

Regularity detection and explanation-based learning jointly support learning about physical events in early infancy

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ABSTRACT

The present research considers statistical learning (SL) and explanation-based learning (EBL) as joint mechanisms to support the development of physical knowledge. Infants watched teaching events in which a cover was lowered over an object and released, with outcomes that violated object principles. The object became fully hidden under a cover that was much shorter, and it remained partly visible under a cover that was much taller. Next, infants watched two test events identical to the teaching events except that one of the events was modified to present a plausible outcome and thus deviated from teaching. Infants at 3.5 months readily detected the regularity in the teaching events and noticed the change in the modified test event, whereas 6.5-month-olds did not. The pattern of response was reversed (1) when 3.5-month-olds were primed to notice the violation of object principles in the teaching events, which interfered with EBL and led infants to miss the change in the modified test event; and (2) when 6.5-month-olds were provided ways to remove the violation from the teaching events, which enabled EBL and led infants to notice the change in the modified test event. Together, the results shed light on young infants' approach to learning about physical events—one that integrates SL for pattern detection and EBL for causal coherence of the rule being learned.

Through acting on objects and observing others do so in everyday life, infants are presented with many examples of how objects interact with one another in the physical world. Extracting rules from examples of physical events is a central task for early cognitive development. Research to date has shown that infants make remarkable progress in their first year in learning about physical rules across different spatial contexts (e.g., [Dejonckheere, Smitsman, & Verhofstadt-Denève, 2005](#); [Hespos & Baillargeon, 2006](#); [Wang, Baillargeon, & Paterson, 2005](#)). Several learning mechanisms contribute to the emerging understanding of physical events in infancy. The present research examined two of these mechanisms: statistical learning and explanation-based learning.

The statistical learning (SL) account contends that infants, like children and adults, extract featural or spatiotemporal *regularities* embedded in their environment (e.g., [Aslin & Newport, 2012](#); [Fiser & Aslin, 2005](#); [Fiser, Scholl, & Aslin, 2007](#); [Kirkham, Slemmer, & Johnson, 2002](#); [Saffran, Aslin, & Newport, 1996](#); [Saffran & Kirkham, 2018](#)). SL focuses on the extraction of structure in the data and proposes that learners across a wide age range readily attend to regularities in the examples they observe. Even for infants, mere exposure to structured input can lead them to extract regularities embedded in the data and expect future events to unfold in a consistent manner. For example, [Kirkham et al. \(2002\)](#) presented infants at 2, 5, and 8 months with visual images in a sequence of different shapes that followed a statistical pattern. Subsequently, infants were presented with two test sequences: one sequence followed the same pattern (familiar sequence), and the other sequence did not (novel sequence). Across all ages, infants looked significantly longer at the novel than at the familiar sequence, suggesting that they detected the pattern and noticed the inconsistency in test. More recently, [Tummeltshammer and Amso \(2018\)](#) showed that infants at 6 and 10 months were sensitive to regularities of

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how the shape and color of objects co-varied (e.g., triangles were blue, circles were red, etc). Infants were faster and more efficient at searching for a target among distractors when the background context presented a familiar co-variation (e.g., blue triangles) than a novel co-variation (e.g., red triangles).

Although SL focuses on extracting the structure of data, several factors have been noted to influence the process, including perceptual salience of the input, memory limits, and prior experience (Aslin, 2011; Saffran & Thiessen, 2003). For example, Lew-Williams and Saffran (2012) showed that prior experience affects SL in 10-month-olds: Infants were better at extracting patterns of speech sounds (e.g., segmentation of trisyllabic words) from fluent speech if they previously heard trisyllabic words (i.e., the test speech conformed to a previously heard regularity) than if they previously heard disyllabic words (i.e., the test speech deviated from the previously heard regularity). Together, these findings indicated that SL is a powerful mechanism underlying young infants' detection of visual and auditory regularities.

The explanation-based learning (EBL) account, on the other hand, characterizes learning as a causal-reasoning process that involves several steps (e.g., Baillargeon & Carey, 2012; Wang & Baillargeon, 2008). According to Baillargeon and DeJong (2017), the *first* step requires infants to notice contrastive outcomes among otherwise similar physical events. For example, when a toy is placed behind a box, infants notice that the toy becomes fully hidden behind one box but remains partly visible behind another box. When similar physical events lead to different outcomes, it suggests to infants that some crucial piece of information is missing from the representation of the events. This step initiates or triggers learning. The *second* step requires infants to search for the crucial information that distinguishes contrastive outcomes. When infants find a feature of the events that could have contributed to the outcomes, they would attempt to build an explanation that is consistent with their background knowledge about physical objects. This step serves as a causal analysis to identify relevant features while omitting irrelevant features, allowing infants to generalize a hypothesized rule. The *third* and final step requires infants to verify the candidate rule with one or more additional exemplars. When the rule is tested and proved accurate, it would be adopted for future predictions or interpretation of physical events. Based on the EBL account, infants will arrive at a rule that is generalizable across different events and stimuli after completing all of the three steps: learning initiation, explanation construction, and empirical verification.

Evidence for EBL in infancy has been obtained across different types of physical events (e.g., Baillargeon et al., 2009, 2012; Wang & Baillargeon, 2008; Wang & Kohne, 2007). Wang and Baillargeon (2008) presented 9-month-old infants with covering events in which an inverted container (cover) was lowered over a rigid object. Infants watched pairs of events involving different covers with the same object. Within each pair, the object became fully hidden under a taller cover but remained partly visible under a shorter cover. Infants typically fail to appreciate that the relative heights of the cover and object determine the outcomes of covering events until they are about 12.5 months. However, after watching two or three pairs of teaching events, 9-month-olds learned the rule of height for covering events and applied it to events involving novel stimuli. They looked significantly longer at the event that violated the rule than at the event that followed it. More recently, Baillargeon and DeJong (2017) showed successful EBL with 11- and 12-month-olds in the context of support events. Infants learned the rule of proportional distribution: An asymmetrical object remains stationary when its larger half is supported by a platform, and will fall off the platform when its smaller half is supported. In this case, successful learning required three pairs of teaching events for 11-month-olds and only two pairs for 12-month-olds. Critically, both of these reports demonstrated that when teaching events were modified to prevent infants from completing one of the three EBL steps, learning would be brought to a halt. For example, when the teaching events failed to present contrastive outcomes (thus removing the trigger for learning), infants failed to learn the rule despite that all other aspects of teaching events remained constant.

It should be noted that although learning a physical rule means that infants will apply the rule to novel stimuli, generalization is often limited to the specific context of physical events for young infants. Many experiments have converged to show that infants in their first year do not generalize rules across different types of physical events. For example, although 3.5-month-old infants learn that height is a relevant feature for predicting outcomes in the context of occlusion events, infants do not recognize that the same rule of height also applies to containment events until they are 7.5 months and to covering events until they are 12 months (Baillargeon & DeVos, 1991; Hespos & Baillargeon, 2001, 2006; Wang et al., 2005). These surprising discrepancies reflect the context-specificity nature of rule learning by young infants.

Another important aspect of EBL concerns background knowledge. During explanation construction, basic principles about how objects should exist and interact in the physical world will serve as background knowledge for infants when building an explanation for how the identified feature may contribute to the outcomes observed. These core object principles include continuity, solidity, cohesion, and unchangeableness (Baillargeon & Carey, 2012; Baillargeon et al., 2012; Cheries, Mitroff, Wynn, & Scholl, 2008; Kibbe & Leslie, 2016; Spelke & Hespos, 2001; Spelke, 1994). Failure to build an explanation that conforms to the principles will bring EBL to a halt. Indeed, in the aforementioned reports in which deliberate teaching was provided to infants (Baillargeon & DeJong, 2017; Wang & Baillargeon, 2008), learning about physical events was brought to a halt when the rule instantiated by the exemplars violated basic object principles.

The mechanisms of SL and EBL differ in many respects and contribute to infants' learning about physical events in different ways. On the one hand, exposure to data should be sufficient for infants to extract regularities out of the observed events, allowing infants to sort through otherwise arbitrary or unrelated examples and to expect that future events will unfold in a manner consistent with the detected regularities. On the other hand, EBL requires the completion of several steps before infants arrive at a generalizable rule. It requires infants to notice contrastive outcomes of otherwise similar events; to identify the key feature that distinguishes the outcomes; to build an explanation in accordance with background knowledge; and to test a candidate rule with additional exemplars. When cognitive resources are limited to support these steps, the learner will encounter various barriers in the EBL process. For example, limited working memory (e.g., Reznick, 2009) may prevent young infants from identifying the key feature that distinguishes the contrastive outcomes observed.

The above analysis suggests a possibility that with very young infants and with taxing tasks, EBL may be brought to a halt while SL could still be completed. Research to date tends to examine these two mechanisms in isolation. The present research examined how SL and EBL jointly support young infants' learning about physical events under different circumstances, using a unique set of anomalous physical events. Anomalous events offer a useful testbed to delineate the learning process in infancy (e.g., [LeCompte & Gratch, 1972](#); [Newcombe, Sluzenski, & Huttenlocher, 2005](#); see [Jaswal, 2010](#) for related work with toddlers). Anomalous events preclude prior exposure and can be formulated to present strong regularities for SL while imposing barriers for EBL, thereby clarifying how the two mechanisms contribute to infants' learning about physical events.

In the present experiments, infants watched several pairs of covering events. In each event, a rigid cover stood next to an object. The cover was then lowered over the object and released. After a pause, the cover was lifted to reveal the object, followed by repetitions of lowering and lifting the cover until the trial ended. The first three pairs of events yielded anomalous outcomes: Within each pair, the object always became fully hidden under a cover that was shorter than the object in one event (short-cover teaching event), and it remained partly visible under a cover that was taller than the object in the other event (tall-cover teaching event). After the teaching events, infants saw one pair of test events. One test event presented the same anomalous outcome as before and thus was consistent with teaching (consistent test event), whereas the other test event presented a plausible outcome and thus deviated from teaching (inconsistent test event).

The outcomes of the three pairs of teaching events were repeated and the stimuli involved were simple to enhance SL and the likelihood that young infants would detect the pattern of the events. However, the outcomes contradicted basic object principles, giving rise to possible interference by EBL. Specifically, basic object principles ([Baillargeon & Carey, 2012](#); [Baillargeon et al., 2012](#); [Cherries et al., 2008](#); [Kibbe & Leslie, 2016](#); [Spelke & Hesplos, 2001](#); [Spelke, 1994](#)) should lead infants to expect that an object continues to exist over time and space while maintaining its physical properties including height (unless it is compressible, for example). The continuity, solidity, and unchangeableness principles should lead infants to expect that an object cannot maintain its original height while being completely hidden under a much shorter cover and that an object cannot remain visible while a taller cover rests on top of it. Thus, even if infants identify the *relative heights* of the cover and object as the key variable that distinguishes event outcomes, their background knowledge would flag the violations, resulting in their failure to construct an explanation (the second step). In addition, the teaching and test events were conducted with the same pair of covers and the same object; they did not provide additional exemplars for verifying a candidate rule (the third step). Taken together, if infants engage in EBL, they should encounter barriers to build an explanation and verify this candidate rule.

Infants at 3.5 and 6.5 months were tested in Experiments 1 and 2 to examine possible developmental differences in their engagement in SL and EBL when learning about the anomalous physical events. As shall be seen, learning by the two age groups differed. Thus, Experiments 3 to 6 were conducted to examine the fine-grained aspects of their learning process, by removing the anomalies of the teaching events, by priming infants to build a candidate rule with the key variable, and by testing the generalizability of the rule.

1. General method

All of the experiments were conducted using the general method described below. Modifications, if any, are described in each experiment.

1.1. Participants

In all of the experiments, healthy full-term infants at approximately 3.5 or 6.5 months of age were recruited from hospitals, local events for infants and families, or birth announcements published in a web-based local newspaper. Participants were primarily Caucasians, from middle-class backgrounds living in Santa Cruz County or neighboring communities. Parents received a small gift or travel reimbursement but were otherwise not compensated for their participation.

1.2. Apparatus and materials

All events were presented on a wooden stage (104 cm wide \times 90 cm high \times 58 cm deep) mounted at the infant's eye level. The sides of the stage were painted white; the back wall was covered with a white foam board and the floor with a black foam board. At the front of the stage was a large opening (97 cm \times 57 cm); between trials, a fabric-covered frame (101.5 cm \times 72.5 cm) was lowered in front of this opening. A window in the back wall (32 cm \times 34.5 cm) was located 35 cm from the right edge, extending from the bottom of the back wall and covered with a white fringe made of ribbon. Through the window, the experimenter reached her gloved right hand into the stage to perform the events. A fabric-covered wood frame (64 cm \times 182 cm) was hinged to each side of the display box, isolating the infant from the rest of the testing room. Each of the frames had a peephole (1 cm in diameter), through which observers monitored the infant's eye gaze while remaining hidden from the infant. Two small cameras captured live images of the ongoing event and infant response, which were synced to a laptop for real-time monitoring and image recording.

Two versions of the cylindrical object were used, one prior to the experiment and the other during the events. The objects were made of mailing tubes (5.5 cm in diameter) covered with solid red contact paper. Object 1 was 16 cm tall, with seven red pom-poms (2 cm in diameter) affixed to its front bottom edge. The infant saw Object 1 being handled by an experimenter prior to any trials (see Procedure). Object 2 was 30 cm tall; in all of the events, it was placed through a hole in the stage floor, resting on a platform below such that its top 16-cm portion was visible to infants. After the cover was lowered over the top two centimeters of Object 2, a

secondary experimenter raised or lowered the platform silently adjusting the portion of Object 2 above the stage floor that was visible to the infant. Seven red pompoms were attached along the edge of the hole to conceal the gap between Object 2 and the hole. Thus, when the 16-cm portion of Object 2 was visible to the infant at the beginning of each event, it looked identical to Object 1 that the infant saw prior to the experiment.

