

Infants Use Compression Information to Infer Objects' Weights: Examining Cognition, Exploration, and Prospective Action in a Preferential-Reaching Task

Petra Hauf

St. Francis Xavier University

Markus Paulus

Ludwig Maximilian University

Renée Baillargeon

University of Illinois

The present research used a preferential-reaching task to examine whether 9- and 11-month-olds ($n = 144$) could infer the relative weights of two objects resting on a soft, compressible platform. Experiment 1 established that infants reached preferentially for the lighter of 2 boxes. In Experiments 2–4, infants saw 2 boxes identical except in weight resting on a cotton wool platform. Infants reached prospectively for the lighter box, but only when their initial exploratory activities provided critical information. At 11 months, infants succeeded as long as they first determined that the platform was compressible; at 9 months, infants succeeded only if they also explored the boxes and thus had advance knowledge that they differed in weight.

Adults' remarkable prospective control in their everyday actions depends in part on their physical knowledge—their understanding of the ways in which objects and other physical entities can move and interact (e.g., Adolph, Eppler, Marin, Weise, & Clearfield, 2000; von Hofsten, 2007). Whether we are stacking dishes, hanging laundry, preparing a salad, or wrapping gifts, we bring to bear our physical knowledge to select objects, to plan what actions to perform with these objects, and to anticipate the outcomes of our actions. As von Hofsten (2007) stated, "Cognition and action are mutually interdependent. . . . [Our] prospective control is possible because events are governed by rules. . . . Knowledge of rules makes smooth and skillful actions possible" (p. 54). In this research, we set out to examine 9- and 11-month-old infants' knowledge of one particular physical rule having to do with

weight and compression (henceforth the *weight-compression rule*): When placed on a soft supporting platform, a heavier object will compress the platform more than a lighter object will. We reasoned that positive results would not only shed light on an uncharted facet of infants' physical knowledge but would also provide researchers with a useful method for investigating the development of infants' knowledge about the various factors (e.g., size, material, contents) that contribute to an object's weight. Finally, and perhaps most interestingly, the present experiments also bore on two broad issues concerning the complex links between cognition and action; each issue is discussed next.

When Do Infants Reveal Their Physical Knowledge in Their Actions?

One long-standing difficulty in determining what physical rules infants possess at each stage of development has been that different methods do not always point to the same answer. In particular, discrepancies have been reported between action and violation-of-expectation tasks. For example, although manual-search findings suggest that

This research was supported by the Max-Planck-Institute for Human Cognitive and Brain Sciences, Munich, Germany, where the experiments were conducted; by Grants from CFI (203229) and NSERC (322013) to Petra Hauf; and by a Grant from NICHD (HD-021104) to Renée Baillargeon. We thank Kris Onishi for helpful suggestions; the Max-Planck-BabyLab Team, Kailee MacDonald, and Charlene Parker for their help with the data collection and coding; and the parents and infants who made this research possible.

Correspondence concerning this article should be addressed to Petra Hauf, Department of Psychology, St. Francis Xavier University, PO Box 5000, Antigonish, NS, Canada B2G 2W5. Electronic mail may be sent to phauf@stfx.ca.

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DOI: 10.1111/j.1467-8624.2012.01824.x

infants younger than 8 months are not able to represent hidden objects (e.g., Diamond, 1985; Piaget, 1954), violation-of-expectation findings suggest that this ability is present much earlier (e.g., Baillargeon & DeVos, 1991; Spelke, Breinlinger, Macomber, & Jacobson, 1992). The discovery of this and other dissociations (e.g., Ahmed & Ruffman, 1998; Vishton, Ware, & Badger, 2005) led to a heated debate between proponents of action and violation-of-expectation methods, which continued unabated until new approaches suggested ways of reconciling these divergent findings (e.g., Berthier et al., 2001; Boudreau & Bushnell, 2000; Keen & Berthier, 2004; Munakata, McClelland, Johnson, & Siegler, 1997). One such approach, the *processing-load* approach, holds that infants' information-processing resources are initially limited and improve gradually with age, that the processing demands of any action task depend on both the difficulty of the physical reasoning involved and the difficulty of the actions involved, and that infants may fail at an action task because the combined demands of the task overwhelm their limited resources (e.g., Boudreau & Bushnell, 2000; Keen & Berthier, 2004). Thus, according to the processing-load approach, the reason why young infants who are able to reach for objects fail at manual-search tasks is not that they cannot represent hidden objects (as they do so in violation-of-expectation tasks; e.g., Luo, Baillargeon, Brueckner, & Munakata, 2003), and not that they cannot plan and execute appropriate actions (as they do so in action tasks with partly visible objects; e.g., Shinsky, 2002), but that the overall demands of manual-search tasks overwhelm their limited processing resources (e.g., Daum, Prinz, & Aschersleben, 2009; Hespos & Baillargeon, 2008).

The processing-load approach has led researchers to seek tasks that minimize action demands when investigating at what ages infants first demonstrate knowledge of specific rules in their actions (e.g., Berthier et al., 2001; Hespos & Baillargeon, 2006; McCurry, Wilcox, & Woods, 2009; von Hofsten, Kochukova, & Rosander, 2007). One such task, the *preferential-reaching* task, is adapted from research on depth perception by Yonas and his colleagues (e.g., Yonas, Cleaves, & Pettersen, 1978). Preferential-reaching tasks are relatively undemanding because infants need only to direct their reach toward one stimulus as opposed to another; inferences are then drawn about the processes responsible for adaptive selections.

In recent years, preferential-reaching tasks with infants aged 5.5 months and older have confirmed several key findings from violation-of-expectation

tasks, indicating that when action demands are minimal, infants can reveal the same physical knowledge in action and violation-of-expectation tasks (e.g., Hespos & Baillargeon, 2006; Wang & Kohne, 2007). For example, Hespos and Baillargeon (2008) used a preferential-reaching task to test 6.5-month-olds' knowledge of the proportion-of-contact rule: When placed on a platform, an object will remain stable only if half or more of its bottom surface rests on the platform. In line with prior violation-of-expectation findings (e.g., Baillargeon, Needham, & DeVos, 1992), infants reached reliably more for a toy with its entire bottom surface resting on its platform than for an identical toy with only 15% of its bottom surface resting on its platform. This and control results indicated that infants used the proportion-of-contact rule to determine which toy was potentially retrievable and which toy was not (the toy with 15% support could retain its position only if it was attached to its platform). The present research built on these findings and used a preferential-reaching task to examine infants' knowledge of the weight-compression rule.

When Does Exploration Contribute to Infants' Use of Their Physical Knowledge?

Infants' actions do not simply mirror their physical knowledge: They also play a critical role in the *acquisition* of this knowledge. Over the past decades, a great deal of research has examined how infants' spontaneous exploratory activities help them learn about objects, surfaces, and events (e.g., Adolph, Eppler, & Gibson, 1993; Gibson, 1988; Piaget, 1954). As Gibson (1988) stated, "Exploratory development during the first year of life occurs as a sequence of phases that build the infant's knowledge of the permanent features of the world, of the predictable relations between events, and of its own capacities for acting on objects and intervening in events" (p. 7).

In addition to making it possible for infants to learn about the physical world, exploration can also contribute to infants' *use* of their physical knowledge in specific situations; exploratory activities within a task are sometimes essential for infants to successfully apply their physical knowledge. In the preferential-reaching task described in the last section (Hespos & Baillargeon, 2008), little exploration—beyond visually examining how much of each toy's bottom surface rested on its platform—was required for infants to act on their knowledge. In contrast, consider a locomotor task that examined 16-month-olds' ability to walk safely across a

narrow bridge spanning a large crevice between two platforms; experimental manipulations included whether a handrail was present or not (Berger & Adolph, 2003), whether the handrail was located nearer or farther from the bridge (Berger, Adolph, & Kavookjian, 2010), and whether the handrail was rigid or “wobbly” (Berger, Adolph, & Lobo, 2005). In all of these experiments, a similar picture emerged: “Infants demonstrated knowledge about needing a suitable floor for crossing, about recruiting implements from the environment to enhance balance control, and about modifying typical locomotor strategies in response to ongoing challenges” (Berger et al., 2010, p. 1374). However, in all cases, whether infants successfully demonstrated this knowledge in more difficult trials crucially depended on their exploratory activities prior to stepping on the bridge. For example, infants who spent time on the starting platform manipulating the wobbly handrail in ways that could yield information about its material properties and its ability to support their weight (e.g., by squeezing it and leaning on it) were reliably more likely to use the handrail effectively and hence to cross the bridge safely (Berger et al., 2005).

