention to the event. When the shelf was not in place, it was placed against the laboratory wall in full view. The experimenter produced the frog and held it approximately 50 cm above the apparatus. The experimenter then released the frog and asked the child to find it immediately. The first window selected by the child was taken as the initial response, although most would make a second attempt if their first choice was incorrect. Children were always shown the correct location on each trial whether they had been correct or incorrect in their search.

Results

The results are presented in Table 4. Overall, the children failed at the task. There was no tendency for

Table 4 Percentage of Toddlers Searching at Upper Window

Condition	% Search at Upper Window
1st shelf test trial (correct response)	45
2nd shelf test trial (correct response)	55
1st no shelf test trial (correct response)	50
2nd no shelf test trial (correct response)	70

children to search differentially at the upper windows on the shelf trials or at the bottom on the no-shelf trials. The mean percentage for correct searches overall was 45%, not different from chance. When the shelf was in place, the mean percentage of the correct choices of the top window was 50%, and when the shelf was not in place, the mean percentage of the correct choices of the bottom window was 40%. A breakdown by trial and location revealed that the mean success for the first trial was 60% (T = 50%, B = 70%), second trial 35% (T = 40%, B = 30%), third trial 50% (T = 60%, B = 40%), and fourth trial 35% (T = 50%, B = 20%). Thus, there was no hint of improvement over the four test trials due to feedback. As in Experiment 3, we analyzed whether the children differentiated shelf from no shelf trials. For each child, we subtracted the percent choice for search at the upper window on the no-shelf trials from the percent choice for search at the upper window on the shelf trials. Nine children had difference scores of 0, three had difference scores in the positive direction, and eight had difference scores in the negative direction. This distribution did not differ from chance on a two-tailed test (Wilcoxon $T = 44$, $N = 11$, $p > .10$).

Discussion

Experiment 4 differed from Experiments 1 and 2 in that there were no familiarization trials before the test. That is, the child did not see the frog land on the bottom three times before the insertion of the shelf for a solidity trial, and the child did not see the frog land on the shelf three times before its removal for a support trial. If the failure of the 2-year-olds in the other experiments was entirely due to their inability to overcome perseveration of response to the previously viewed location, they should have succeeded in Experiment 4. They did not. Overall performance on the task was at chance with the mean percent of correct responses for each child at 45%. Only three children scored 75% or higher over the four trials. Mean performance on support trials was 50% and mean performance on solidity trials was 40%. Thus Experiment 4 confirms that the failure of 2-year-old children to search correctly is not due solely to the inability to overcome a bias induced by the familiarization sequence.

It must be noted, however, that Experiment 4 placed additional demands on the child in comparison with Experiments 1–3. For example, the trials were not blocked and alternated randomly between having a shelf present or absent. This may have placed heavy attentional demands on the child to note the presence or absence of the shelf. Although the presence of the shelf was always readily visible, future studies should determine to what extent the child is attending to this barrier. Furthermore, the control trials may have biased the child to assume that the task was a guessing game, thus decreasing the likelihood that the presence of the shelf was taken into consideration in the test trials.

GENERAL DISCUSSION

In response to the main question of these studies, it would appear that object knowledge of solidity and support does not guide successful search until at least 2½ years of age. Two-year-old children failed to search correctly in tasks that require establishing the location of hidden objects on the basis of the effect of a barrier on their trajectories. In the first three experiments, 2-year-olds searched for a hidden object where they had seen it before, even though to reach this position on the relevant test trials, the object would have had to pass through a solid shelf or barrier wall. In addition, Experiments 2 and 4 revealed that children of this age seemed not to know that, in the absence of a shelf, a dropped object would be found on the stage floor. Two-year-olds were susceptible to location biases if these were introduced prior to search. These biases did not require an overt motor response because children's searches were influenced by object locations they had merely previously seen.

Although perseveration may have masked knowledge of solidity and support in Experiments 1–3, 2-year-olds failed in Experiment 4 as well, even in the absence of similar familiarization trials. Experiment 4, however, may have introduced new problems by including unblocked multiple trials, with or without the shelf, as well as the inclusion of the control trials, which could conceivably have encouraged the children to search randomly. Nonetheless, we doubt that the failure on the search tasks is solely attributable to an inability to correct a perseverative response introduced by familiarization. This doubt is supported by a recent toddler study with a related paradigm (Berthier, Deblois, Poirier, Novak, & Clifton, 2000). Berthier et al. used a horizontal ramp with four doors and multiple trials with no familiarization; there were no control trials that could have introduced random responding. There was always a barrier present that could be at one of four locations and the experimenter always drew the child's attention to the barrier before search. Again, children did not pass this task reliably until 3 years of age.