Two rectangular covers were also used (11 cm wide \times 11 cm deep). They were made of white foam core (0.5 cm thick); the edges were trimmed with red electric tape, and the interior top was covered with red contact paper and a star-shaped decoration. One cover was 18 cm tall, and the other 6.5 cm tall.

1.3. Events

Each infant watched six teaching events and two test events. In the following sections, the events are described from the infant's point of view. A metronome beat once per second to ensure that the experimenters adhered to the prescribed scripts. At the beginning of each trial, the fabric-covered frame in the front of the apparatus was lifted to reveal the initial display of one cover standing 4 cm to the left and centered front-to-back on the object and 19.5 cm from the front of the stage. The primary experimenter's gloved right hand was seen grasping the left side of the cover. The frame remained lifted through pre-trials and was not lowered until the end of the main trial (see below); each event, though comprising multiple segments, was conducted in a continuous way.

Each teaching event began with two segments in which specific actions occurred (pre-trials), immediately followed by the repeated covering events (main trial). During the first pre-trial, the primary experimenter (E1) rotated the cover upward 90 degrees to show the infant the hollow interior of the cover (2 s) and then paused until the infant had looked at the paused scene for 2 cumulative seconds, ending this pre-trial. During the second pre-trial, E1 rotated the cover back and lowered it at its starting position (2 s) and paused until the infant had looked at the scene for 2 cumulative seconds, ending this pre-trial. During the *main trial* (see Fig. 1, Teaching Events), E1 lifted the cover (2 s), moved it to the right (from the infant's perspective) until it was centered 4 cm above the object (1 s), and lowered the cover over the object (1 s) to hide its top 2 cm. E1 continued to lower the cover while the secondary experimenter (E2) adjusted the platform raising or lowering the object (2 s), and then released the cover (2 s). Next, E1 grasped the cover (1 s), lifted it (1 s), and continued with the lifting action while E2 adjusted the platform to its original position (2 s). Finally, E1 moved cover to the left (1 s), lowered it to the starting position (2 s), and paused (1 s). Each cycle of the teaching event thus lasted about 16 s; cycles were repeated until the trial ended (see Procedure).

The tall and short covers were used in alternation across teaching trials; within each pair of trials, whether the tall cover was used first or second was counterbalanced across infants. In the tall-cover teaching event, the bottom 10 cm of the object remained visible to the infant when the cover was released; in the short-cover teaching event, the object became fully hidden.

After three pairs of teaching trials, the infants received two test trials. The test events (see Fig. 1, Test Events) differed from the teaching events in two ways. First, the cover was never rotated at the beginning of the event. Each test event began with only one pre-trial in which E1 grasped the cover that stood next to the object; when infants had accumulated 2 s of looking at this static scene, the main trial began. Second, when the tall cover was used, the object became fully hidden, presenting an outcome different from the tall-cover teaching event (inconsistent test event). During this trial, E2 adjusted the platform up and back down to the original position as in the other test trial for consistency. When the short cover was used, the test event was identical to the short-cover teaching event (consistent test event).

1.4. Procedure

Infants were tested in a brightly lit room. Each infant sat on a parent's lap approximately 45 cm from the lowered fabric-covered frame. The infant's eye level was about 15 cm above the stage floor and centered in front of the object; the experimenter used a marking on the exterior wall of the apparatus to ensure that all infants were seated at this level. Parents were instructed to remain neutral and quiet and to close their eyes during the test trials.

After the infant was seated, while the fabric-covered frame was lowered (and thus hiding the interior of the stage), E1 came around the right side of the stage and waved her gloved hand at the infant. Using the gloved hand, she placed Object 1 (see Apparatus and Materials) on her left palm with the pom-poms facing the infant and patted the top of the object five times with her gloved hand, showing that the object was rigid and not compressible.

During the experiment, the infant received three pairs of teaching trials conducted with Object 2. Within each pair, half of the infants always saw the short-cover teaching event first, and half the tall-cover teaching event first. Immediately after the teaching trials, infants saw the test events on two successive trials. The test event conducted with the short cover was presented first for infants who saw the short-cover teaching event first. Each teaching or test trial ended when (a) infants looked away from the main-trial portion of the event for 1 consecutive second after having looked at it for at least 16 cumulative seconds, or (b) when they had looked at the main-trial portion of the event for 60 cumulative seconds. The 1-sec look-away criterion has been widely used in the previous research on infant cognition and perception (e.g., Coubart, Steri, Dolores de Hevia, & Izard, 2015; Duh & Wang, 2019; Luo & Baillargeon, 2005; Luo, Kaufman, & Baillargeon, 2009; Scott, Richman, & Baillargeon, 2015; Setoh, Wu, Baillargeon, & Gelman, 2013; Sommerville, Schmidt, Yun, & Burns, 2013; Wang, Zhang, & Baillargeon, 2016). Pilot data suggested that it was appropriate for the present research and thus was used consistently throughout all of the six experiments. The 16-s minimum looking time was chosen to ensure that infants had the opportunity to observe at least one cycle of the covering/uncovering event.

Two observers, who were unaware of the research hypothesis and the order of trials, monitored infants' visual attention. They pressed a button on a controller linked to a computer when the infant was looking at the event. The observers were seated over one

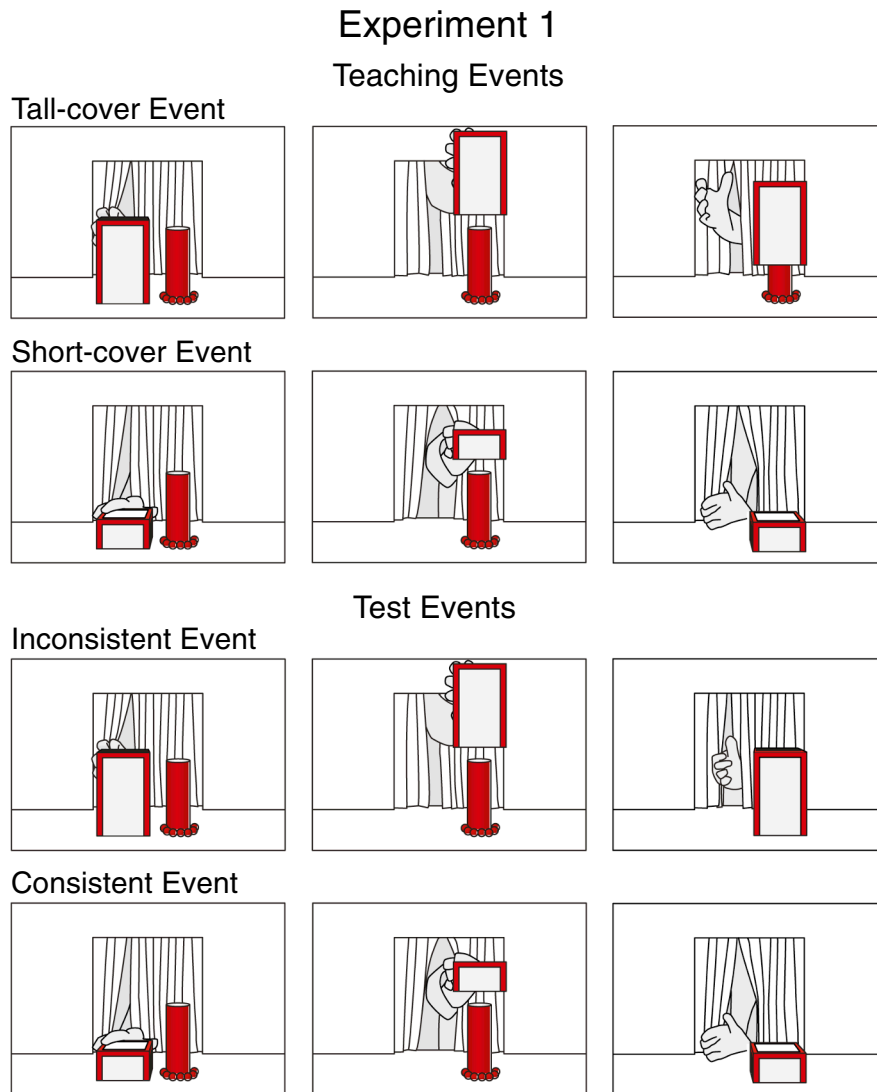


Fig. 1. Schematic depiction of the teaching events and the test events in Experiment 1 for both 3.5- and 6.5-month-olds. In test, the object always became fully hidden. Thus, the test event conducted with the tall cover deviated from teaching (Inconsistent Event), whereas the test event conducted with the short cover was the same as teaching (Consistent Event).

meter apart with the apparatus in between, and could not see or hear each other during the event over the metronome's beating sound. Reported looking times were based on input from the primary (typically more experienced) observer. To assess inter-observer agreement, the main-trial portion of each trial was divided into 100-ms intervals. Percent agreement was calculated by dividing the number of intervals in which the observers agreed whether the infant was looking at the event or not by the total number of intervals.

1.5. Manipulation check

During the teaching events, the cylindrical object might be seen as moving up and down when the cover was being lowered or lifted and E2 was adjusting the platform. The solid dark-red color combined with the cylindrical shape of the object should make it difficult for infants to notice the object's movement. Nonetheless, it was critical to rule out the possibility that the movement was noticeable during the events. To this end, 16 college students were instructed to rate the salience of the cylindrical object's movement as they watched the short- and tall-cover teaching events. Each participant was seated in front of the fabric-covered frame at the infant's eye level (on a low chair). E1 showed the object and covers to the participant as with infants. Next, the participant received one pair of teaching trials. After each trial, the participant answered the question "Did you see the red cylinder move?" on a scale of 1 (*not at all*) to 7 (*definitely*), with 4 being *unsure*. Whether the short-cover teaching event was shown first or second was counter-balanced across participants. The results indicated that the participants did not notice obvious movements of the object during the short-cover ($M = 1.31$, $SD = 0.60$) or the tall-cover ($M = 1.50$, $SD = 0.73$) teaching event; the majority of them judged the

movement to be 1 or 2 (short-cover: $n = 15$, tall-cover: $n = 13$). The ratings were similar across the two events, $t(15) = 0.423$, and not significantly different from 1, $t(31) = 0.002$. These results supported the claim that the object's movement during the teaching trials was not noticeable to viewers.

2. Experiment 1

Experiment 1 presented infants with anomalous teaching events and compared 3.5- and 6.5-month-olds' detection of inconsistency that occurred in one of the test events (see Fig. 1). Infants first watched three pairs of teaching events as described in the General Method. In one event, the cover was taller than the object; however, when the cover was released on top of the object, the bottom portion of the object was still visible (tall-cover event). In the other event, the cover was shorter than the object; however, the object became fully hidden beneath it (short-cover event).

Immediately after the teaching events, infants watched two test events in which the object became *fully hidden under each cover*. The test event conducted with the short cover presented the same anomalous outcome as the short-cover teaching event and thus was consistent with teaching (consistent event), whereas the test event conducted with the tall cover presented a physically plausible outcome that deviated from teaching (inconsistent event).

After the cover was lowered over the object, the object was partly *visible* in the tall-cover teaching trials and *not visible* in the short-cover teaching trials. This salient difference in the outcomes of the teaching events was designed to help infants notice the contrast. Infants could engage in SL only, which would allow them to detect the highly stable pattern of the teaching events: With the tall cover, the object remained partly visible; with the short cover, the object became fully hidden. This detected regularity should allow infants to notice the inconsistency between the tall-cover teaching event and the physically plausible test event in which the tall cover fully hid the object. However, if infants further engaged in EBL, the contrastive outcomes of teaching events should trigger infants to search for a feature that distinguished the outcomes. If infants identified *height* as the key feature, basic object principles should prohibit infants from building an explanation involving this feature because the outcomes violated the principles. The violation should thus prevent infants from completing this second step of EBL, resulting in their failure to notice the inconsistency between the tall-cover teaching event and the physically plausible test event. Given the different predictions, the results of Experiment 1 shall inform about the process by which 3.5- and 6.5-month-olds learned about these physical events—whether infants engaged only in SL or further in EBL and whether the process differed by age.

2.1. Participants

Participants were 16 infants from 2 months 29 days to 4 months 18 days ($M = 3$ months 21 days; 7 males, 9 females) and 16 infants from 5 months 18 days to 7 months 26 days ($M = 6$ months 14 days; 9 males, 7 females). Four additional infants, two from each age group, were tested but excluded due to fussiness ($n = 3$) or inattentiveness ($n = 1$). Inter-observer agreement was measured for all infants and averaged 91.58% ($SD = 7.58\%$) across trials and infants.

2.2. Results

In this and the following experiments, preliminary analyses revealed no significant interactions involving event (inconsistent or consistent test event) and either sex or trial order (whether the event conducted with the tall cover was shown first or second), $F_s < 3.01$, $p_s > 0.10$. Therefore, the data were collapsed across sex and order in subsequent analyses. An alpha level of 0.05 (two-tailed) was used for all analyses.