The preceding experiments make clear that there exists a continuum from tasks where little exploration is needed for infants to reveal their physical knowledge in their actions, to tasks where exploration is essential for infants to do so. What factors determine whether exploration is required in a given task? Is it simply that exploration is helpful when novel objects have relevant properties that cannot be ascertained from visual inspection alone? Or could exploration—perhaps when infants’ physical knowledge is less well entrenched—also help infants focus on the relevant information and interpret it according to the relevant prior knowledge? To address these questions, as explained next, we also investigated whether infants’ spontaneous gathering of weight and compressibility information played a role in their ability to demonstrate their knowledge of the weight-compression rule.

The Present Research

The present experiments examined 9- and 11-month-olds’ knowledge of the weight-compression rule using tasks that built on the findings described in the previous sections in two ways. First, we used preferential-reaching tasks: We speculated that because such tasks pose minimal action demands, infants might be more likely to reveal their physical knowledge. Experiment 1 served as a baseline and

established that after manipulating two boxes that differed in both color and weight, 9- and 11-month-olds remembered which color box was lighter and which was heavier and reached consistently for the lighter box (see Figure 1a). In Experiment 2, infants first manipulated a cotton wool platform and two boxes that were identical except in weight. Next, in the test trials, infants saw the two boxes resting on the cotton wool platform; one box compressed the platform very little and the other box compressed it very much (see Figure 1b). We predicted that if infants noticed how much each box compressed the platform and could infer—by applying the weight-compression rule—which box was lighter and which was heavier, then they should again reach prospectively for the lighter box.

Second, we were interested in determining whether or how infants’ exploratory activities contributed to their success in identifying the lighter box. In Experiment 1, the two boxes rested on a rigid platform in the test trials so infants could succeed only if they gathered (and remembered) information about the colors and weights of the boxes as they manipulated them at the start of the experiment. However, this was not the case in Experiment 2: By simply looking at Figure 1b, adults can readily infer the relative weights of the two boxes. This raised the question of whether infants’ spontaneous exploration of the platform and boxes at the start of Experiment 2 played any role in their responses in the test trials. To address this question, in our subsequent experiments we curtailed infants’ exploratory behavior prior to the test trials: In Experiment 3, infants were allowed to manipulate the platform but not the boxes, and in Experiment 4, they were allowed to manipulate neither the platform nor the boxes. To give a general preview of the results of Experiments 2–4, infants succeeded in identifying the lighter box only when they engaged in specific exploratory activities prior to the test trials. Furthermore, the 9-month-olds required more exploration than did the 11-month-olds to identify the lighter box. In the General Discussion section, we speculate on the roles that infants’ exploratory activities may have played, at each age, in their test responses. More generally, we reflect on the links that can exist between cognition, exploration, and prospective action, even in seemingly very simple action tasks.

Experiment 1

Analyses of infants’ manual actions on objects indicate that, by 8 or 9 months of age, infants encode

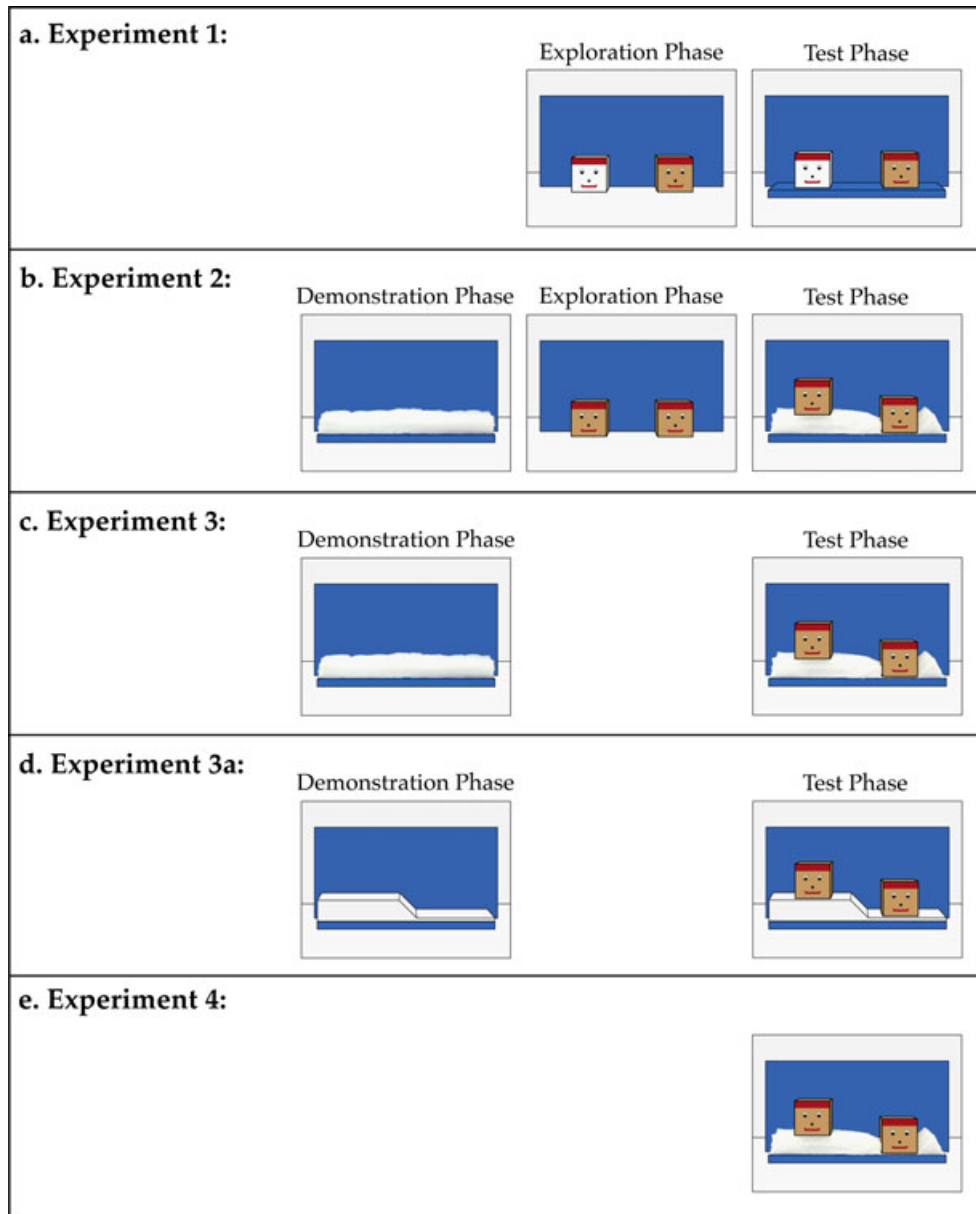


Figure 1. Schematic depiction of the stimuli and procedure used in Experiments 1-4.

the weights of objects and expect the same object to weigh the same on repeated presentations (e.g., Itier, Provasi, & Bloch, 2001; Mash, 2007; Molina & Jouen, 2003; Paulus & Hauf, 2011). For example, Mash (2007) familiarized 9-, 12-, and 15-month-olds with two objects that differed only in color and weight. Next, infants were presented with two test objects that were similar to the familiarization objects except that their weights were reversed. At all ages, infants reached faster for the test object they expected to be light, and they used more force to lift the test object they expected to be heavy, indicating that they remembered the weight of each

familiarization object. Experiment 1 built on these findings and asked whether 9- and 11-month-olds, after being familiarized with two boxes that differed only in color and weight, would reach preferentially for the lighter, more portable box.

Infants were tested with a two-phase procedure that consisted of an exploration and a test phase (see Figure 1a). During the exploration phase, infants received two trials in which they were presented with two boxes, one per trial. The boxes differed in both color (white or brown) and weight (300 or 2,000 g); the color and order of presentation of the lighter and heavier boxes were counterbalanced

across infants. During the test phase, infants received four trials in which they saw the two boxes standing apart on a rigid platform; the left and right positions of the boxes were counterbalanced across trials.