The failures of the older 2-year-olds may be fairly limited in the present studies. In Experiments 1 and 3, toddlers of 2½ years of age appeared to use knowledge of solidity to determine where the object would be found, although the study by Berthier et al. (2000) suggests there may be some age variation depending on the task. Further research on 2½-year-olds is clearly justified; in Experiment 1, their success was not calibrated against baseline and control conditions, although there is no reason to expect that these would not be like the baseline and control conditions for 2-year-olds. Therefore, in response to the question about when explicit responses, such as search for or pointing to the location of hidden objects, become constrained by the principles of solidity and support, the answer appears to be somewhere between 2 and 2½ years of age.

The failure of the younger 2-year-olds was consistent. At 24 months, children failed all four versions of the task in this series of studies as well as that of Berthier et al. (2000). Where do these results leave the core knowledge hypothesis? Why is there an apparent discrepancy between the performance of toddlers and infants? There are at least four possibilities worth considering: (1) infant looking-time experiments have been misinterpreted and do not reveal core knowledge of solidity or support; (2) the dependent measures of looking-time studies are statistically more sensitive than are the dependent measures of search/pointing studies; (3) the concept of *knowledge* is theoretically suspect—there is no such thing as knowledge apart from the contexts in which it is deployed; (4) infants and toddlers have knowledge of solidity and support but there are theoretically principled distinctions among types of knowledge or processes that operate on given representations of the world, development of which still continues into the third year of life. We discuss each of these possibilities in turn.

First, some researchers (e.g., Haith & Benson, 1998) have suggested that the infant looking-time studies, upon which the current set of experiments was modeled, do not reflect knowledge of solidity (or support) at all but instead reflect perceptual preferences or novelty preferences based on perceptual features of the displays. If this were so, then the failure of 2-year-olds to reveal understanding of solidity (or support) in the present studies could simply reflect the relatively late acquisition of knowledge of these principles. This issue is not settled, but results from many infant looking-time experiments, with appropriate controls for perceptual preferences or perceptual novelty, provide convergent evidence for infant knowledge of solidity (Baillargeon, 1995; Huntley-Fenner & Carey, 1999; Sitskoorn & Smitsman, 1995; Spelke et al., 1992) and support (Spelke et al., 1992). Thus, in the rest of our discussion, we assume that there is a real conflict in findings—failure of toddlers to reveal knowledge of solidity and support in the face of infant knowledge of the same principles.

Second, infant measures may be statistically more sensitive than the reaching and pointing measures deployed in these studies and in Berthier et al. (2000). Infant looking-time measures typically rely on a within-child comparison between two conditions rather than outright success on a single trial. This cannot be the whole story, however, given the results from Experiments 3 and 4, as well as those of Berthier et al. (2000), where there are multiple trials and within-child comparisons of responses on different types of trial. Another statistical reason the infant studies may reveal earlier competence is that the dependent measure in a looking-time study is continuous (duration of looking), whereas reaching or pointing are categorical and more appropriate for nonparametric analyses, which have less statistical power. Looking-time data, however, including some of those from studies showing knowledge of solidity and support, are often analyzed with nonparametric as well as parametric analyses. Thus, we find it unlikely that statistical factors such as these fully account for the fact that infant looking-time studies reveal knowledge of solidity and support whereas the reaching/pointing studies with young 2-year-olds do not.

The third and fourth possibilities we consider are closely related; they depend upon the theoretical stance one takes on the concept of "knowledge" itself. Philosophers and psychologists from widely different theoretical perspectives have questioned constructs such as "knowledge" or "mental representation" (Churchland & Sejnowski, 1992; Rorty, 1979; Thelen & Smith, 1994), at least as imputed to nonlinguistic creatures. On this view, it is a mistake to ask when a child comes to have some piece of "knowledge": the explanation of behavior must be in nonrepresentational terms (at a neural level, in terms of connectionist or dynamic systems-level modeling). On this view, it is to be expected that action is highly context specific, and empirical work of developmental psychologists should be to discover in as exquisite detail as possible the effects of contextual variables on behavior. If one adopts this perspective, then the contribution of the present studies is to demonstrate a systematic and very large context effect on behavior: Looking times are influenced by certain manipulations in the world a full 2 years earlier in development than are certain patterns of action.

Even if one believes that psychology requires theoretical constructs such as "knowledge," or "mental representation," one may nevertheless agree with theorists such as those cited above that there are many separable systems of mental representations (see Fodor, 1983), and thus many different kinds of knowledge. On this view, the task of developmental psychology, like that of cognitive science in general, is to contribute to the enterprise of finding the distinct systems of mental representation and to understand their development and integration. In this light, the challenge laid down by the current results is to characterize what it is about the mental representations of the presence or absence of the barriers that constrains representations of where the object should be in looking-time studies and how these representations differ from those that guide search or pointing in the present studies. We seek theoretically principled and empirically supported distinctions among types of knowledge or processes that operate on given representations of the world, development of some of which still continues into the third year of life. We have no definitive answer to this quest but rather end with several ways one might think about this problem. Our suggestions are not mutually exclusive; it is likely that several distinct aspects of cognitive architecture are undergoing development during these years and contribute to the earlier manifestation of knowledge in looking time than in reaching studies.