Teaching trials. The infants' looking times during the three pairs of teaching trials (see Fig. 2, top panel) were analyzed by a $2 \times 2 \times 3$ mixed model analysis of variance (ANOVA) with age (3.5 or 6.5 months) as a between-subjects factor and with event (short- or tall-cover) and pair (first, second, or third) as within-subject factors. The analysis yielded a significant main effect of pair, $F(2, 60) = 17.97$, $p < 0.001$, $\eta^2 = 0.37$. Across three pairs of trials, the infants' looking times decreased (for the first, second, and third pairs, respectively: $M_s = 51.78$, 45.76, and 36.00; $SD_s = 14.38$, 15.86, and 17.22). Post hoc comparisons using the Bonferroni correction revealed that across the two age groups, infants looked significantly shorter during the third pair of teaching trials than during the first ($p < 0.001$) or the second pair ($p = 0.001$); their looking times during the first and the second pair were not significantly different ($p = 0.066$). The main effect of age was significant, $F(1, 30) = 5.11$, $p < 0.05$, $\eta^2 = 0.15$. The 3.5-month-olds looked significantly longer ($M = 48.65$, $SD = 15.51$) than the 6.5-month-olds ($M = 40.38$, $SD = 17.63$). Because each event cycle in the teaching trials lasted 16 s, the 3.5-month-olds saw approximately 3.0 event cycles and the 6.5-month-olds saw 2.5 event cycles per trial.

The main effect of event was not significant, $F(1, 30) = 1.89$, $p > 0.10$, nor were any interaction effects, $p_s > 0.10$. Within each age group, the infants looked about equally at the short- and tall-cover teaching events (3.5-month-olds: $M_s = 50.29$ and 47.01, $SD_s = 9.86$ and 10.99; 6.5-month-olds: $M_s = 40.75$ and 40.00, $SD_s = 12.71$ and 10.86).

Test trials. The infants' looking times during the two test trials (see Fig. 2, bottom panel) were analyzed using a 2×2 ANOVA with age (3.5 or 6.5 months) as a between-subjects factor and event (inconsistent or consistent test event) as a within-subject factor. The analysis revealed a significant main effect of age, $F(1, 30) = 11.38$, $p < 0.01$, $\eta^2 = 0.28$, and of event, $F(1, 30) = 5.51$, $p < 0.05$, $\eta^2 = 0.13$, and a significant Age \times Event interaction, $F(1, 30) = 5.74$, $p < 0.025$, $\eta^2 = 0.14$. Planned comparisons indicated that the 3.5-month-olds looked reliably longer at the inconsistent ($M = 38.69$, $SD = 15.94$) than at the consistent ($M = 27.65$, $SD = 13.80$) test event, $F(1, 30) = 11.26$, $p < 0.01$, Cohen's $d = 0.71$, whereas the 6.5-month-olds looked about

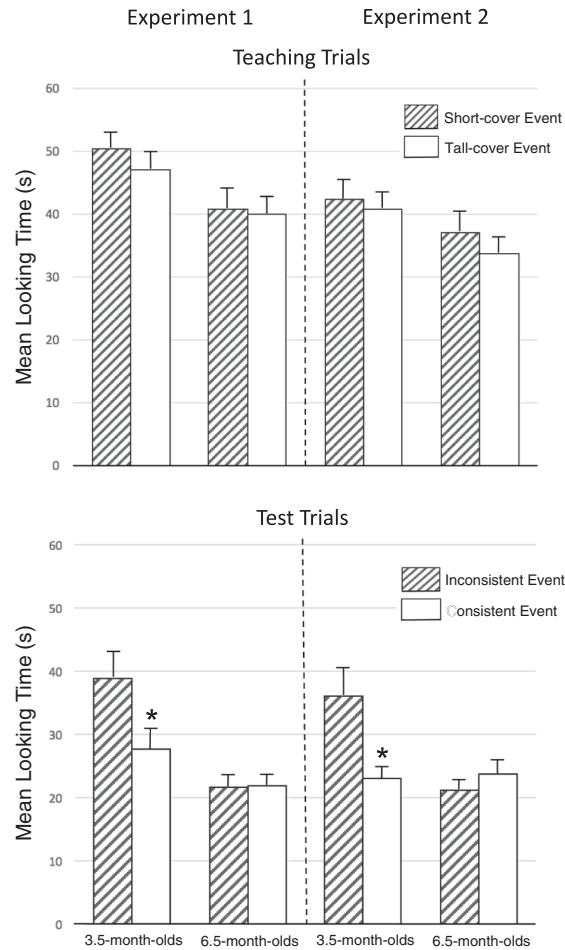


Fig. 2. Mean looking times of the infants in Experiments 1 and 2. Error bars represent standard errors. An asterisk indicates a reliable difference between the inconsistent and consistent test events within the condition at $p < 0.05$.

equally at the two events (inconsistent: $M = 21.64$, $SD = 7.05$; consistent: $M = 21.76$, $SD = 6.99$), $F(1, 30) = 0.001$. Nonparametric Wilcoxon signed-ranks tests confirmed these results (3.5-month-olds: $T = 22$, $p < 0.025$; 6.5-month-olds: $T = 62$, $p > 0.10$). Thirteen of the 3.5-month-olds (versus 8 of the 6.5-month-olds) looked longer at the inconsistent than the consistent test event.

2.3. Discussion

During the teaching trials, infants at both ages looked about equally at the short- and tall-cover events, suggesting that they did not consider one teaching event to be more appealing than the other. In addition, infants' looking times dropped considerably by the third pair of teaching events. During the test trials, the 3.5-month-olds looked reliably longer at the physically plausible test event that showed a different outcome from teaching than at the physically implausible test event that showed the same outcome as teaching. The result suggested that 3.5-month-olds engaged in SL, detected the regularity of the teaching events, and noticed the inconsistency between the plausible test event and the tall-cover teaching event.

In contrast, the 6.5-month-olds looked about equally at the two test events, suggesting that they did not notice the deviation in the inconsistent test event. The result supported the possibility that the 6.5-month-olds might have further engaged in the EBL process and identified height as the key feature for distinguishing the contrastive outcomes of the teaching events. At this point, infants' background knowledge about object principles led them to realize that the object should not be able to maintain its full height under the short cover, and that the bottom portion of the object should not remain visible while the tall cover was resting on top of the object. These anomalies, flagged by basic object principles, would interfere with the construction of an explanation, preventing infants from engaging further in EBL.

In Experiment 1, older infants failed to notice an inconsistency that infants 3 months younger succeeded in detecting. Experiment 2 sought to confirm this seemingly contradictory pattern of response, using test events that featured a different deviation from teaching. Instead of involving the tall cover in the test event that deviated from teaching, Experiment 2 involved the short cover in the inconsistent test event.

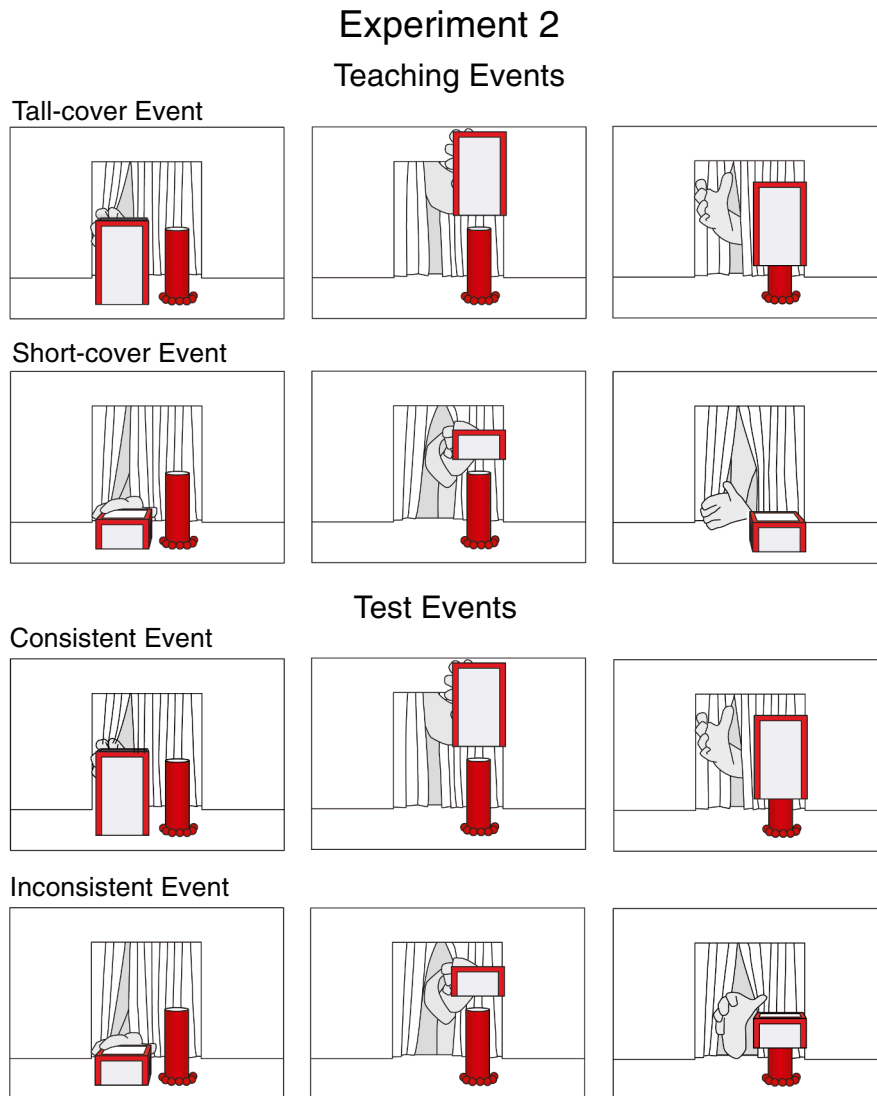


Fig. 3. Schematic depiction of the teaching events and the test events in Experiment 2 for both 3.5- and 6.5-month-olds. In test, the object always became partly hidden. Thus, the test event conducted with the tall cover was now the same as teaching (Consistent Event), whereas the test event with the short cover deviated from teaching (Inconsistent Event).

3. Experiment 2

In Experiment 2, another group of 3.5- and 6.5-month-old infants watched the same teaching events as in Experiment 1. However, the test events were modified: The object always became *partly* hidden with its bottom 10 cm remaining visible under each cover (see Fig. 3). Thus, the test event conducted with the short cover presented an outcome that deviated from teaching (inconsistent event), whereas the test event conducted with the tall cover was consistent with teaching (consistent event). With the switch of the cover in the inconsistent test event, the 3.5-month-olds in Experiment 2 were expected to detect the regularity and switch their looking-time pattern: They should now look significantly longer at the test event conducted with the short cover than with the tall cover. For the 6.5-month-olds, they were expected to look about equally at the two test events because the anomalies in the teaching events would still prevent them from completing the second step of EBL.

3.1. Participants

Thirty-two infants, who had not taken part in Experiment 1, participated in Experiment 2: Half of them were 3.5 months old ($M = 3$ months 23 days; range = 3 months 6 days to 4 months 19 days; 9 males, 7 females), and half were 6.5 months old ($M = 6$ months 20 days; range = 5 months 18 days to 7 months 13 days; 8 males, 8 females). Six additional 3.5-month-olds and 4

additional 6.5-month-olds were tested but their data were excluded because they were fussy ($n = 6$), or distracted ($n = 2$), or because they looked for the maximum amount of time on both test trials ($n = 2$). Inter-observer agreement during the test trials was measured for 31 of the 32 infants (only one observer was present for one infant) and averaged 92.36% ($SD = 6.42\%$) across trials and infants.

3.2. Results

Teaching trials. The infants' looking times during the teaching trials (see Fig. 2, top panel) were analyzed as in Experiment 1. The 2 (age) \times 2 (event) \times 3 (pair) mixed model ANOVA yielded a significant main effect of pair,¹ $F(2, 58) = 12.74, p < 0.001, \eta^2 = 0.30$. Across the three pairs of trials, looking times decreased ($M_s = 45.06, 39.45, 31.77; SD_s = 16.89, 16.20, 13.98$ for the first, second, and third pairs, respectively). Post hoc comparisons using the Bonferroni correction revealed that the infants looked significantly shorter during the third pair than the first ($p < 0.001$) or the second pair ($p < 0.025$); their looking times on the first and the second pair were not significantly different ($p = 0.065$). The main effect of age was not significant, $F(1, 29) = 3.49, p = 0.072, \eta^2 = 0.11$ (3.5-month-olds: $M = 42.28, SD = 15.78$; 6.5-month-olds: $M = 35.43, SD = 16.56$). Because each event cycle lasted 16 s, the 3.5-month-olds saw approximately 2.6 event cycles and the 6.5-month-olds 2.2 event cycles per trial.

The main effect of event was not significant, $F(1, 29) = 1.78, p > 0.10$, nor were any interaction effects, $p_s > 0.405$. As in Experiment 1, the 3.5-month-olds looked about equally at the short-cover ($M = 42.40, SD = 12.11$) and tall-cover ($M = 40.77, SD = 10.17$) teaching events, and so did the 6.5-month-olds (short-cover: $M = 37.09, SD = 13.17$; tall-cover: $M = 33.77, SD = 9.84$).