Method

Participants

The final sample consisted of 32 healthy term infants and included sixteen 9-month-olds (8 boys and 8 girls; $M = 8.81$ months, $SD = 0.24$, range = 8.57–9.40) and sixteen 11-month-olds (8 boys and 8 girls; $M = 11.12$ months, $SD = 0.32$, range = 10.50–11.50). Another 6 infants (three 9-month-olds and three 11-month-olds) were excluded because they refused to remain seated (2), refused to touch one or both boxes during the exploration trials (3), or did not reach for a box in two or more test trials (1). For all experiments, infants were recruited through public birth records and word of mouth in the Munich metropolitan area and were tested in a research laboratory setting. Infants were primarily white and from middle-class families.

Stimuli

Four wooden boxes (each 10 cm a side) were used in the experiment. Two boxes were painted white and two were painted brown; in each color pair, one box weighed 300 g and the other box weighed 2,000 g. All the boxes were decorated with a small identical face to help attract infants' attention. Stimuli also included a wooden screen (30 cm high \times 60 cm wide) and a wooden platform (2.5 cm \times 50 cm \times 15 cm), both painted blue.

Procedure

Each infant sat on a parent's lap at a test table in a cut-out area (30 cm \times 25 cm); the experimenter sat across from the infant. Parents were instructed to hold their infants at the hips, to remain silent and neutral, and to look down at their infant during the test trials.

Exploration phase. The exploration phase involved two trials. In each trial, the screen stood centered on the table, 40 cm from and parallel to the top of the cut-out area. The experimenter brought the first box from behind the screen, placed it on the table in front of the infant, and encouraged the infant to play with it; after 45 s, the experimenter returned the box behind the screen. During the second trial, the experimenter repeated the same actions with

the second box. When moving a box, the experimenter always grasped it with both hands, so that his or her grip did not differ between the two boxes.

Because infants could reach preferentially for the lighter box in the test phase only if they detected the weight difference between the two boxes in the exploration phase, we paid special attention to how infants manipulated the boxes (see Table 1). For each box, a primary coder measured how long infants spent *touching* the box overall, and how long they engaged in three behaviors that could yield information about the box's weight: *pushing* the box along the surface of the table, *lifting* the box in midair, and *tipping* the box so that one end was off the table (other behaviors, such as mouthing and patting, seemed less likely to help infants distinguish the boxes' weights and were not pursued here). A secondary coder independently scored 25% of the infants in Experiments 1–3A on their behaviors prior to the test phase; correlation coefficients ranged from $r = .97$ to 1.0. The data from the four dependent measures (time spent touching, pushing, lifting, and tipping each box) were entered into a 2 (age: 9 or 11 months) \times 2 (weight: lighter or heavier box) multivariate analysis of variance (MANOVA) with repeated measures on the last factor. This analysis yielded a main effect of weight, $F(4, 27) = 26.56$, $p < .001$, $\eta_p^2 = .80$. Subsequent univariate analyses (corrected using the Huynh–Feldt procedure) revealed that infants touched the lighter box significantly longer than the heavier box, $F(1, 30) = 9.92$, $p = .004$, $\eta_p^2 = .25$. In addition, although infants spent about as much time pushing the two boxes, $F(1, 30) = 1.22$, $p = .278$, $\eta_p^2 = .04$, they spent significantly more time lifting the lighter box, $F(1, 30) = 69.54$, $p < .001$, $\eta_p^2 = .70$ (as shown in Table 1, no infant succeeded in lifting the heavier box), and they spent significantly more time tipping the heavier box, $F(1, 30) = 7.69$, $p = .009$, $\eta_p^2 = .20$. On average, infants spent 37.77 s ($SD = 5.07$) touching the lighter box, and 67% of that time (25.30 s, $SD = 9.45$) was spent in weight-relevant behaviors (pushing, lifting, and tipping); infants spent 34.84 s ($SD = 6.62$) touching the heavier box, and 55% of that time (19.00 s, $SD = 9.20$) was spent in weight-relevant behaviors (pushing and tipping). As they explored the two boxes, most infants thus had ample opportunity to detect their different weights. This conclusion is consistent with extensive evidence that, well before their first birthday, infants explore objects and surfaces to discover their properties, and adaptively tailor their behaviors to these properties (e.g., Adolph et al., 1993; Fontenelle, Kahrs, Neal, Newton, & Lockman, 2007).

Table 1
 Mean Duration of the 9- and 11-Month-Old Infants' Behaviors on the Platform (Demonstration Phase) and Lighter and Heavier Boxes (Exploration Phase) in Experiments 1-3

	Platform			Lighter box			Heavier box			Overall touching	
	Overall touching	Pushing	Lifting	Tipping	Sum	Overall touching	Pushing	Lifting	Tipping		Sum
Experiment 1											
9 months	—	14.28 (6.81)	9.74 (6.43)	0.87 (2.82)	24.89 (10.05)	38.04 (4.69)	14.37 (6.43)	0.00 (0.00)	5.94 (6.20)	20.31 (9.32)	34.88 (5.77)
11 months	—	11.40 (5.67)	12.24 (8.36)	2.07 (2.37)	25.71 (9.13)	37.50 (5.56)	14.28 (6.05)	0.00 (0.00)	3.41 (4.50)	17.69 (9.19)	34.80 (7.58)
Both	—	12.84 (6.34)	10.99 (7.44)	1.47 (2.64)	25.30 (9.45)	37.77 (5.07)	14.32 (6.14)	0.00 (0.00)	4.67 (5.48)	19.00 (9.20)	34.84 (6.62)
Experiment 2											
9 months	6.90 (2.01)	13.62 (5.57)	7.54 (7.17)	2.55 (2.63)	23.71 (11.48)	36.65 (8.08)	15.19 (5.57)	0.00 (0.00)	7.20 (5.94)	22.39 (10.39)	34.83 (7.59)
11 months	7.74 (1.45)	14.74 (6.10)	8.26 (5.43)	4.82 (4.83)	27.83 (8.03)	37.82 (4.86)	15.82 (5.23)	0.00 (0.00)	7.90 (5.52)	23.72 (8.00)	34.51 (5.89)
Both	7.32 (1.78)	14.18 (5.77)	7.90 (6.27)	3.68 (4.00)	25.77 (9.97)	37.24 (6.59)	15.51 (5.33)	0.00 (0.00)	7.55 (5.65)	23.06 (9.15)	34.67 (6.69)
Experiment 3											
9 months	6.92 (2.10)	—	—	—	—	—	—	—	—	—	—
11 months	7.10 (1.72)	—	—	—	—	—	—	—	—	—	—
Both	7.01 (1.89)	—	—	—	—	—	—	—	—	—	—

Note. Sum = the sum of the duration of the three weight-relevant behaviors (pushing, lifting, and tipping) on each box. Values in brackets are standard deviations.

Test phase. The test phase involved four trials. Each trial started with the screen centered on the table, 40 cm from the cut-out area. The experimenter first moved the screen closer to his or her end of the table to reveal the two boxes centered 15 cm apart on the platform. The experimenter then slid the platform forward until it stood 40 cm from the cut-out area, and tapped the top of each box gently for 1 s, to draw the infant's attention to it. Next, the experimenter pushed the platform toward the infant, stopping at the edge of the infant's reaching space. The infant was given up to 15 s to respond; during that time, the experimenter looked at the center of the platform to avoid inadvertently cueing the infant. Because we wanted to know if infants could use information from the exploration phase to identify the lighter box, infants could not be allowed to touch the boxes (and thus possibly gain information about their weights) during the test phase. As the infant's hand approached a box, the experimenter pulled the platform back as needed to make sure the infant's hand did not actually contact the box (manipulation checks in this and the following experiments confirmed that infants did not touch the boxes; reaches typically terminated within about 5 cm of each box). Following the child's reach, the experimenter cheered, slid the platform to his or her end of the table, placed the screen in front of the platform, and reset the boxes to begin the next trial. The positions of the white and brown boxes were reversed across trials; the order in which these positions were presented, and the order in which the boxes were tapped, were counterbalanced across infants.

Two video cameras recorded the infant's reaching behavior. One camera captured a side view of the infant, and the other camera was fixed to the left of the experimenter to capture the experimenter's hands, the infant's torso, head, and hands, and most of the tabletop. The images from the two cameras were combined using a video mixer.