One factor clearly implicated in these studies is the influence of perseveration on these explicit pointing and reaching measures. This too, however, cannot be the whole story, as shown in Experiment 4 and the study by Berthier et al. (2000). Also, because the infant studies also have several familiarization trials before the test trials, the perseveration account simply raises another puzzle: Why are reaching measures more sensitive to perseveration of a response to a previously seen (not reached to or pointed to) location than are the looking-time measures? Perhaps reaching and pointing tasks are susceptible to perseveration because the individual acts or plans for action. At the physiological level, the intent to act can be indistinguishable in terms of neuronal activity from the execution of action, which suggests that much of the preparation may be susceptible to perseverative influences (Rizzolatti, Riggio, & Sheliga, 1994).

The failure of 2-year-olds in these experiments seems to be a particularly striking case of response sensitivity. Other studies of 2-year-olds have also demonstrated different object knowledge depending on the response mode. For example, Kyeong & Spelke (1991, 1999) have shown that when 2-year-olds view the launching of an object off a cliff, they judge impossible falling trajectories where the object falls straight down to "look silly" in comparison with correct parabolic motion. When asked, however, to predict the landing location of such an object in advance of seeing the motion, 2-year-olds choose the straight-down position that is consistent with the impossible trajectory and not the one defined by the correct parabolic movement.

Two types of explanation for this sort of response sensitivity have been offered in the literature. In one explanation, researchers have drawn a systematic distinction between kinds of representations called upon in different tasks—for example, the knowledge drawn upon in the looking-time methods is perceptual, or implicit, or encapsulated within a visual module, whereas the knowledge drawn upon in the reaching/pointing methods is conceptual, or explicit, or widely accessible. Researchers in the field, however, have not succeeded in agreeing upon how to draw the perceptual/conceptual, implicit/explicit, encapsulated/accessible distinctions nor on how to establish which infant representations are which. This isn't to say that we won't eventually need such distinctions in our accounts of early cognition but only that evaluating proposals based on them is difficult as of now. However, even if knowledge of solidity is encapsulated within the processes subserving perception, and hence perceptual or implicit, the output of these processes would likely be a representation of objects and their locations, and these should guide reaching/pointing. Otherwise, perceptual processes would be redundant, and only some of them would guide the action system. This seems implausible because of the way evolutionary mechanisms tend to select against mechanisms that do not translate into the basis of action (Cosmides & Tooby, 1994).

A second type of explanation for differential success in looking-time and reaching/pointing measures appeals to details of the processing of a single type of representation. For example, Munakata and colleagues (Munakata, McClelland, Johnson, & Siegler, 1997) suggested that reaching requires a stronger, more robust, representation (e.g., a stronger memory trace of the hidden object) than does looking and argued reasonably that continued learning about the physical world leads to more robust representations. Another idea within this second class of explanation involves the contrast between prediction, on the one hand, and making sense of what has happened after the fact, on the other. When the infant is shown the possible and impossible outcomes in the violation-of-expectancy paradigms, the infant has all the relevant information to compare the outcome with the memory of the specific event leading up to that outcome (see Meltzoff & Moore, 1998, for a similar account of prediction versus postdiction). Infants may try to make a representation of the total event, now revealed, that is consistent with their physical knowledge, and in the impossible outcomes they are unable to do so. In the reaching/pointing versions of the task, however, the infant must recruit knowledge of the relevant aspects of the event to make a prediction. This is a much less constrained problem, and apparently even 2-year-olds do not spontaneously succeed. It is not that their representation of the hidden object location relative to the barrier is less robust; it is that they have not formed such a representation at all. They have represented the object as behind the screen which is why they search, but they have not taken the barrier into account in forming a representation of location. This interpretation of the children's failure implies that infants in the violation-of-expectancy studies are also not predicting where the object will be on the shelf and then seeing whether the outcome matches the predictions. Rather, this account implies that infants, as well as 2-year-olds, are noting the physical arrangement of details, making no prediction as to outcome, and then evaluating whether the shown outcome is consistent with the physical arrangement.

In sum, we hyothesize that knowledge of solidity and support is not revealed in the present search tasks at 2 years of age because toddlers of this age may not yet have the capacity to readily recruit this knowledge in situations where they have to make predictions. Prediction under circumstances where there is limited or absent perceptual input would seem to require the capacity to recognize and organize the relevant features and then simulate the final outcome in a feedforward manner. Under these circumstances, 2-year-olds are most likely to guess at the outcome or resort to various biases that can be experimentally induced.

The resolution of the puzzle provided by these data awaits further empirical and conceptual work. What is clear, however, is that even aspects of putative "core knowledge" are not available to guide simple explicit responses until late into the third year of life.

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