Test trials. The infants' looking times during the test trials (see Fig. 2, bottom panel) were also analyzed as in Experiment 1. The analysis yielded a significant main effect of age, $F(1, 30) = 5.10, p < 0.05, \eta^2 = 0.15$, and of event, $F(1, 30) = 5.72, p < 0.025, \eta^2 = 0.12$, and a significant Age \times Event interaction, $F(1, 30) = 12.37, p < 0.0025, \eta^2 = 0.26$. Planned comparisons indicated that the 3.5-month-olds looked reliably longer at the inconsistent ($M = 36.02, SD = 17.34$) than at the consistent ($M = 22.86, SD = 7.05$) test event, $F(1, 30) = 17.45, p < 0.01, d = 0.92$, whereas the 6.5-month-olds looked about equally at the two test events (inconsistent: $M = 21.13, SD = 6.34$; consistent: $M = 23.62, SD = 8.93$), $F(1, 30) = 0.63$. Nonparametric Wilcoxon signed-ranks tests confirmed these results (3.5-month-olds: $T = 10, p < 0.01$; 6.5-month-olds: $T = 54, p > 0.10$); twelve of the 3.5-month-olds (versus 8 of the 6.5-month-olds) looked longer at the inconsistent than at the consistent test event.

3.3. Discussion

During the test trials, the 3.5-month-olds in Experiment 2 responded with prolonged looking time at the inconsistent test event conducted with the *short* cover. Recall that the 3.5-month-olds in Experiment 1 looked significantly longer at the inconsistent test event conducted with the *tall* cover. Thus, across the two experiments, the 3.5-month-olds' test responses did not reflect a superficial preference for a particular cover. Instead, the results in Experiments 1 and 2 converged to show that 3.5-month-olds engaged in SL, detected the regularity of the teaching events, and noticed the inconsistency in test which led them to look longer at the test event that did not conform to the regularity, regardless of whether it was conducted with the tall or the short cover.

In contrast, the 6.5-month-olds in Experiment 2 again looked about equally at the inconsistent and consistent test events. One interpretation for this result could be that the 6.5-month-olds engaged in SL but were unable to detect the regularity of the teaching events. Given that 3.5-month-olds succeeded in detecting the regularity of the same teaching events, this interpretation is unlikely to be true. Another interpretation for the null result is that the 6.5-month-olds further engaged in EBL and completed the first step, which led them to search for the key feature that distinguished the outcomes. As the infants identified *height* as the key feature, their background knowledge flagged the events as violating basic object principles and prevented infants from completing the second step of constructing an explanation. This interpretation would predict that if 6.5-month-olds watched physically plausible teaching events or were provided with a reconciliation for the violation of the teaching events, they might be able to complete the second step of EBL and arrive at a candidate rule. Experiment 3 tested these predictions.

4. Experiment 3

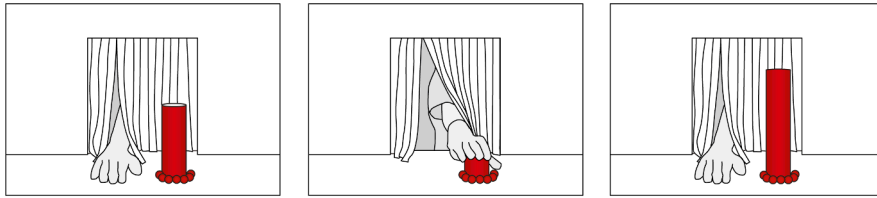
Infants at 6.5 months were assigned to one of two conditions: a collapsible-object condition and a true-rule condition. In the *collapsible-object* condition, infants watched the same teaching and test events as in Experiment 1. However, prior to the teaching and test trials, they received an orientation trial in which the object's height changed (see Fig. 4, top panel). In this orientation event, E1 placed her gloved hand on top of the 16-cm object and compressed it to about 5 cm. Next, the object apparently extended itself to about 25 cm tall. Infants watched this cycle of compression and extension until the orientation trial ended.

The compression and extension of the object should alter how the unchangeableness principle (e.g., Baillargeon & Carey, 2012) applied to the teaching events. The object could have extended itself after the tall cover was lowered over it and become much taller than the cover, making it plausible for the object to remain partly visible under the tall cover. The object could also have collapsed after the short cover was lowered over it and become shorter than the cover, making it plausible for the object to be fully hidden under the short cover. Therefore, the orientation event should help remove the contradiction between the teaching events and basic object principles. When basic object principles no longer flagged the outcomes as violations, the interference with explanation

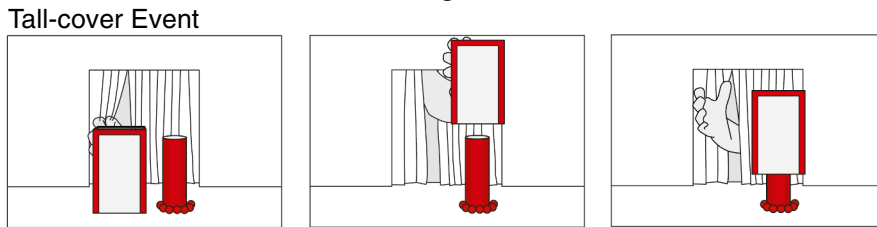
¹ Data from one infant in the younger group were excluded due to the failure of the computer to record looking times during the first three teaching trials.

Experiment 3 (Collapsible-object Condition)

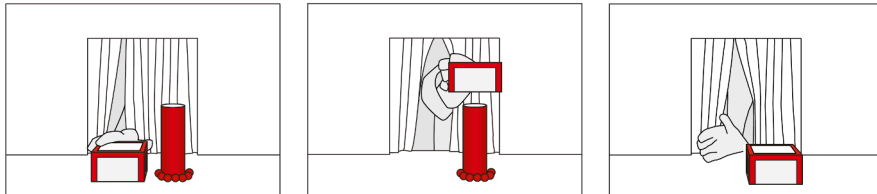
Orientation Event



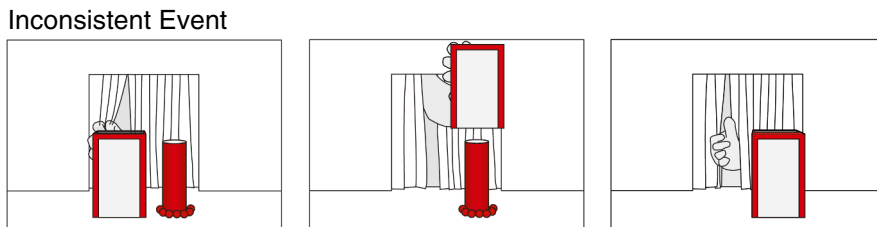
Teaching Events



Short-cover Event



Test Events



Consistent Event

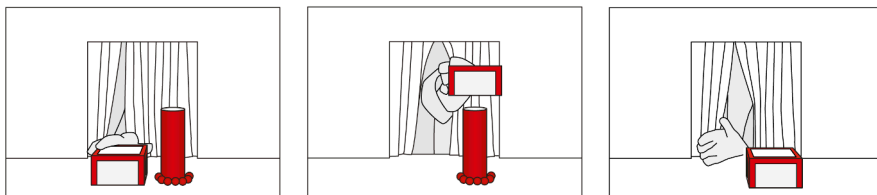


Fig. 4. Schematic depiction of the orientation, teaching and test events in the collapsible-object condition of Experiment 3 for 6.5-month-olds. The teaching and test events were identical to those in Experiment 1.

construction was removed. Using available features, the infants might notice that the object tended to extend with the tall cover and tended to collapse with the short cover. Constructing this skeletal rule would suffice for the infants to notice the inconsistency in test when the object did *not* extend under the tall cover (see Fig. 4 for the inconsistent test event). In contrast, if the 6.5-month-olds did not engage in EBL in the first place, the orientation event should not exert any effect on their processing of the teaching events. Given that the teaching and test events were identical to those in Experiment 1, the 6.5-month-olds in the collapsible-object condition should respond to the test events as the 6.5-month-olds in Experiment 1, looking about equally at the two test events.

In the *true-rule* condition, the 6.5-month-olds watched a new set of teaching events that presented physically plausible outcomes

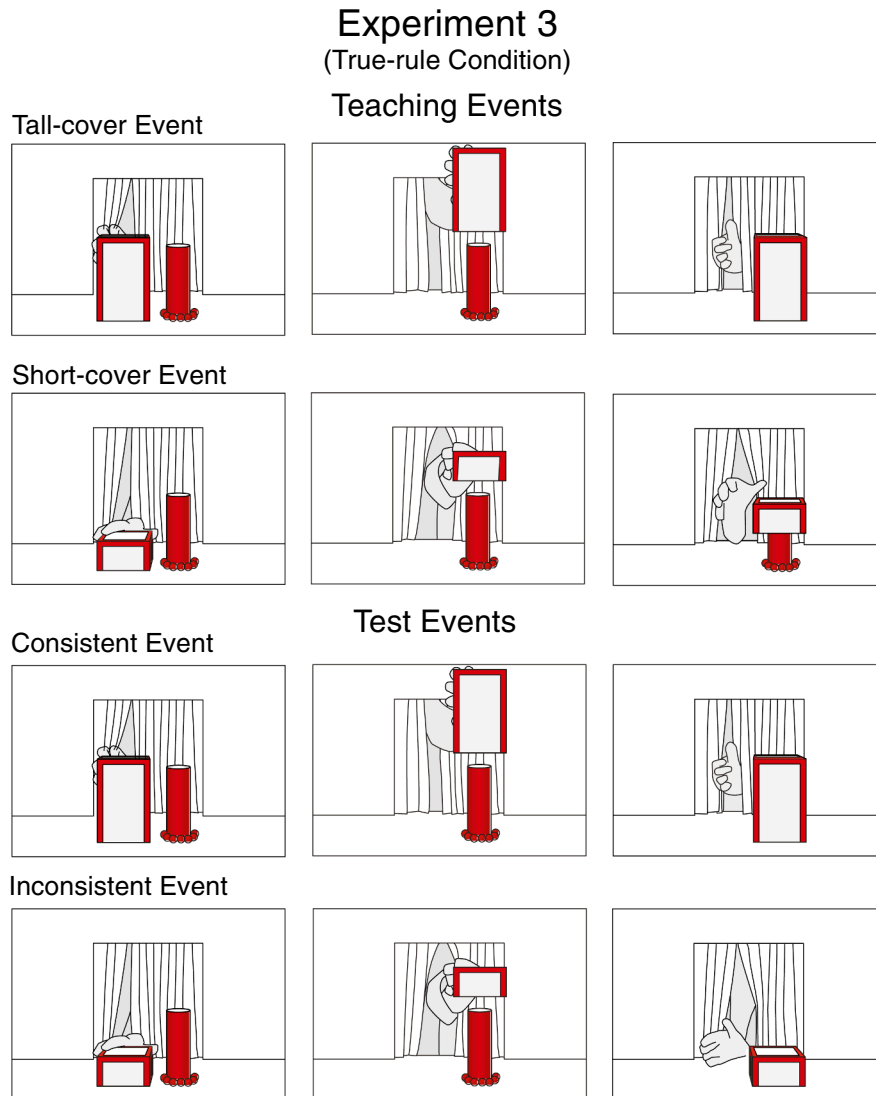


Fig. 5. Schematic depiction of the teaching and test events in the true-rule condition of Experiment 3 for 6.5-month-olds. The teaching events now presented plausible outcomes. In test, the object always became fully hidden. Thus, the test event conducted with the tall cover was consistent with teaching (Consistent Event), whereas the test event with the short cover deviated from teaching (Inconsistent Event).

(see Fig. 5, top panel). The object became fully hidden under the taller cover and remained partly visible under the shorter cover. Next, the infants watched the same test events as in Experiment 1 (see Fig. 5, bottom panel), in which the object became fully hidden under either the tall or the short cover. Thus, the test event conducted with the short cover now deviated from teaching (inconsistent event). Because the teaching events did not violate basic object principles, the 6.5-month-olds in the true-rule condition should be able to build an explanation for the teaching events and arrive at a candidate rule, completing the second step of EBL. Given that the same stimuli were used across the teaching and test events, generalization was not required—the candidate rule should be sufficient to lead the infants to notice the inconsistency in test.

4.1. Participants

Thirty-two infants, who had not participated in Experiment 1 or 2, were assigned to the collapsible-object condition ($M = 6$ months 15 days; 9 males, 7 females) or the true-rule condition ($M = 6$ months 20 days; 9 males, 7 females). The age range was 5 months 21 days to 7 months 5 days. Seven additional infants were tested but their data were excluded because they were too fussy to complete the experiment ($n = 1$), unable to look at the teaching events for the minimum amount of time required ($n = 1$), or distracted ($n = 5$). Among the infants whose data were excluded from the analysis, 4 infants were from the collapsible-object condition and 3 from the true-rule condition. Inter-observer agreement during the test trials was measured for 29 of the 32 infants (only one observer was present for three infants) and averaged 93.43% ($SD = 5.80\%$) across trials and infants.