Coding. Each videotaped session was viewed by two independent coders who were blind to the infant's exploration phase. On each test trial, the coders judged whether the infant reached for the white or the brown box. Discrepancies between the two coders were resolved through discussion; this occurred on < 3% of the trials in the present experiments. All infants who reached for a box in three or more of the four test trials were retained in the analyses (three 9-month-olds and one 11-month-old in the present experiments completed only three test trials; all four infants were in Experiment 1 and reached for the lighter box in all three trials).

Preliminary analyses of the test data in Experiments 1–4 revealed no significant effects of box color condition (Experiment 1 only), sex, order of presentation, or order of tapping; the data were therefore collapsed across these factors in subsequent analyses.

Results and Discussion

For each infant, we calculated the proportion of test trials that the infant reached for the lighter box (e.g., an infant who reached for the lighter box on three of four trials received a score of .75). Two-tailed one-sample t tests against chance (50%) indicated that infants reached preferentially for the lighter box at 9 months ($M = 77\%$, $SD = 19$), $t(15) = 5.51$, $p < .001$, and at 11 months ($M = 72\%$, $SD = 13$), $t(15) = 7.00$, $p < .001$ (see Figure 2). The responses of the two age groups did not differ reliably, $F(1, 30) < 1$.

Infants could select the lighter box reliably above chance only if they had learned in the exploration phase which color box was lighter and which was heavier. Accordingly, we next examined whether infants' behaviors during the exploration phase correlated with their performance in the test phase; in these analyses, the two age groups were combined as no reliable differences were found between them. To compute the time infants spent in *weight-relevant behaviors* during the exploration phase, we summed the time they spent pushing, lifting, and tipping the two boxes (see Table 1); to compute the time infants spent in *weight-irrelevant behaviors*, we subtracted the time they spent in weight-relevant behaviors from the total time they spent touching the two boxes. Infants' test performance was positively correlated with the time they spent in

weight-relevant behaviors ($r = .71$, $p < .001$), and negatively correlated with the time they spent in weight-irrelevant behaviors ($r = -.48$, $p = .005$). Thus, the more time infants spent in weight-relevant behaviors during the exploration phase, the more likely they were to reach for the lighter box in the test phase (see Figure 3); conversely, the more time infants spent in weight-irrelevant behaviors, the less likely they were to do so.

Finally, to gain a sense of infants' individual performances, we examined how many infants succeeded at our task, with success defined as reaching for the lighter box on at least three test trials (e.g., Hespos & Baillargeon, 2006). Although the probability of an infant reaching for the lighter box in any one trial was .50, the probability of an infant doing so on at least three trials was .3125. In line with the results reported earlier, twelve of the sixteen 9-month-olds (cumulative binomial probability, $\theta = .3125$, $p < .001$) and thirteen of the sixteen 11-month-olds ($p < .001$) reached preferentially for the lighter box on three or more trials. Of the seven unsuccessful infants, one 9-month-old and one 11-month-old reached equally for the two boxes, and three 9-month-olds and two 11-month-olds showed a side bias, reaching for the box on the same side of midline (e.g., the box on the right) on all four trials (we discuss infants with a side bias after Experiment 4).

Together, the preceding results suggest that most of the 9- and 11-month-olds in Experiment 1 detected the difference in the boxes' weights during the exploration phase, remembered which color box was lighter and which was heavier during the test phase, and reached preferentially for the lighter box. How should we interpret this preference? One possibility is that the infants recognized that the lighter box was more portable or retrievable than the heavier box, as they had had more difficulty moving the heavier box in the exploration phase. Another possibility is that the infants particularly enjoyed the actions they could perform on the lighter box. Whatever the case may be, the main goal of Experiment 1 was to establish that 9- and 11-month-olds would reach consistently for the lighter of two boxes. Armed with this finding, we could proceed in Experiment 2 to examine infants' knowledge of the weight-compression rule.

Experiment 2

As adults, we understand that an object resting on a platform exerts a force on the platform, and that a

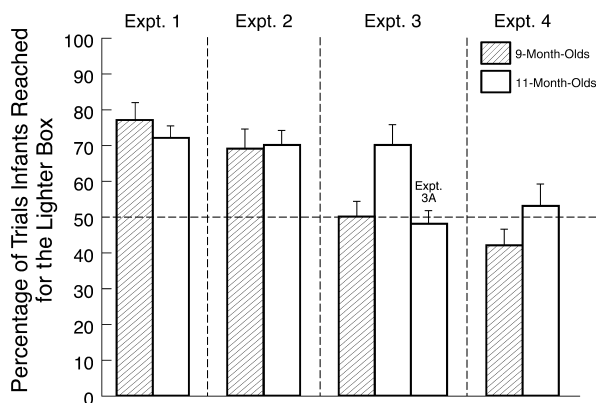


Figure 2. Mean percentage of trials 9- and 11-month-olds reached preferentially for the lighter box in Experiments 1–4. Note. Error bars represent standard errors of the mean.

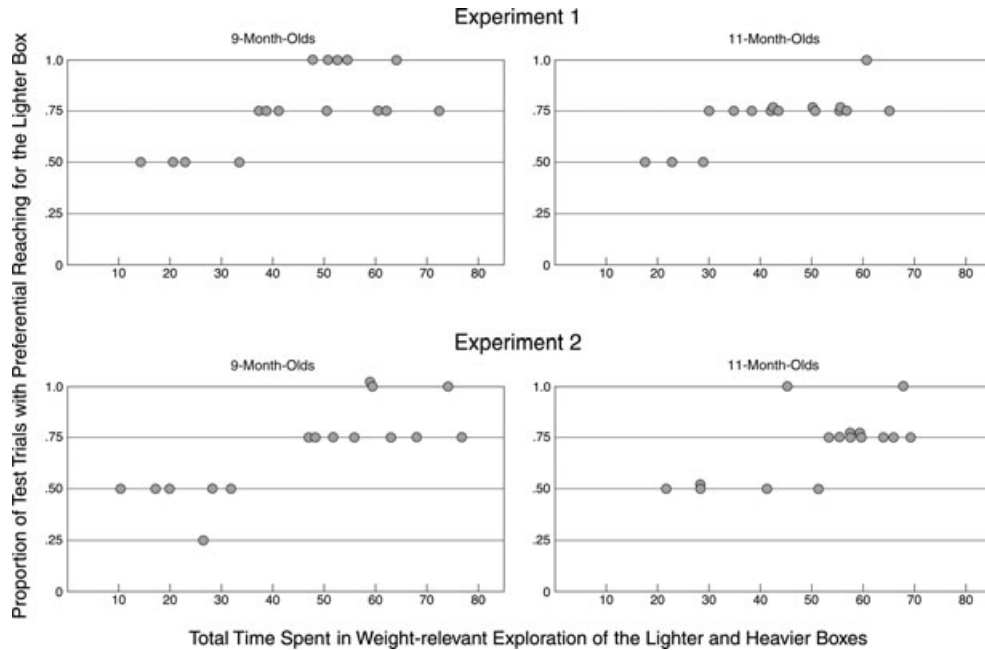


Figure 3. Correlations between time spent in weight-relevant exploration of the lighter and heavier boxes during the exploration phase (of a maximum of 90 s, with 45 s per box) and reaching preferentially for the lighter box during the test phase. Note. Correlations are shown separately for the 9- and 11-month-olds in Experiment 1 (top) and Experiment 2 (bottom).

heavier object exerts more force than a lighter object does: We would blanch if we saw a mover unload a large television, but not a small radio, onto our delicate antique table. Do considerations about objects' weights and their associated forces also play a role in infants' expectations about support events? To begin investigating this question, we presented 9- and 11-month-old infants with two objects, identical except in weight, resting on a compressible platform. How likely were the infants to perceive the object causing more compression as heavier and the object causing less compression as lighter? Several bodies of research tentatively suggested that they might do so. First, analyses of infants' manual actions on objects indicate that they encode whether objects are compressible or rigid (e.g., Bourgeois, Khawar, Neal, & Lockman, 2005; Paulus & Hauf, 2011). For example, 6- to 10-month-olds squeezed a compressible cube more than a rigid cube, and pressed their hands into a compressible surface more than into a rigid surface (Bourgeois et al., 2005). Second, violation-of-expectation findings indicate that infants hold different expectations for physical events involving compressible as opposed to rigid objects, and especially recognize that exerting pressure on a compressible object can reduce its size or alter its shape (e.g., Aguiar & Baillargeon, 1998; Schweinle & Wilcox, 2004). For example, 8.5-month-olds detected a

violation when a large rigid ball, but not a large compressible ball, was lowered into a small rigid container (Aguiar & Baillargeon, 1998). Finally, violation-of-expectation findings indicate that infants also hold different expectations for physical events involving heavier as opposed to lighter objects (e.g., Wang & Baillargeon, in Baillargeon, 2002; Wang, Kaufman, & Baillargeon, 2003). Thus, when shown events in which a heavier or a lighter cylinder rolled down a ramp and hit a box, 9.5-month-olds expected the heavier cylinder to exert more force than the lighter cylinder: They detected no violation when the heavier cylinder displaced the box but the lighter cylinder did not (e.g., Wang & Baillargeon, in Baillargeon, 2002). Given these various findings, it seemed possible that 9- and 11-month-olds might have some knowledge of the weight-compression rule and hence might be able to infer the relative weights of two objects on a compressible platform.