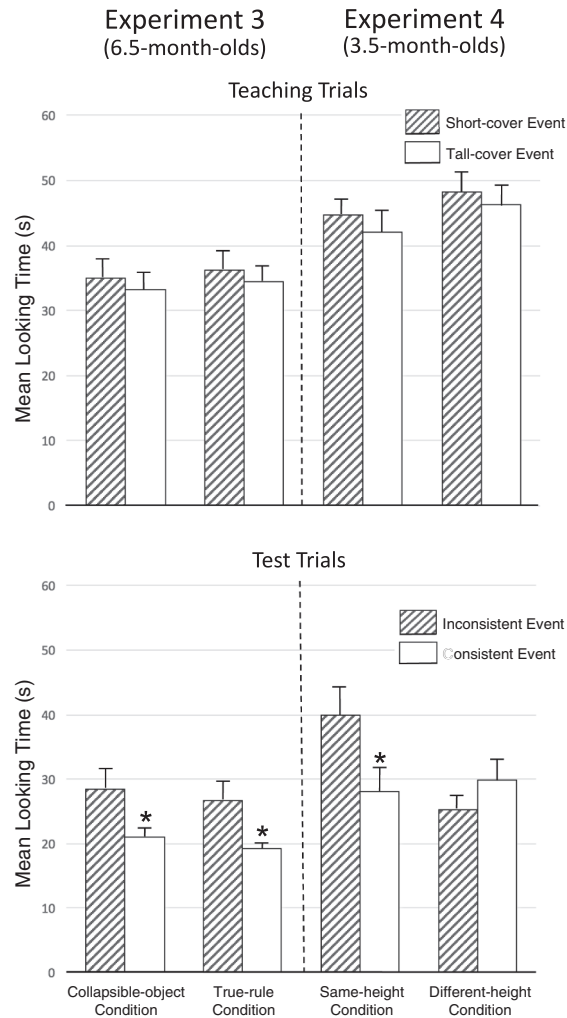


Fig. 6. Mean looking times of the infants in Experiments 3 and 4. Error bars represent standard errors. An asterisk indicates a reliable difference between the inconsistent and consistent test within the condition at $p < 0.05$.

4.2. Orientation event

Infants in the collapsible-object condition received an orientation trial (see Fig. 4, top panel) at the beginning of the experiment. In this trial, the platform underneath the apparatus was adjusted so that the 16-cm portion of Object 2 was visible to the infant above the apparatus floor just as in all other events. At the start of the orientation event, E1's gloved hand rested to the left of the object. After infants had looked at this static display for 2 cumulative seconds, E1 placed her hand on top of the object (1 s), pushed it down until it was only 5 cm tall (2 s), and returned her hand to the starting position next to the 5-cm object (1 s). Next, apparently on its own, the object extended its height to 25 cm (3 s), followed by a pause (1 s). The 8-s sequence of compression and extension was repeated until (a) infants looked away from the event for 1 consecutive second after having looked at it for at least 8 cumulative seconds (1 event cycle), or until (b) they had looked at the event for 40 cumulative seconds (5 event cycles).

4.3. Results

Orientation trial. The 6.5-month-old infants' looking times during the orientation trial averaged 36.42 s ($SD = 7.91$). Thus, they watched about 4.6 cycles of the object changing from its shortest to its tallest form.

Teaching trials. The infants' looking times during the teaching trials (see Fig. 6, top panel) were analyzed by a $2 \times 2 \times 3$ mixed model ANOVA with condition (collapsible-object or true-rule) as a between-subjects factor and event (short- or tall-cover) and pair (1, 2, 3) as within-subject factors. The analysis yielded a significant main effect of pair, $F(2, 60) = 27.70, p < 0.001, \eta^2 = 0.47$. The infants' looking times decreased across the three pairs of trials, ($M_s = 43.40, 34.67, \text{ and } 26.18; SD_s = 16.76, 15.91, \text{ and } 11.42$ for the first, second, and third pair, respectively), $p_s < 0.01$ for all pairwise comparisons using the Bonferroni correction. The interactions and other main effects were not significant, all $F_s < 1, p_s > 0.226, \eta^2_s < 0.05$.

The 6.5-month-olds in the collapsible-object condition looked about equally at the short- ($M = 35.07$, $SD = 11.65$) and tall-cover ($M = 33.20$, $SD = 11.65$) teaching events, $F(1, 30) = 0.15$, $p = 0.706$, and so did those in the true-rule condition (short-cover: $M = 36.30$, $SD = 11.62$; tall-cover: $M = 34.43$, $SD = 9.65$), $F(1, 30) = 0.15$, $p = 0.706$. Because each event cycle lasted 16 s, the infants in the collapsible-object and true-rule conditions saw approximately 2.1 and 2.2 event cycles per trial, respectively.

Test trials. The infants' looking times during the test trials (see Fig. 6, bottom panel) were analyzed using a 2×2 ANOVA with condition as a between-subjects factor and event (consistent or inconsistent with teaching) as a within-subject factor. The main effect of event was significant, $F(1, 30) = 12.95$, $p = 0.001$, $\eta^2 = 0.30$. Neither the main effect of condition nor the Condition \times Event interaction was significant, $F_s < 0.01$, $p_s > 0.983$, $\eta^2_s < 0.01$, suggesting that infants responded similarly across the two conditions. Planned comparisons indicated that the 6.5-month-olds in the collapsible-object condition looked reliably longer at the inconsistent test event (which was physically plausible and deviated from teaching; $M = 28.47$, $SD = 12.17$) than at the consistent test event (which was physically implausible and consistent with teaching; $M = 21.12$, $SD = 5.30$), $F(1, 30) = 6.40$, $p = 0.017$, $d = 0.79$. The infants in the true-rule condition also looked reliably longer at the inconsistent test event (which was physically implausible and deviated from the true rule demonstrated in teaching; $M = 26.73$, $SD = 11.71$) than at the consistent test event (which was physically plausible and consistent with teaching; $M = 19.29$, $SD = 3.06$), $F(1, 30) = 6.56$, $p = 0.016$, $d = 0.57$. Nonparametric Wilcoxon signed-ranks tests confirmed these results (collapsible-object: $T = 18$, $p = 0.010$; true-rule: $T = 30$, $p = 0.049$); thirteen of the 16 infants in the collapsible-object condition and 12 of the 16 infants in the true-rule condition looked longer at the inconsistent than at the consistent test event.

4.4. Discussion

The results of Experiment 3 indicated that when the teaching events did not violate basic object principles, the 6.5-month-olds were capable of noticing the inconsistency in test. Specifically, when (a) additional information was provided to remove the contradiction between the teaching events and basic object principles in the collapsible-object condition, or when (b) the teaching events presented physically plausible event outcomes in the true-rule condition, the 6.5-month-olds responded with prolonged looking times at the test event that deviated from teaching.

Watching a single orientation event for less than 40 s in which the object demonstrated its changeableness in height was sufficient to shift 6.5-month-olds' responses in test in a profound way. How did this orientation event affect infants' learning about the teaching events? There are a few possibilities. Watching the orientation event might have piqued infants' interest in the object, resulting in an overall increase of attention to the teaching events. According to this possibility, the infants in Experiment 3 should have looked longer at the teaching events than the infants in Experiments 1 and 2. However, the mean looking times during the teaching trials of Experiments 1, 2, and 3—40.38 s, 35.43 s, and 34.13 s, respectively—did not indicate greater attention in Experiment 3, suggesting that this was not the case.

Recall that prior to every experiment, the experimenter brought the object to the infant and showed that the object was rigid and not compressible (see General Method). Another possibility is that the orientation event might have led the 6.5-month-olds to revise this initial impression about the object and to realize that the teaching events involving covers being lowered over an object that could compress and extend would not violate any basic object principles. When infants' background knowledge no longer flagged the teaching events as violations, it no longer prevented infants from engaging further in EBL. The 6.5-month-olds could now proceed to constructing an explanation and building a candidate rule for the teaching events, making it possible for them to notice the inconsistency in test.

How might infants construct an explanation for the teaching events involving the collapsible object, and what explanation might they consider? The infants in the collapsible-object condition could not have reasoned about the relative heights of the cover and object in the same way as those in the true-rule condition who watched physically plausible events. But they could reason about the feature in a different way that was coherent with other features of the events. For example, infants could identify *height* as the key feature and construct an explanation that the tall cover made the object grow and the short cover made the object shrink. An explanation like this might be skeletal, but it would not violate basic object principles and would be sufficient to guide infants to notice the inconsistency in test when the object did not grow under the tall cover.

A curious question arose about whether infants, upon watching the teaching events involving a collapsible object, engaged only in SL and not in EBL. Experiments 1 and 2 converged to show that the 6.5-month-olds spontaneously engaged in EBL beyond SL; otherwise, they would have responded as the 3.5-month-olds. Whether it is likely for the 6.5-month-olds to disengage from EBL for special types of objects (such as collapsible objects) remains an open question—one that shall be explored later in this paper. However, whether infants only engaged in SL or further engaged in EBL would predict the same result. Therefore, it was difficult to disambiguate the process underlying the present result—to clarify whether the infants noticed the inconsistency in test because they detected a regularity or because they arrived at a candidate rule. Furthermore, it would be challenging to preclude the scenario in which infants draw on the detected regularity for processing the subsequent test events while searching for the key feature for building an explanation.

5. Experiment 4

The 6.5-month-olds in the previous experiments were affected by the violations of basic object principles in the teaching events, whereas the 3.5-month-olds seemed unaffected by them. In the past research, infants as young as 2.5 months have no difficulty detecting violations of basic object principles when they watch physical events (e.g., Aguiar & Baillargeon, 2002; Hespos &

Baillargeon, 2001; Luo et al., 2009; Wang et al., 2005). How might we reconcile this apparent contradiction—that 3.5-month-olds seemed unable to detect the violations of basic object principles? There are two hypotheses. *First*, the highly stable pattern of the teaching events—the object always became fully hidden under the short cover, and remained partly visible under the tall cover—might have led the 3.5-month-olds to focus on regularity detection without engaging in EBL at all. *Second*, the 3.5-month-olds might have engaged in EBL and noticed contrastive outcomes that sometimes the object was fully hidden, and sometimes it remained partly visible. Although this observation triggered EBL, the 3.5-month-olds were not as skilled as the 6.5-month-olds in identifying the key feature that distinguished the contrastive outcomes (due to working memory limitations, for example; Cuevas & Bell, 2010; Reznick, Morrow, Goldman, & Snyder, 2004). Thus, this step of EBL was brought to a halt for the 3.5-month-olds.

Based on the second hypothesis, inducing 3.5-month-olds to attend to the object feature *height* could lessen the task demand and allow infants to proceed to explanation construction. To test this possibility, 3.5-month-olds in Experiment 4 watched the same anomalous teaching events and the same test events as in Experiment 1. However, prior to the teaching and test trials, infants received an orientation trial in which they saw a display of three objects (see Fig. 7). The objects differed systematically in height in one condition, and were identical in the other condition.

Visual comparison can facilitate infants' representation of object height in static displays (Duffy, Huttenlocher, Levine, & Duffy, 2005; Huttenlocher, Duffy, & Levine, 2002). For example, Li and Baillargeon (2005) showed 8-month-old infants a display of three objects that only differed in height over two trials. On the first trial, the objects were placed in the order of the tallest to shortest from left to right, and on the second trial, from right to left. Without these two trials, infants at 8 months typically failed to use height information in reasoning about events involving tubes. After watching the display of three objects with the systematic height difference, the 8-month-olds readily detected a height violation in the events involving tubes (cited in Baillargeon, Li, Ng, & Yuan, 2009). Finally, research on relational mapping also showed that comparison elevates young children's sensitivity to relational attributes of stimuli such as "taller than" (e.g., Christie & Gentner, 2010; Gentner, Anggoro, & Klibanoff, 2011; Gentner, Loewenstein, & Hung, 2007). Thus, seeing the display of three objects that systematically differed in height could prime 3.5-month-olds to focus on this object feature and proceed to explanation construction. Their background knowledge should now flag the violations of basic object principles in the teaching events, preventing infants from proceeding further in EBL. As a result, the infants in the different-height condition of Experiment 4 should fail to notice the inconsistency in test, looking equally at the two test events. In contrast, seeing the display of three identical objects would exert no such effect. The infants in the same-height condition of Experiment 4, like the 3.5-month-olds in Experiments 1 and 2, should detect the regularity of the teaching events, notice the inconsistency in test, and look reliably longer at the inconsistent than at the consistent test event.

5.1. Participants

Thirty-two 3.5-month-olds, who had not participated in the previous experiments, were randomly assigned to the different-height condition ($M = 3$ months 21 days; 8 males, 8 females) or the same-height condition ($M = 3$ months 24 days; 9 males, 7 females). The age range was 3 months 4 days to 4 months 6 days. Thirteen additional infants were tested but their data were excluded because they were too fussy to complete the experiment ($n = 7$), or distracted ($n = 2$), or because they looked for the maximum amount of time allowed on both test trials ($n = 4$). Among the infants whose data were excluded from the analyses, 3 infants were from the different-height condition, and 10 from the same-height condition.

The higher attrition rate in the same-height condition was consistent with the experimental manipulation. Compared to the display of three objects that differed in height, the display of three identical objects could be less engaging and thus might result in more infants becoming fussy or distracted (6 fussy and 2 distracted babies in the same-height condition, compared to 1 fussy and 0 distracted babies in the different-height condition).² Inter-observer agreement during the test trials was measured for 25 of the 32 infants (only one observer was present for 7 infants) and averaged 92.57% ($SD = 7.08\%$) across trials and infants.

5.2. Orientation events

Two sets of 3 rectangular blocks (5.5 cm wide \times 5.5 cm deep) were used in the orientation trial. In the different-height condition, the blocks placed from left to right (from the infant's perspective) were 4, 10, and 16 cm tall; in the same-height condition, all of the blocks were 10 cm tall. In both conditions, the blocks were placed 2.5 cm apart on a black rectangular platform (36 cm wide \times 32 cm deep \times 3 cm tall) that concealed the opening in the stage floor; the front edge of the center block was 22 cm from the front of the stage and centered left-right on the infant.

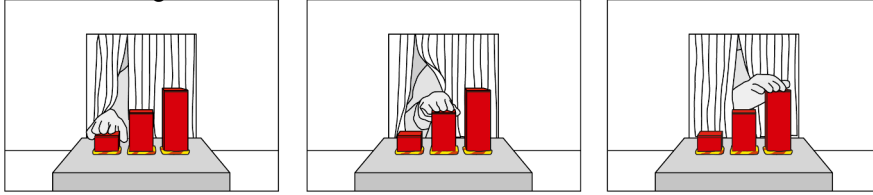
The orientation trial started with a static display of the blocks (see Fig. 7, top panel). After infants had looked at the scene for 2 consecutive seconds, E1's gloved hand entered the stage and rested on top of the left block (2 s), paused (2 s), moved to rest on top of the middle block (2 s), paused (2 s), moved to rest on top of the right block (2 s), and then paused (2 s). Next, E1 withdrew her hand from the stage (2 s). Infants watched the final static display of the blocks until (a) they had looked away from the display for 1 consecutive second after having looked at it for at least 3 cumulative seconds, or until (b) they had looked at the display for 40 cumulative seconds (the maximum amount of time allowed).

² Nonetheless, as will be seen in the Results section, the infants who completed the experiment without being fussy or distracted responded to the teaching events with similar looking patterns across the two conditions, suggesting that they were equally engaged during the teaching trials.

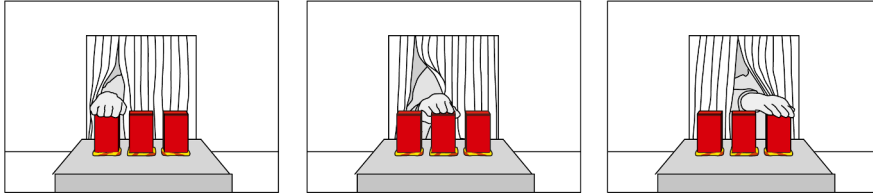
Experiment 4

Orientation Events

Different-height Condition

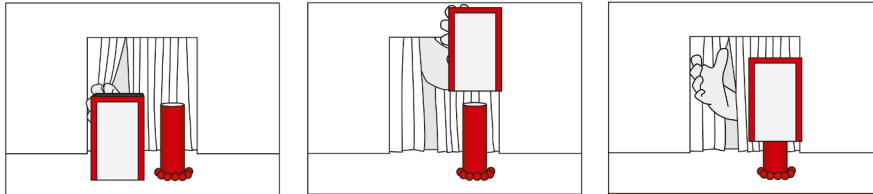


Same-height Condition

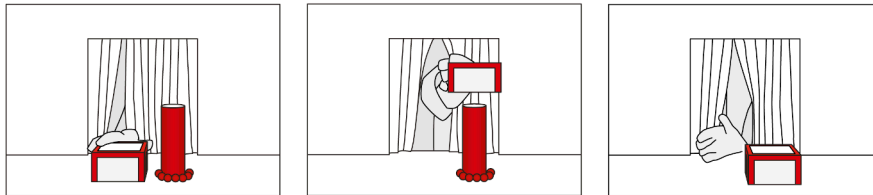


Teaching Events

Tall-cover Event

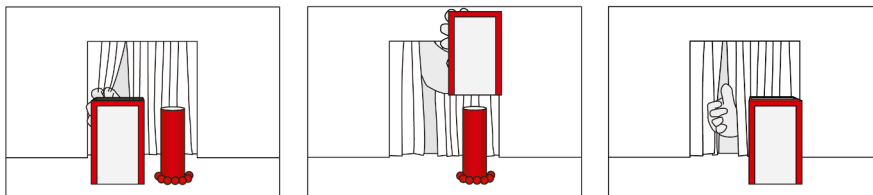


Short-cover Event

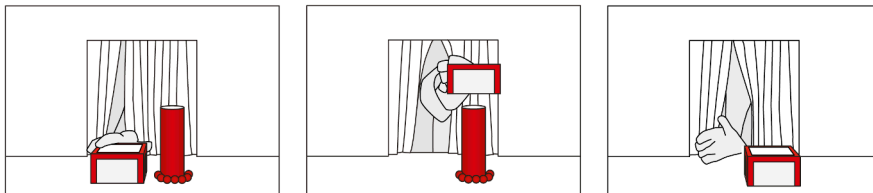


Test Events

Inconsistent Event



Consistent Event



(caption on next page)

Fig. 7. Schematic depiction of the orientation, teaching and test events in Experiment 4 for 3.5-month-olds. Infants in the different-height condition watched the orientation event conducted with three objects that varied systematically in height, and those in the same-height condition watched the orientation event conducted with three identical objects. The teaching and test events were the same as those in Experiment 1.

5.3. Results

Orientation trial. The infants in the different-height condition looked reliably longer ($M = 24.64$, $SD = 8.60$) than did those in the same-height condition ($M = 17.03$, $SD = 8.59$) during the orientation trial, $t(15) = 3.11$, $p < 0.01$, $d = 0.73$. This pattern was expected given the greater complexity of the orientation event in the different-height condition, with the three blocks varying in height as opposed to being identical.

Teaching trials. The infants' looking times during the teaching trials (see Fig. 6, top panel) were analyzed by a $2 \times 2 \times 3$ ANOVA with condition (same- or different-height) as a between-subjects factor and event (short- or tall-cover) and pair (1, 2, 3) as within-subject factors. The analysis yielded a significant main effect of pair, $F(2, 60) = 6.60$, $p < 0.005$, $\eta^2 = 0.18$. The infants' looking times decreased across the three pairs of trials ($M_s = 50.38$, 45.17 , and 40.36 ; $SD_s = 14.86$, 17.79 , and 17.92 for the first, second, and third pairs, respectively). Post hoc comparisons revealed that the infants looked significantly shorter on the third than the first pair ($p < 0.005$); their looking times were not significantly different in other pair-wise comparisons, $p_s > 0.10$. The interactions and other main effects were not significant, $F_s < 2.44$, $p_s > 0.10$. The interactions and other main effects were not significant, $F_s < 2.44$, $p_s > 0.10$.

The 3.5-month-olds in the same-height condition looked about equally at the short-cover ($M = 44.69$, $SD = 12.02$) and the tall-cover ($M = 42.13$, $SD = 13.19$) teaching events, $F(1, 30) = 1.51$, $p > 0.10$, and so did those in the different-height condition (short-cover: $M = 48.16$, $SD = 9.51$; tall-cover: $M = 46.22$, $SD = 13.85$), $F(1, 30) = 1.68$, $p > 0.10$. Because each event cycle in the teaching trials lasted 16 s, the infants in the same- and different-height conditions saw approximately 2.7 and 2.9 event cycles per trial, respectively.

Test trials. The infants' looking times during the test trials (see Fig. 7, bottom panel) were analyzed using a 2×2 ANOVA with condition as a between-subjects factor and event as a within-subject factor. Neither of the main effects was significant, $F_s < 2.45$, $p_s > 0.12$. However, the analysis revealed a significant Condition \times Event interaction, $F(1, 30) = 10.55$, $p < .005$, $\eta^2 = 0.25$. Planned comparisons indicated that the 3.5-month-olds in the same-height condition looked reliably longer at the physically plausible test event that deviated from teaching ($M = 39.99$, $SD = 17.37$) than at the physically implausible test event that was consistent with teaching ($M = 28.14$, $SD = 14.65$), $F(1, 30) = 10.99$, $p < 0.01$, $d = 0.76$, whereas those in the different-height condition looked about equally at the two test events (inconsistent: $M = 25.28$, $SD = 8.20$; consistent: $M = 29.84$, $SD = 13.53$), $F(1, 30) = 1.63$, $p > 0.10$, $d = 0.39$. Nonparametric Wilcoxon signed-ranks tests confirmed these results (same-height: $T = 19.5$, $p < 0.025$; different-height: $T = 40$, $p > 0.10$); twelve of the 16 infants in the same-height condition (versus 6 in the different-height condition) looked longer at the inconsistent than at the consistent test event.

5.4. Discussion

After watching the orientation event that highlighted the feature *height*, the 3.5-month-olds in the different-height condition gave no evidence of noticing the inconsistency in test. The negative result was not due to the lengthened procedure with the additional orientation trial because the 3.5-month-olds in the same-height condition still noticed the inconsistency in test. Together, the findings in Experiment 4 suggested that seeing the display of objects that were systematically different in height might have lessened the task demand by inducing 3.5-month-olds to focus on this feature for constructing an explanation. However, explanation construction was unsuccessful when infants' background knowledge flagged the violations of basic object principles in the teaching events. Unable to proceed further, the 3.5-month-olds in the different-height condition failed to notice the inconsistency in test.

An interesting contrast emerged between the 3.5- and 6.5-month-olds' processing of the teaching events. In Experiment 3, the 6.5-month-olds noticed the inconsistency in test after they saw the object changing its height prior to the teaching events. As mentioned before, one interpretation for this result was that the 6.5-month-olds might have disengaged from EBL when basic object principles could no longer predict exactly how the events would unfold, because the object could now change its height. In contrast, the 3.5-month-olds in Experiment 4 seemed to make an opposite shift from engaging in SL only to further engaging in EBL. As indicated by the results in Experiments 1 and 2, the 3.5-month-olds were well positioned to detect the regularity of the teaching events. However, when the orientation event primed them to focus on the feature *height*, the 3.5-month-olds gave no evidence of detecting the regularity. Together, these results suggest that at 3.5 months, infants might be open to either engaging in SL only or further engaging in EBL (i.e., SL + EBL), depending on the nature of the task at hand. In the following section, further analyses were conducted to address the question of whether at 6.5 months, infants are also open to taking either of these routes of learning.

6. Further analyses: Individual differences

Experiments 1 and 2 converged to show that with the highly stable pattern of the teaching events, 3.5-month-olds readily engaged in regularity detection. In contrast, 6.5-month-olds further engaged in EBL and were capable of building a candidate rule for the teaching events as long as they involved *no* violation of basic object principles. Thus, from 3.5 to 6.5 months, infants seemed to shift their learning process from engaging in SL only to engaging in SL + EBL, at least for the teaching events used here. Might there be

individual differences in making this shift?

In Experiments 1 and 2, the 3.5-month-olds tended to look longer at the teaching events than the 6.5-month-olds. Exploratory analyses of the looking times during the teaching trials indicated that the 3.5-month-olds tended to look at the first two pairs of teaching events for a similar amount of time (Experiment 1: $M^{\text{Pair 1}} = 54.16$, $M^{\text{Pair 2}} = 49.44$, $p = 0.141$; Experiment 2: $M^{\text{Pair 1}} = 46.59$, $M^{\text{Pair 2}} = 43.05$, $p = 0.255$), whereas the 6.5-month-olds as a group showed a significant decrease in looking times from Pair 1 to Pair 2 (Experiment 1: $M^{\text{Pair 1}} = 49.39$, $M^{\text{Pair 2}} = 42.08$, $p = 0.016$; Experiment 2: $M^{\text{Pair 1}} = 43.54$, $M^{\text{Pair 2}} = 35.85$, $p = 0.019$). However, it was unclear whether all of the 6.5-month-olds responded with reduced looking times in Pair 2. It could be that despite the general trend of reduced looking in Pair 2, some of the 6.5-month-olds responded to the teaching events similarly to the 3.5-month-olds, with the pattern of sustained looking times across Pairs 1 and 2.

To examine potential individual differences among the 6.5-month-olds, a ratio score was calculated by dividing the total looking times of Pair 2 by the total looking times of Pair 1. Thus, a ratio of 1 or greater than 1 indicates sustained or increased attention from Pair 1 to Pair 2, whereas a ratio below 1 indicates reduced attention.³ Data from the 6.5-month-olds in Experiments 1 and 2 were pooled and divided into two groups based on whether their ratio scores were below 1 or not.⁴ Half of the infants had a ratio score of 1 or greater (sustained-attention group), and half of the infants had a ratio score below 1 (reduced-attention group). The following analyses compared the looking times of the sustained- and reduced-attention groups at the teaching and test events. Although the inconsistent test event was conducted with the tall cover in Experiment 1 and with the short cover in Experiment 2, they similarly required infants to notice whether the outcome deviated from those of the teaching events.

6.1. Results

Teaching trials. The 6.5-month-olds' looking times during the teaching trials, across the data pooled from Experiments 1 and 2, were analyzed by a $2 \times 2 \times 2 \times 3$ ANOVA with attention group (sustained or reduced) and experiment (1 or 2) as between-subjects factors and with event (short- or tall-cover) and pair (1, 2, 3) as within-subject factors. The analysis yielded a significant main effect of pair, $F(2, 56) = 34.11$, $p < 0.001$, $\eta^2 = 0.46$, qualified by an interaction with attention group, $F(2, 56) = 12.21$, $p < 0.001$, $\eta^2 = 0.16$. The significant interaction indicated that the two groups differed in the distribution of looking times across pairs (see Fig. 8, top panel). Post hoc comparisons using the Bonferroni correction indicated an expected difference of the looking-time distribution across the two groups. That is, the looking times of the sustained-attention group were significantly longer in Pair 1 than in Pair 3 ($p = 0.023$), and in Pair 2 than in Pair 3 ($p = 0.002$); there was no significant difference between Pair 1 and Pair 2 ($p = 0.090$). In contrast, the looking times of the reduced-attention group were significantly longer in Pair 1 than in Pair 2 ($p < 0.001$) or Pair 3 ($p < 0.001$); there was no significant difference between Pair 2 and Pair 3 ($p = 0.540$). The main effect of attention group was not significant, $F(1, 28) = 0.70$, $p = 0.411$, $\eta^2 = 0.02$, indicating that the overall looking times at the teaching events were similar across the two groups. The main effect of event was not significant, $F(1, 28) = 1.34$, $p = 0.256$, $\eta^2 = 0.04$, nor was the main effect of experiment, $F(1, 28) = 1.28$, $p = 0.205$, $\eta^2 = 0.05$; all of the other interactions were below statistical significance, all $F_s < 2.33$, $p_s > 0.107$, $\eta^2 < 0.07$.