Infants were tested using a three-phase procedure that consisted of a demonstration, an exploration, and a test phase (see Figure 1b). During the demonstration phase, infants observed the experimenter press a platform made of cotton wool, and then they were allowed to touch it themselves. During the exploration phase, infants received two trials in which they manipulated two brown boxes, one per trial; the boxes differed only in weight (300

or 2,000 g). Finally, in the test phase, infants received four trials in which they saw the two boxes resting on the cotton wool platform; one box compressed the platform very little and the other compressed it very much. We reasoned that if infants noticed how much each box compressed the platform and possessed relevant physical knowledge to correctly interpret this information, then they should reach preferentially for the lighter box, like the infants in Experiment 1.

Method

Participants

Participants were 32 healthy term infants and included sixteen 9-month-olds (8 boys and 8 girls; $M = 8.87$ months, $SD = 0.22$, range = 8.60–9.27) and sixteen 11-month-olds (8 boys and 8 girls; $M = 11.14$ months, $SD = 0.17$, range = 10.77–11.37). Another 5 infants (three 9-month-olds and two 11-month-olds) were excluded because they refused to remain seated (1), refused to touch one or both boxes during the exploration trials (2), or did not reach in two or more test trials (2).

Stimuli

The stimuli used in Experiment 2 were identical to those in Experiment 1, with the following exceptions. First, during the demonstration phase, the infants were shown a blue wooden platform similar to that in Experiment 1 except that it was 10 cm deep and covered with a thick layer of cotton wool 6 cm high. Second, the two boxes used in the exploration and test trials were the two brown boxes from Experiment 1; as before, one box weighed 300 g and the other weighed 2,000 g. Third, in the test trials, one box rested on top of the cotton wool whereas the other box compressed the cotton wool completely and thus rested just above the wooden portion of the platform (see Figure 1b).

Procedure

The procedure in Experiment 2 was similar to that in Experiment 1 except as noted next.

Demonstration phase. At the start of the demonstration phase, the screen stood centered on the table, 40 cm from the cut-out area. The experimenter brought the cotton wool platform from behind the screen and placed it on the table about 15 cm from the cut-out area. While the infant was watching, the experimenter pressed down on the

cotton wool with both hands, keeping it compressed for about 3 s. Next, the experimenter lifted both hands and then pressed down on the cotton wool alternately with one hand and then the other, for about 2 s each. Finally, the experimenter slid the platform closer to the cut-out area and encouraged the infant to touch the cotton wool. After about 10 s, the experimenter returned the platform behind the screen.

Because infants watched the experimenter press the cotton wool, they had information that it was compressible. Coders also measured how long infants spent *touching* the cotton wool; even a slight pressure was sufficient to compress it, providing infants with additional information about its compressibility (see Table 1). On average, infants touched the platform for 7.32 s ($SD = 1.78$), and no reliable difference was found between the responses of the 9- and 11-month-olds, $F(1, 30) = 1.88$, $p = .181$, $\eta_p^2 = .06$.

Exploration phase. The order of presentation of the lighter and heavier brown boxes was counter-balanced across infants. As in Experiment 1, coders measured how long infants spent touching, pushing, lifting, and tipping each box (see Table 1). A MANOVA similar to that in Experiment 1 revealed a main effect of weight, $F(4, 27) = 14.09$, $p < .001$, $\eta_p^2 = .68$. Subsequent univariate analyses showed that the infants touched the lighter box significantly longer than the heavier box, $F(1, 30) = 10.69$, $p = .003$, $\eta_p^2 = .26$. In addition, although infants spent about as much time pushing the two boxes, $F(1, 30) = 1.60$, $p = .216$, $\eta_p^2 = .05$, they spent significantly more time lifting the lighter box, $F(1, 30) = 49.41$, $p < .001$, $\eta_p^2 = .62$ (as before, no infant succeeded in lifting the heavier box), and they spent significantly more time tipping the heavier box, $F(1, 30) = 14.46$, $p = .001$, $\eta_p^2 = .33$. On average, infants spent 37.24 s ($SD = 6.59$) touching the lighter box, and 69% of that time (25.77 s, $SD = 9.97$) was spent in weight-relevant behaviors (pushing, lifting, and tipping); infants spent 34.70 s ($SD = 6.68$) touching the heavier box, and 66% of that time (23.06 s, $SD = 9.15$) was spent in weight-relevant behaviors (pushing and tipping). Infants thus had ample opportunity to gather information about the boxes' weights.

Comparison of the exploration phases in Experiments 1 and 2 revealed no reliable differences in the times infants spent touching the boxes, $F(1, 62) < 1$, or exploring them in weight-relevant ways, $F(1, 62) = 1.18$, $p = .282$, $\eta_p^2 = .02$.

Test phase. In each trial, the lighter and heavier brown boxes rested on the cotton wool platform.

The left and right positions of the two boxes were reversed across trials; as before, the order of presentation and order of tapping were counterbalanced across infants.

Coding. The infants' test responses were coded as in Experiment 1. Videotaped sessions from Experiments 2–4 were first edited to include only the test phase; they were then coded by two independent observers blind to the infants' experiment.

Results and Discussion

The test data were analyzed as in Experiment 1. Infants reached for the lighter box reliably above chance at 9 months ($M = 69\%$, $SD = 21$), $t(15) = 3.50$, $p = .003$, and at 11 months ($M = 70\%$, $SD = 16$), $t(15) = 4.96$, $p < .001$ (see Figure 2). The responses of the two age groups did not differ reliably, $F(1, 30) < 1$. Infants' test performance was positively correlated with the time they spent during the demonstration phase touching the cotton wool platform ($r = .38$, $p = .033$); it was also positively correlated with the time they spent during the exploration phase producing weight-relevant behaviors on the two boxes ($r = .75$, $p < .001$; see Figure 3) and negatively correlated with the time they spent producing weight-irrelevant behaviors on the two boxes ($r = -.61$, $p < .001$). Thus, the longer infants spent gathering information about the compressibility of the platform and about the different weights of the two boxes, the stronger was their preference for the lighter box during the test phase. As in Experiment 1, we also examined how many infants succeeded at our task, with success defined as before as reaching for the lighter box on three or more test trials. In Experiment 2, ten of the sixteen 9-month-olds (cumulative binomial probability, $\theta = .3125$, $p = .010$) and eleven of the sixteen 11-month-olds ($p = .002$) reached for the lighter box on three or more test trials. Of the 11 unsuccessful infants, five 9-month-olds and five 11-month-olds showed a side bias; the last 9-month-old reached for the heavier box on three test trials. Finally, as suggested by visual inspection of Figure 3, we found in a last analysis that the successful infants in Experiment 2 ($n = 21$) spent more time in weight-relevant manipulations of the boxes during the exploration phase ($M = 59.90$, $SD = 8.50$) than did the successful infants in Experiment 1 ($n = 25$; $M = 50.28$, $SD = 10.66$), $F(1, 44) = 11.14$, $p = .002$, $\eta_p^2 = .20$; there was no reliable difference in how long they spent touching the boxes, $F(1, 44) = 1.81$, $p = .185$, $\eta_p^2 = .04$. It may be that, because the boxes in Experiment 2 were

identical in appearance, infants initially expected them to also be similar in weight (e.g., Mash, 2007) and thus spent time exploring this unexpected weight difference.

The 9- and 11-month-olds in Experiment 2, like those in Experiment 1, reached preferentially for the lighter box in the test trials. These results indicate that the majority of the infants noticed how much each box compressed the cotton wool platform in the test phase and were able to correctly interpret this information to identify the lighter box—even though they never saw the boxes on the cotton wool platform prior to the test phase. Thus, these results suggest that by 9 months of age infants already possess some knowledge about weight and compression and can use this knowledge prospectively to identify and reach for lighter, more portable objects.