Across three pairs of teaching events, the sustained-attention group looked about equally at the short- ($M = 40.70$, $SD = 15.01$) and tall-cover ($M = 38.29$, $SD = 12.07$) teaching events, $F(1, 30) = 0.32$, $p = 0.573$, as did the reduced-attention group (short-cover: $M = 37.14$, $SD = 10.49$; tall-cover: $M = 35.49$, $SD = 9.24$), $F(1, 30) = 0.15$, $p = 0.699$. Thus, the two groups paid similar attention to the short- and tall-cover teaching events, even though their looking times in Pair 1 and Pair 2 were distributed differently. Because each event cycle lasted 16 s, the sustained- and the reduced-attention group watched about 2.5 and 2.3 event cycles per teaching trial, respectively.

Test trials. The 6.5-month-olds' looking times during the test trials, pooled across Experiments 1 and 2, were analyzed using a $2 \times 2 \times 2$ ANOVA, with attention group and experiment as between-subjects factors and event (consistent or inconsistent with teaching) as a within-subject factor (see Fig. 8, bottom panel). The analysis revealed a significant Attention Group \times Event interaction, $F(1, 28) = 12.68$, $p = 0.001$, $\eta^2 = 0.30$. Planned comparisons indicated that infants in the sustained-attention group looked reliably longer at the inconsistent ($M = 25.09$, $SD = 8.96$) than at the consistent ($M = 18.53$, $SD = 3.12$) test event, $F(1, 28) = 9.83$, $p = 0.004$, $d = 0.84$, whereas those in the reduced-attention group looked about equally at the two test events (inconsistent: $M = 20.28$, $SD = 6.16$; consistent: $M = 24.25$, $SD = 7.92$), $F(1, 28) = 3.60$, $p = 0.068$, $d = 0.49$. Nonparametric Wilcoxon signed-ranks tests confirmed these results (sustained: $T = 5.0$, $p = 0.002$; reduced: $T = 33.5$, $p = 0.074$); thirteen of the 16 infants in the sustained-attention group, as opposed to 3 of the 16 infants in the reduced-attention group, looked longer at the inconsistent than at the consistent test event.

6.2. Discussion

The results of these further analyses suggested that the distribution of looking times across the first two pairs of teaching trials was related to 6.5-month-olds' test response. Infants who continued to pay attention to the teaching events after Pair 1 tended to detect the inconsistency in test. This finding underscores the importance of exploring individual variations within the same age group and clarifies several aspects of learning by young infants.

³ As reported in Experiments 1 and 2, 6.5-month-olds' looking times dropped significantly in Pair 3.

⁴ The analysis of the data combined across experiments was feasible because Experiments 1 and 2 used identical teaching events.

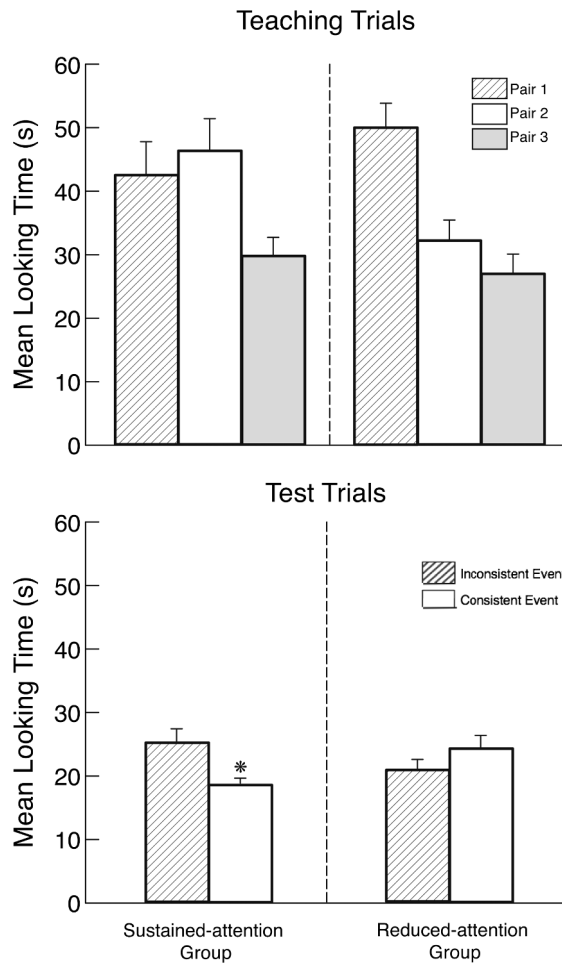


Fig. 8. Mean looking times of the 6.5-month-old infants in Experiment 5. Error bars represent standard errors. An asterisk indicates a reliable difference between the inconsistent and consistent test events within the group at $p < 0.05$.

First, the results indicated that infants at the same age may respond differently to the same physical events. Here, individual differences were observed in infants' attention to the first two pairs of teaching events. Some of the 6.5-month-olds became less attentive by the time the second pair of the events started, whereas others remained attentive throughout the first two pairs. Second, individual differences in the distribution of attention during the first two pairs of teaching trials were linked to individual differences in the test response. The 6.5-month-olds who showed less of a decline in looking times during teaching were more likely to notice the inconsistency in test, even though the teaching events were contradictory to basic object principles. Third, the early decline of attention could be linked to infants' engagement in EBL. Shorter looking times might have reflected a difficulty in progressing further in EBL when basic object principles prevented infants from constructing an explanation (i.e., bringing EBL to a halt). In contrast, sustained attention could be linked to infants' engagement in SL only. The fact that infants responded to the teaching events with different distributions of attention suggests that at 6.5 months of age, infants might still be open to taking either the SL-only or the SL + EBL route of learning. Finally, the variations in infants' responses to teaching and test events within the same age group raised the need to transcend the perspective of considering cognitive development as a timetable that specifies the age at which infants learn about a specific concept.

7. Experiment 5

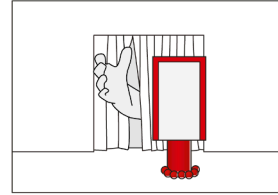
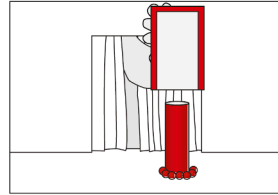
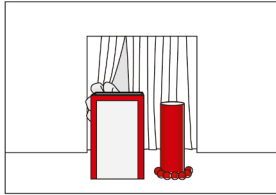
Experiments 1 and 2 showed that 3.5-month-olds were capable of detecting the regularity of the teaching events. A single pair of covers and the same object were used throughout the teaching and test trials in these experiments. Experiment 5 tested the extent to which infants would generalize the regularity to test events that involved different stimuli.

Recall that in Experiment 1, the red object was used in the teaching and test events. In Experiment 5, the teaching events were identical to those in Experiment 1, using the red object. In test, a different object was used: It was decorated with alternating blue and yellow vertical stripes (1.27 cm wide, see Fig. 9, bottom panel). The striped object became fully hidden under the tall cover in one test event (an outcome deviated from the regularity of the teaching events), and under the short cover in the other test event (an outcome

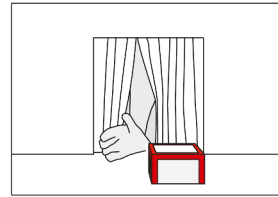
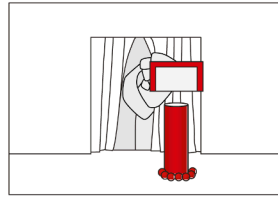
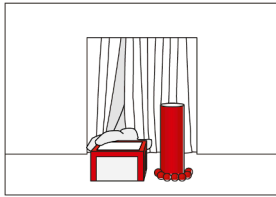
Experiment 5 (3.5-month-olds)

Teaching Events

Tall-cover Event

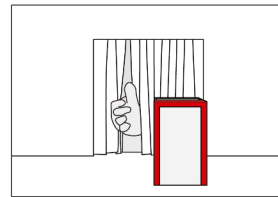
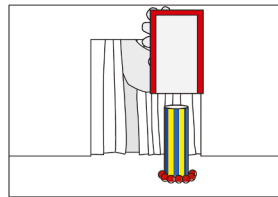
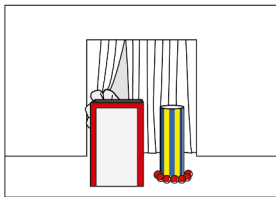


Short-cover Event



Test Events

Inconsistent Event



Consistent Event

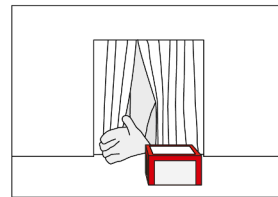
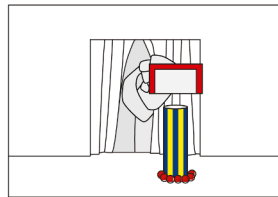
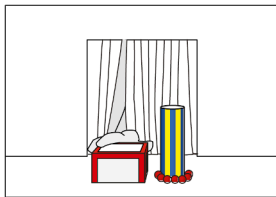


Fig. 9. Schematic depiction of the teaching and test events in Experiment 5 for 3.5-month-olds. The events were similar to those in Experiment 1, except that the object used in test differed from the object used in teaching.

consistent with the regularity of the teaching events). If the 3.5-month-olds generalized the detected regularity to the events that involved a different object, they should look reliably longer at the inconsistent than at the consistent test event. If the infants did not generalize the regularity to the novel object, they should look about equally at the two test events.

7.1. Participants

Sixteen healthy full-term infants, who had not participated in the previous experiments, participated in Experiment 5 ($M = 3$ months 21 days; range: 3 months 1 day to 4 months 5 days), including 9 males and 7 females. Five additional infants were tested but their data were excluded due to fussiness ($n = 2$), parental interference ($n = 1$), observer error ($n = 1$), or the infant's looking at both test events for the maximum time allowed ($n = 1$). Inter-observer agreement during the test trials was measured for 14 of the 16 infants (only one observer was present for two infants) and averaged 93.07% ($SD = 7.69\%$) across trials and infants.

7.2. Results and discussion

Teaching trials. The 3.5-month-olds' looking times during the teaching trials of Experiment 5 (conducted with a different test object) and Experiment 1 (conducted with the same test object) were compared by a $2 \times 2 \times 3$ ANOVA with condition (different- or

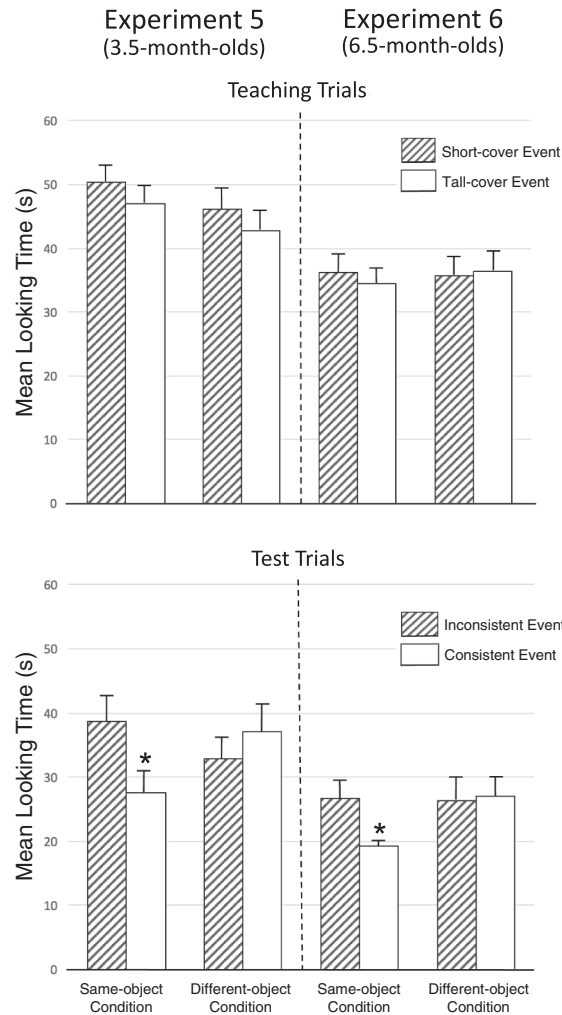


Fig. 10. Mean looking times of the infants in Experiments 5 and 6. Error bars represent standard errors. An asterisk indicates a reliable difference between the inconsistent and consistent test events within the condition at $p < 0.05$.

same-object) as a between-subjects factor and with event (short- or tall-cover) and pair (1, 2, 3) as within-subject factors. The analysis yielded a significant main effect of pair, $F(2, 60) = 9.50, p < 0.001, \eta^2 = 0.24$. In Experiment 5, infants' looking times again decreased by the third pair of trials ($M_s = 47.00, 46.58, \text{ and } 39.64; SD_s = 17.18, 17.24, \text{ and } 14.97$ for the first, second, and third pairs, respectively). The main effect of event was not significant, $F(1, 30) = 2.96, p = 0.095, \eta^2 = 0.09$, nor was the main effect of condition, $F(1, 30) = 1.33, p = 0.258, \eta^2 = 0.04$; all of the interactions were below statistical significance, all $F_s < 1, p_s > 0.414, \eta^2_s < 0.03$.