Before any firm conclusions could be drawn about the knowledge infants brought to the laboratory, however, one important question that was left unclear by the data of Experiment 2 was whether infants' exploratory activities on the cotton wool platform (demonstration phase) and boxes (exploration phase) contributed in significant ways to their responses in the test phase. As mentioned earlier, for adults simple inspection of the test display in Figure 1b would be sufficient to establish that one box was heavier than the other. Was that true for infants as well? To address this issue, we next tested infants using the same procedure as in Experiment 2 but without an exploration phase (Experiment 3) and without either a demonstration or an exploration phase (Experiment 4).

Experiment 3

Would the 9- and 11-month-olds in Experiment 2 have succeeded in identifying the lighter box on the cotton wool platform if they had *not* first explored the two boxes? Experiment 3 was designed to address this question; it was similar to Experiment 2 except that there was no exploration phase, only a demonstration and a test phase (see Figure 1c). At least three outcomes were possible. One was that the infants would still succeed: They would notice the differential compression of the cotton wool platform in the test phase, infer that a lighter box and a heavier box were present on the platform, and reach preferentially for the lighter box. Another possibility was that the infants would now fail, suggesting that the exploration phase was in fact essential to induce the infants to notice and

to correctly interpret the differential compression of the cotton wool platform. Yet, another possibility was that the 11-month-olds would succeed but the 9-month-olds would not, indicating that the exploration phase was essential for the younger infants only.

Method

Participants

Participants were 32 healthy term infants and included sixteen 9-month-olds (8 boys and 8 girls; $M = 8.83$ months, $SD = 0.17$, range = 8.57–9.07) and sixteen 11-month-olds (8 boys and 8 girls; $M = 11.06$ months, $SD = 0.23$, range = 10.53–11.37). Another 6 infants (three 9-month-olds and three 11-month-olds) were excluded because of parental interference (2) or because they refused to remain seated (1), refused to touch the cotton wool platform in the demonstration phase (1), or did not reach for a box in two or more test trials (2).

Stimuli and Procedure

The stimuli and procedure used in Experiment 3 were identical to those in Experiment 2, except that the infants received no exploration phase. On average, infants touched the platform for 7.01 s ($SD = 1.89$); no reliable difference was found between the demonstration responses of the 9- and 11-month-olds in Experiment 3, $F(1, 30) < 1$, or between the demonstration responses of the infants in Experiments 2 and 3, $F(1, 62) < 1$.

Results and Discussion

The test data were analyzed as in Experiment 1. Infants reached for the lighter box reliably above chance at 11 months ($M = 70\%$, $SD = 16$), $t(15) = 4.96$, $p < .001$, but not at 9 months ($M = 50\%$, $SD = 22$), $t(15) = 0$, $p = 1.00$ (see Figure 2), and these responses were reliably different, $F(1, 30) = 8.59$, $p = .006$, $\eta_p^2 = .22$. Comparison of the test data in Experiments 2 and 3 indicated that, although the responses of the 11-month-olds did not differ reliably, $F(1, 30) < 1$, those of the 9-month-olds did, $F(1, 30) = 5.87$, $p = .022$, $\eta_p^2 = .16$. Test responses in Experiment 3 were significantly correlated with the time infants spent touching the cotton wool platform during the demonstration phase at 11 months ($r = .51$, $p = .044$), but not at 9 months ($r = -.25$, $p = .350$). Finally, eleven of the sixteen 11-month-olds (the same number as in Experiment 2; cumulative binomial probability, $\theta = .3125$, $p = .002$), but

only three of the sixteen 9-month-olds ($p = .918$), succeeded at the task, with success defined as before as reaching for the lighter box on three or more test trials. The 9-month-olds' performance was significantly poorer than that of the 9-month-olds in Experiment 2 (Fisher's exact test, $p = .029$) or that of the 11-month-olds in Experiment 3 ($p = .011$). Of the 18 unsuccessful infants, seven 9-month-olds and five 11-month-olds showed a side bias, three 9-month-olds reached equally for the two boxes, and three 9-month-olds reached for the heavier box on three or more test trials.

The 11-month-olds in Experiment 3 reached preferentially for the lighter box, even though they did not manipulate the two boxes prior to the test phase and thus had no advance knowledge that one box was much heavier than the other. In contrast, the 9-month-olds did not reach preferentially for the lighter box. Together, these results indicate that exploration of the two boxes in Experiment 2 was essential for infants' success at 9 months, but not at 11 months. How exactly did the exploration phase help the 9-month-olds in Experiment 2, and what developmental changes rendered this phase unnecessary for the 11-month-olds in Experiment 3? We return to these questions in the General Discussion section.

Experiment 3A

Like the 11-month-olds in Experiment 2, those in Experiment 3 reached preferentially for the lighter box. One interpretation of these results was that the infants did not need to manipulate the lighter and heavier boxes in the exploration phase to notice and correctly interpret the differential compression of the platform in the test phase. However, another possible interpretation was that when faced with a test display presenting two identical objects, one higher and one lower, 11-month-olds tend to reach for the higher object (the fact that the 9-month-olds in Experiment 3 did not reach preferentially for the lighter box suggests that they did not have such a tendency). To rule out this alternative interpretation, additional 11-month-olds were tested in Experiment 3A using the same procedure as in Experiment 3 except that the platform was now made of rigid Styrofoam (see Figure 3d). This new platform had two different levels (with a gradual incline between them) so that the two boxes were positioned at about the same heights as the lighter and heavier boxes on the cotton wool platform.

Participants were sixteen 11-month-olds (8 boys and 8 girls; $M = 11.15$ months, $SD = 0.20$,

range = 10.80–11.47). Another 2 infants were excluded because they refused to remain seated. Experiment 3A was similar to Experiment 3 except that the 6-cm layer of white cotton wool on the blue wooden platform was replaced with a layer of white Styrofoam that was 6 cm on one half of the platform and 1 cm on the other half (see Figure 3d). During the demonstration phase, the experimenter pressed on the Styrofoam (with no visible effect) and then encouraged the infant to touch the Styrofoam. On average, the infants spent 5.20 s ($SD = 2.28$) touching the Styrofoam platform, which was reliably less than what the 11-month-olds in Experiment 3 spent touching the cotton wool platform, $F(1, 30) = 7.03$, $p = .013$, $\eta_p^2 = .19$; this difference was no doubt due to the fact that the cotton wool platform was more interesting because it compressed easily. Coders judged whether the infant reached for the higher or the lower box in each test trial.

Infants did not reach for the higher box significantly above chance ($M = 48\%$, $SD = 14$), $t(15) = -0.44$, $p = .666$. This performance was reliably different from that of the 11-month-olds in Experiment 3, $F(1, 30) = 16.15$, $p < .001$, $\eta_p^2 = .35$. Test performance in Experiment 3A was not correlated with the time infants spent touching the Styrofoam platform, $r = .41$, $p = .117$. Only two of the sixteen 11-month-olds in Experiment 3A reached for the higher box on three or more test trials (cumulative binomial probability, $\theta = .3125$, $p = .979$), reliably less than in Experiment 3 (Fisher's exact test, $p = .003$). Of the remaining fourteen 11-month-olds, 10 showed a side bias, 3 reached preferentially for the lower box, and 1 reached equally for the two boxes.

The results of Experiment 3A thus cast doubt on the notion that the 11-month-olds in Experiments 2 and 3 simply tended to reach for the higher of the two boxes they were shown. The 11-month-olds in Experiment 3A were also presented with a higher and a lower box; however, the position of each box no longer conveyed information about its weight, because the boxes rested on a rigid bilevel platform, and the infants no longer reached preferentially for the higher box.

Experiment 4

The 9- and 11-month-olds in Experiment 2 received both a demonstration phase (in which they manipulated the cotton wool platform) and an exploration phase (in which they manipulated the lighter and the heavier box), and they reached preferentially

for the lighter box in the test phase. In Experiment 3, the infants no longer received an exploration phase, and only the 11-month-olds reached preferentially for the lighter box. In Experiment 4, we continued this line of investigation and asked how infants would respond if they received only a test phase (see Figure 1d). As the 9-month-olds in Experiment 3 did not reach preferentially for the lighter box, we expected that the same would be true of the 9-month-olds in Experiment 4. The question of interest was how the 11-month-olds would respond. If they still reached preferentially for the lighter box, it would suggest that the demonstration phase played little role in the successful responses of the infants in Experiments 2 and 3; conversely, if the infants no longer reached preferentially for the lighter box, it would suggest that the demonstration phase was in fact critical for their success.

Method

Participants

Participants were 32 healthy term infants and included sixteen 9-month-olds (8 boys and 8 girls; $M = 9.08$ months, $SD = 0.11$, range = 8.83–9.27) and sixteen 11-month-olds (8 boys and 8 girls; $M = 10.88$ months, $SD = 0.23$, range = 10.53–11.20). Another 5 infants (three 9-month-olds and two 11-month-olds) were excluded because they refused to remain seated (2) or did not reach for a box in two or more test trials (3).

Stimuli and Procedure

The stimuli and procedure used in Experiment 4 were identical to those in Experiment 2, except that the infants received no demonstration or exploration phase, only a test phase.

Results and Discussion

The test data were analyzed as in Experiment 1. Infants failed to reach for the lighter box significantly above chance at 9 months ($M = 42\%$, $SD = 18$), $t(15) = -1.78$, $p = .095$, and at 11 months ($M = 53\%$, $SD = 24$), $t(15) = 0.52$, $p = .612$ (see Figure 2), and the responses of the two age groups did not differ reliably, $F(1, 30) = 2.17$, $p = .151$, $\eta_p^2 = .07$. The performance of the 9-month-olds in Experiment 4 was reliably different from that of the 9-month-olds in Experiment 2, $F(1, 30) = 14.70$, $p < .001$, $\eta_p^2 = .33$, but not from that of the 9-month-olds in Experiment 3, $F(1, 30) = 1.21$, $p = .280$, $\eta_p^2 = .04$. The

performance of the 11-month-olds in Experiment 4 was reliably different from that of the 11-month-olds in Experiment 2, $F(1, 30) = 5.62$, $p = .024$, $\eta_p^2 = .16$, and in Experiment 3, $F(1, 30) = 5.62$, $p = .024$, $\eta_p^2 = .16$. Finally, only one of the sixteen 9-month-olds (cumulative binomial probability, $\theta = .3125$, $p = .998$) and five of the sixteen 11-month-olds ($p = .593$) succeeded at our task, with success defined as before as reaching for the lighter box on three or more test trials. The performances of the two age groups did not differ reliably (Fisher's exact test, $p = .172$). The 9-month-olds' performance was reliably different from that of the 9-month-olds in Experiment 2 (Fisher's exact test, $p = .002$), but similar to that of the 9-month-olds in Experiment 3 (Fisher's exact test, $p = .600$). The 11-month-olds' performance was reliably different from that of the 11-month-olds in Experiments 2 and 3 combined (Fisher's exact test, $p = .029$). Of the remaining 26 infants, nine 9-month-olds and seven 11-month-olds showed a side bias, five 9-month-olds and three 11-month-olds reached for the heavier box on three or more test trials, and one 9-month-old and one 11-month-old reached equally for the two boxes.

As predicted, the 9-month-olds in Experiment 4, like those in Experiment 3, did not reach preferentially for the lighter box. The 11-month-olds in Experiment 4 also failed to reach preferentially for the lighter box, unlike those in Experiment 3. This negative result suggests that the demonstration phase was essential for infants' success. Why was this case? We return to this question in the General Discussion section.

Final Analyses: Side Bias Data

One intriguing aspect of the present findings was that in the experiments where infants failed to reach preferentially for the lighter box, they showed a tendency to reach for the box on the same side (left or right) of the platform across all four test trials. In a final set of analyses, we examined these data statistically. For the 11-month-olds, we compared the number of infants with a side bias in Experiments 1, 2, and 3 (12 of 48), where infants were generally successful, and in Experiments 3A and 4 (17 of 32), where they were not; this difference was reliable (Fisher's exact test, $p = .017$). For the 9-month-olds, we compared the number of infants with a side bias in Experiments 1 and 2 (8 of 32), where infants generally succeeded, and in Experiments 3 and 4 (16 of 32), where they did not; this difference was marginally reliable (Fisher's exact test, $p = .070$). In general, infants were thus less likely to show a side bias

when they could determine that a lighter and a heavier box rested on the platform. When they could not, they "settled" into a pattern of reaching for the box on the same side of the platform across trials, usually with the same hand: Of the 53 infants who showed a side bias in the present research, 29 reached for the right box with the right hand and 20 reached for the left box with the left hand; the remaining 4 infants (all 11-month-olds) reached for the right box with either hand. Infants thus tended to act in a repetitive manner when they had no specific knowledge that could inhibit this pattern and guide their actions adaptively toward the lighter box (e.g., Diamond, 1990).

General Discussion

Experiment 1 served as a baseline: 9- and 11-month-olds first manipulated two boxes that differed in color and weight, and then they saw the two boxes resting on a rigid platform. At both ages, infants remembered which color box was lighter and which was heavier, and they reached preferentially for the lighter, more portable box. Armed with this finding, we proceeded to examine infants' knowledge of the weight-compression rule. In Experiment 2, infants first received a demonstration phase in which they watched an experimenter press a soft, cotton wool platform and then they touched it themselves. Next, infants received an exploration phase in which they manipulated, one at a time, two boxes that differed only in weight. In the test phase, infants saw, for the first time, the two boxes resting on the cotton wool platform. At both ages, infants reached preferentially for the lighter box, suggesting that they could use the differential compression of the platform to identify the lighter box. Our next experiments asked what role, if any, the demonstration and exploration phases in Experiment 2 had played in infants' responses. For adults, simple inspection of Figure 1b would be sufficient to establish which box was lighter and which box was heavier. However, this was not the case for our infants. When the exploration phase was eliminated in Experiment 3, only the 11-month-olds were able to determine that one box was lighter than the other. When both the demonstration and the exploration phases were eliminated in Experiment 4, neither the 11- nor the 9-month-olds were able to determine that one box was lighter than the other.

Together, these findings raise interesting questions about the nature of the physical knowledge

infants brought to our task and about the role infants' exploratory activities played in their use of this knowledge. In the next sections, we discuss these issues separately for the 11- and 9-month-olds in our experiments. In a final section, we return to our discussion of the links between cognition, exploration, and prospective action and draw a few cautionary conclusions.

11-Month-Olds

The 11-month-olds in Experiments 2 and 3 attended to how much each box compressed the cotton wool platform and they interpreted this information correctly, reaching prospectively for the lighter box. In Experiment 3, the infants succeeded even though they were exposed only to the platform prior to the test phase and thus had no advance knowledge that the boxes differed in weight. One interpretation of these results is suggested by a recent account of the development of infants' physical reasoning (e.g., Baillargeon et al., 2012; Baillargeon, Li, Gertner, & Wu, 2011; Baillargeon, Li, Ng, & Yuan, 2009). According to this account, for each event category, infants identify *variables* that enable them to respond to events within the category more adaptively. A variable both calls attention to a certain type of information in an event and provides a rule for interpreting this information (these rules are, of course, unconscious: Infants are no more conscious of the rules they use to reason about physical events than they are conscious of the rules they use as they begin to understand sentences). To illustrate, at about 7.5 months of age, infants identify the variable height as relevant to containment events. From that point on, when watching a containment event, infants routinely attend to the relative heights of the object and container, and they expect the object to become fully hidden only if it is shorter than the container. Thus, infants detect a violation when a tall object becomes fully hidden inside a short container, and they reach for a tall as opposed to a short container when searching for a tall object (e.g., Hespos & Baillargeon, 2001, 2006).

In line with these findings, we would suggest that by 11 months of age, infants have identified the variable *compression* as relevant to support events involving compressible platforms; when faced with such events, infants routinely attend to the available compression information, and—in accordance with the weight-compression rule—they expect objects causing more compression to be heavier than those causing less compression.

If 11-month-olds routinely attend to compression information when faced with support events involving compressible platforms, why did the 11-month-olds in Experiment 4 (who received only a test phase) fail to reach preferentially for the lighter box? Our intuition is that it was simply not clear to the infants that they *were* faced with a compressible platform, in part because they were unfamiliar with cotton wool and in part because they were unskilled at reading the visual cues available via inspection of the compressed platform. Thus, without some prior indication that the platform was compressible, the infants could not arrive at an unambiguous interpretation of the test display: It might involve two boxes identical in appearance but different in weight resting on a compressible platform, or it might involve two boxes identical in both appearance and weight resting on a rigid bilevel platform (roughly similar to the Styrofoam platform in Experiment 3A).

According to this analysis, the 11-month-olds in Experiments 2 and 3—who were allowed to manipulate the cotton wool platform prior to the test phase—were thus similar to the 16-month-olds tested by Berger et al. (2005), who crossed the narrow bridge safely as long as they first spent time establishing that the wobbly handrail was compressible rather than rigid. In each case, infants' exploratory activities provided them with essential information about the material properties of the objects used in the task.

Support for this analysis comes from the finding that in both Experiments 2 and 3, the 11-month-olds' test performance was positively correlated with the time they spent manipulating the cotton wool platform during the demonstration phase; in Experiment 4, infants no longer received a demonstration phase and their performance deteriorated. This picture is, incidentally, quite different from the one that emerged with respect to the 11-month-olds' manipulation of the boxes: Although test performance in Experiment 2 was positively correlated with the time the infants spent in weight-relevant manipulations during the exploration phase, test performance did *not* deteriorate in Experiment 3 when the exploration phase was eliminated. These results suggest that the successful infants in Experiment 2 tended to be those who were engaged by the task, noticed the (somewhat unexpected) weight difference between the two brown boxes during the exploration phase, and spent time exploring this difference. However, these exploratory activities were not, strictly speaking, essential for 11-month-olds to arrive at a correct interpretation of the test

display: As long as there was some prior indication that the platform was compressible, infants who were engaged by the task were likely to spontaneously attend to how much each box compressed the platform, to interpret this information correctly, and to act adaptively.

9-Month-Olds

The 9-month-olds in Experiment 2 reached preferentially for the lighter box, but those in Experiments 3 and 4 did not. These results suggest that both the demonstration and the exploration phases were critical for the success of the 9-month-olds in Experiment 2; without one (Experiment 3) or both (Experiment 4) of these phases, the infants no longer reached preferentially for the lighter box in the test trials. How did each phase contribute to the infants' responses? We assume that the demonstration phase again allowed the infants to gather information about the compressibility of the cotton wool platform. But what of the exploration phase? Why was it necessary for the 9-month-olds to succeed at our task?

One possibility is suggested by prior findings that infants who have not yet identified a variable in an event category can nevertheless succeed at tasks involving this variable if they are temporarily *induced*, through contextual manipulations, to attend to the relevant information (e.g., Baillargeon et al., 2009; Wilcox & Chapa, 2004). As an example, consider the variable height in covering events, which is typically not identified until about 12 months of age (e.g., Wang, Baillargeon, & Paterson, 2005). At 9 months, infants generally fail at tasks involving this variable: For example, they fail to detect a violation when a tall object becomes fully hidden under a short cover, and they reach randomly for a tall or a short cover when searching for a tall object (e.g., Wang & Kohne, 2007; Wang et al., 2005). However, after being induced to attend to height information, 9-month-olds succeed at such tasks (e.g., Baillargeon et al., 2009; Wang & Baillargeon, 2005). How do they do so? As infants still lack the relevant variable rule to interpret this information, they must be using more general physical knowledge to do so; in this instance, infants might be applying the knowledge that two solid objects—such as a short cover and a tall object—cannot occupy the same space at the same time (e.g., Spelke et al., 1992).

In line with the preceding results, we might suggest that (a) the 9-month-olds in the present research, unlike the 11-month-olds, had not yet

identified compression as a variable relevant to support events involving compressible platforms; (b) as a result, the 9-month-olds in Experiment 3 did not spontaneously attend to the compression of the cotton wool platform in the test phase; and (c) the 9-month-olds in Experiment 2 did attend to the compression of the cotton wool platform in the test phase because their experiences in the exploration phase *induced* them to do so. Specifically, after exploring the boxes and discovering that they differed in weight, the infants naturally sought to determine in the test trials which of the two boxes on the cotton wool platform was the heavier one and which was the lighter one. At that point, infants might have applied their general physical knowledge about weight (a heavier object exerts a greater force than a lighter object does) and compression (exerting a force on a compressible object can reduce its size) to identify the lighter box (e.g., Aguiar & Baillargeon, 1998; Wang et al., 2003).

What experiences might enable infants, between 9 and 11 months of age, to identify the variable compression as relevant to support events involving compressible platforms? The results of Experiment 2 suggest that infants' exploratory activities can play a critical role in this process. The 9-month-olds who manipulated the boxes in weight-relevant ways in the exploration phase subsequently attended to the differential compression of the cotton wool platform in the test phase, and they correctly interpreted this information using their physical knowledge about weight and compression. In contrast, the infants who manipulated the boxes primarily in weight-irrelevant ways were unable to identify the lighter box on the cotton wool platform. The advance knowledge that one box was heavier than the other thus actively directed infants to focus on the possible consequences of the boxes' different weights in the test phase and to notice how much each box compressed the platform (infants otherwise ignored or overlooked this compression information).

The preceding analysis supports two broad generalizations on the links between cognition, exploration, and prospective action (e.g., Adolph et al., 2000; Gibson, 1988; von Hofsten, 2007). First, after infants have learned through experience to identify or differentiate what information is relevant in an event, little exploration may be required for infants to attend to this information and to use it adaptively: To paraphrase von Hofsten (2007), knowledge of the appropriate rule makes prospective action possible. Second, and conversely, when

infants have not yet learned what information to attend to in an event, exploration can play a critical role in leading infants to focus on the relevant information and to use it prospectively in their actions.

Of course, different exploratory activities will be required in different tasks. For example, in recent experiments (e.g., Hauf & Paulus, 2011; Paulus & Hauf, 2011), 13-month-olds expected the weights of two different materials to be consistent across objects: After manipulating two objects (e.g., cubes) that differed only in material and weight, infants reached preferentially for the lighter of two novel objects (e.g., pyramids) made of the same materials. At 11 months, infants failed to generalize to novel objects—but they did so if given two different pairs of objects (e.g., cubes and globes) to manipulate in the exploration phase. As in this research, more exploration was needed when knowledge was more limited.

Cautionary Notes

From a methodological perspective, the present research makes clear that, even in a seemingly very simple preferential-reaching task, one cannot assume that infants' actions will transparently reflect their physical knowledge. Had we conducted only Experiment 4 (test phase), we might have concluded that neither the 11- nor the 9-month-olds had any knowledge of the weight-compression rule; had we conducted only Experiment 2 (demonstration, exploration, and test phases), we might have inferred that both age groups did, and to the same extent. Furthermore, had we compared only Experiments 2 and 4, we might have assumed that at both ages, infants' exploratory activities during the demonstration and exploration phases were critical to help them identify the lighter box in the test phase: Recall that at both ages, test performance was positively correlated with the time infants spent touching the cotton wool platform and manipulating the boxes in weight-relevant ways. However, comparison with Experiment 3 (demonstration and test phases) made clear that although the demonstration phase was critical for infants' success at both ages, the exploration phase was necessary only at 9 months: The 11-month-olds succeeded in Experiment 3 without advance knowledge that the boxes differed in weight.

Together, these results suggest two cautionary conclusions. First, infants may fail at a preferential-reaching task not because they lack knowledge of the physical rule examined in the task but because

they lack information about some of the properties (e.g., compressibility) of the objects used in the task. Second, when infants engage in initial exploratory activities in a preferential-reaching task, care must be taken to assess whether or how these activities contribute to infants' test performance. On the one hand, exploration may play little role in that infants demonstrate the same physical knowledge whether or not exploration occurs. On the other hand, exploration may provide a necessary scaffold that directs infants to attend to critical information in the test display, thereby making possible adaptive action. Exactly what physical knowledge one attributes to infants in a given task will thus depend in part on how large a role their exploratory activities played in their success.

In sum, the present research showed using a novel preferential-reaching task that 9- and 11-month-old infants can use compression information (following appropriate exploratory activities) to infer the relative weights of two objects on a compressible platform. These results shed light on a new facet of infants' knowledge about support events, they provide a useful method for investigating the development of infants' knowledge about weight, and they call attention to the complex links than can exist between cognition, exploration, and prospective action, even in a seemingly very simple preferential-reaching task.

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