As shown in the top panel of Fig. 10, the 3.5-month-olds in the different-object condition (Experiment 5) looked about equally at the short- ($M = 46.14, SD = 13.50$) and tall-cover ($M = 42.68, SD = 12.43$) teaching events, $F(1, 30) = 1.51, p > 0.10$, as did the 3.5-month-olds in the same-object condition (Experiment 1; short-cover: $M = 50.29, SD = 9.86$; tall-cover: $M = 47.01, SD = 10.99$), $F(1, 30) = 1.68, p > 0.10$. Because each event cycle in the teaching trials lasted 16 s, the infants in the different-object condition watched about 2.7 event cycles per trial, whereas those in the same-object condition watched about 2.9 cycles.

Test trials. The infants' looking times during the test trials (see Fig. 10, bottom panel) of the different-object condition (Experiment 5) were also compared with those of the same-object condition (Experiment 1), by a 2×2 ANOVA with condition as a between-subjects factor and event as a within-subject factor. The analysis revealed a significant Condition \times Event interaction, $F(1, 30) = 4.34, p = 0.046, \eta^2 = 0.12$. Planned comparisons indicated that the 3.5-month-olds in the same-object condition looked significantly longer at the inconsistent ($M = 38.69, SD = 15.94$) than at the consistent test event ($M = 27.65, SD = 13.80$), $F(1, 30) = 4.53, p = 0.042, d = 0.71$, whereas those in the different-object condition looked about equally at the two test events (inconsistent: $M = 32.86, SD = 13.62$; consistent: $M = 37.10, SD = 17.54$), $F(1, 30) = 0.67, p = 0.420, d = 0.18$. Nonparametric Wilcoxon signed-ranks tests confirmed these results (same-object: $T = 22, p = 0.017$; different-object: $T = 53, p = 0.438$); thirteen of the 16 infants in the same-object condition looked longer at the inconsistent than at the consistent test event, whereas only 6 of the 16 infants in the different-object condition did so.

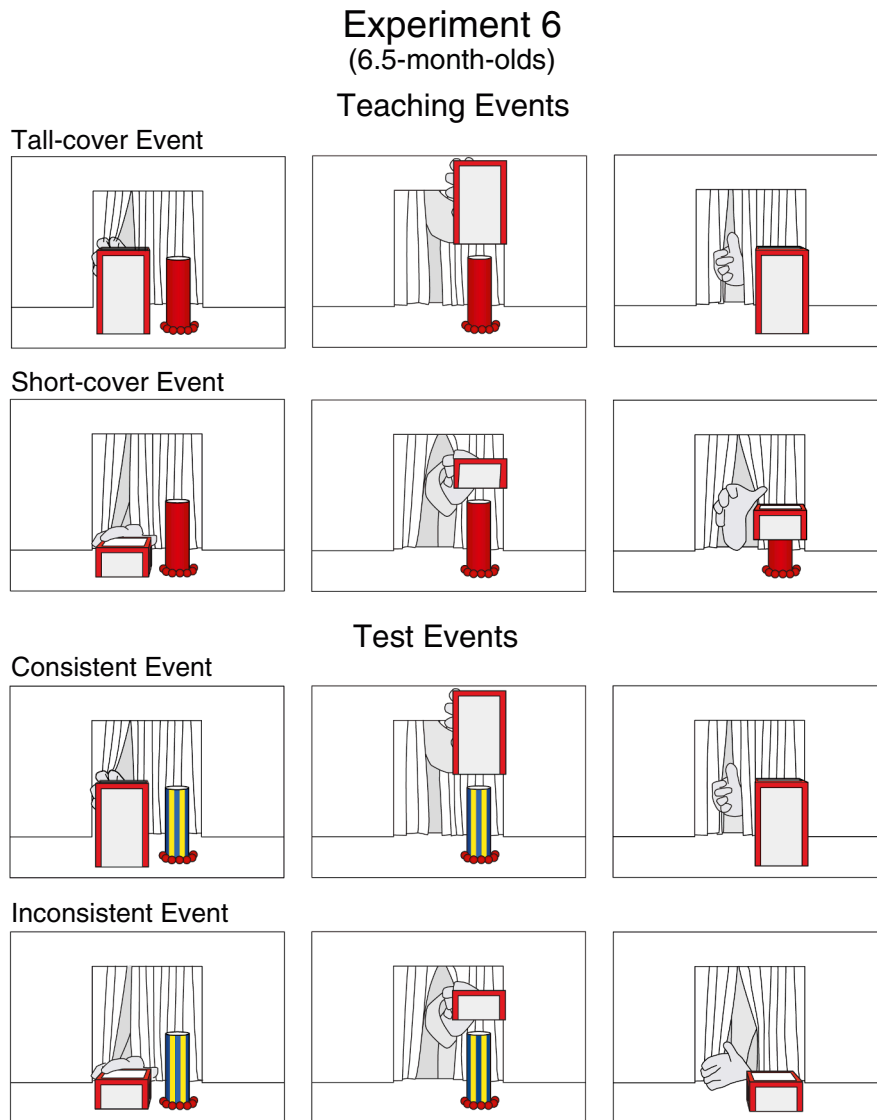


Fig. 11. Schematic depiction of the teaching and test events in Experiment 6 for 6.5-month-olds. The teaching events presented physically plausible outcomes, as in the true-rule condition of Experiment 3. The test object differed from the teaching object and always became fully hidden. Thus, the test event conducted with the tall cover was consistent with teaching and the test event with the short cover deviated from teaching.

The results indicated that although the 3.5-month-olds detected the anomalous regularity of the teaching events, they gave no evidence of noticing the inconsistency in test when a novel object was used in the events. This finding suggested that although the 3.5-month-olds were capable of detecting the regularity of the teaching events, they did not generalize the regularity across different stimuli. Despite the fact that the teaching and test objects in Experiment 5 were similar in several respects (e.g., size, shape, and texture) and that the test events involved the same pair of covers, differences in color and pattern between the teaching and test objects were sufficient to prevent the 3.5-month-olds from applying the regularity to the test events. Perhaps the lack of learning transfer was related to the anomaly of the regularity. If this was the case, a stronger transfer of learning should be observed when infants learned a physically plausible rule. Experiment 6 addressed this question with 6.5-month-olds.

8. Experiment 6

Experiment 3 showed that 6.5-month-olds were capable of building a candidate rule for physically plausible events. The EBL account suggests that in order for the rule to be generalizable across different stimuli, infants need to complete the last step of EBL—seeking empirical evidence with at least one additional exemplar. Thus, watching a single exemplar of plausible teaching events in the true-rule condition of Experiment 3 should not be sufficient for 6.5-month-olds to complete this step. As a result, infants should not be able to apply the candidate rule to events involving a different object. Experiment 6 tested this prediction.

Infants at 6.5 months watched the same teaching events as in the true-rule condition of Experiment 3 (see Fig. 11, top panel) wherein the red object became fully hidden under the tall cover and remained partly visible under the short cover. The test events were the same as Experiment 5 (see Fig. 11, bottom panel): The object with blue and yellow stripes became fully hidden under either the tall or the short cover. Thus, the test event conducted with the tall cover was consistent with teaching, whereas the test event with the short cover deviated from teaching. If the 6.5-month-olds applied the candidate rule to this novel object, they should look reliably longer at the inconsistent than at the consistent test event. In contrast, if they failed to apply the candidate rule, they should look about equally at the two test events.

8.1. Participants

Sixteen 6.5-month-olds, ranging from 6 months 6 days to 6 months 28 days, participated in Experiment 6 ($M = 6$ months 20 days; 8 males, 8 females); none of them had participated in the previous experiments. No data from any infant were excluded from the final analysis. Inter-observer agreement during the test trials was measured for 14 of the 16 infants (only one observer was present for two infants) and averaged 95.63% ($SD = 3.93\%$) across trials and infants.

8.2. Results and discussion

Teaching trials. The 6.5-month-olds' looking times during the teaching trials (see Fig. 10, top panel) of the different-object condition in Experiment 6 and the true-rule condition in Experiment 3 (now serving as the same-object condition) were compared by a $2 \times 2 \times 3$ ANOVA with condition (same- or different-object) as a between-subjects factor and with event (short- or tall-cover) and pair (1, 2, 3) as within-subject factors. The analysis yielded a significant main effect of pair, $F(2, 60) = 40.54, p < 0.001, \eta^2 = 0.57$. In Experiment 6, infants' looking times significantly decreased across the three pairs of trials, (for the first, second, and third pair, respectively: $M_s = 45.28, 35.48, \text{ and } 27.42; SD_s = 16.52, 17.26, \text{ and } 12.07$), $p_s < 0.001$ for all pairwise comparisons. The main effect of event was not significant, $F(1, 30) = 0.07, p = 0.790, \eta^2 < 0.01$, nor was the effect of condition, $F(1, 30) = 0.04, p = 0.835, \eta^2 < 0.01$; all of the interaction effects were below statistical significance, all $F_s < 0.335, p_s > 0.567, \eta^2_s < 0.02$.

The 6.5-month-olds in the different-object condition (Experiment 6) looked about equally at the short- ($M = 35.72, SD = 11.59$) and tall-cover ($M = 36.40, SD = 12.06$) teaching events, $F(1, 30) = 0.12, p = 0.732$, as did the 6.5-month-olds in the same-object condition (Experiment 3; short-cover: $M = 36.30, SD = 11.62$; tall-cover: $M = 34.43, SD = 9.65$), $F(1, 30) = 0.02, p = 0.902$. Because each event cycle in the teaching trials lasted 16 s, the infants in the same- and different-object conditions watched about 2.2 and 2.3 event cycles per trial, respectively.

Test trials. The infants' looking times during the test trials (see Fig. 10, bottom panel) of the different-object condition (Experiment 6) were also compared with those of the same-object condition (Experiment 3, true-rule condition), using a 2×2 ANOVA with condition as a between-subjects factor and event as a within-subject factor. The Condition \times Event interaction was not significant, $F(1, 30) = 2.77, p = 0.10, \eta^2 = 0.08$. However, planned comparisons indicated that the 6.5-month-olds in the same-object condition looked reliably longer at the inconsistent test event ($M = 26.73, SD = 11.71$) than at the consistent test event ($M = 19.29, SD = 3.06$), $F(1, 30) = 4.63, p = 0.040, d = 0.57$, whereas the infants in the different-object condition looked about equally at the two events (inconsistent: $M = 26.38, SD = 14.50$; consistent: $M = 27.08, SD = 12.35$), $F(1, 30) = 0.04, p = 0.841, d = 0.05$. Non-parametric Wilcoxon signed-ranks tests were consistent with these results (same-object: $T = 30, p = 0.049$; different-object: $T = 52, p = 0.408$); twelve of the 16 infants in the same-object condition looked longer at the inconsistent than the consistent test event, but only 5 of the 16 infants in the different-object condition did so.

The results indicated that the 6.5-month-olds in the same-object condition noticed the inconsistency in test, whereas those in the different-object condition did not. This finding was consistent with the prediction of EBL. Although the 6.5-month-olds completed the second step (explanation construction) and built a candidate rule for the physically plausible teaching events, they were only given a single exemplar in teaching and could not complete the last step of EBL, empirical verification. Without verifying the candidate rule, the infants applied the rule narrowly to the same set of stimuli. When the test events involved an object that differed from the teaching object in color and pattern, the infants failed to notice the inconsistency in test.

These results were in stark contrast with the previous findings that 9-month-olds applied a physical rule to different stimuli (Wang & Baillargeon, 2008) and across different response modalities (Wang & Kohne, 2007). The prior research that showed a successful transfer of learning has always used multiple pairs of covers in the teaching trials; across pairs, the covers were different in several respects. Thus, infants in the prior research had received multiple exemplars that instantiated the same rule. Together, these findings support the EBL account, specifically, the notion that infants would generalize a rule across events and stimuli after they have verified the candidate rule with at least one additional exemplar.

9. General discussion

Research in the cognitive and developmental sciences has underscored the roles of statistical and causal mechanisms in learning by children and adults. However, these mechanisms are often examined as separate entities. The present research proposed that the statistical learning (SL) and explanation-based learning (EBL) mechanisms jointly support early cognitive development and provide infants with multiple pathways to learning. With two age groups, the present research showed that 3.5-month-olds and 6.5-month-olds might have taken different routes of learning and engaged in different processes. Younger infants detected the regularity of the teaching events and noticed the inconsistency in test, whereas older infants engaged in EBL wherein the contradiction between basic

object principles and the teaching events interfered with their construction of the rule. As a whole, the present experiments specified that infants' learning about physical events could be affected by the following factors: (a) whether the events were anomalous and if so, whether reconciliation was possible, (b) the differential ability across ages to identify the relevant feature that distinguished the contrastive outcomes and whether effective support was provided, and (c) the number of exemplars provided in teaching.

The big picture of how infants learn about physical events, sketched out by this series of experiments, is as follows. *First*, with a single exemplar of physically plausible events, 6.5-month-olds construct a candidate rule and notice the inconsistency in test, but they give no evidence of generalizing the rule to a different object. *Second*, with a single exemplar of anomalous events *and* with reconciliation of the anomaly, 6.5-month-olds either detect an anomalous regularity or construct a skeletal rule (additional work is needed to differentiate these two), and notice the inconsistency in test. *Third*, with a single exemplar of anomalous events *but* without a reconciliation for the anomaly, 6.5-month-olds identify the relevant feature but the anomaly prevents infants from proceeding further. Infants give no evidence of noticing the inconsistency in test. In contrast, 3.5-month-olds (whose ability to identify the relevant feature is limited) detect the anomalous regularity and notice the inconsistency in test, but give no evidence of generalizing the regularity to a different object. *Finally*, with anomalous teaching events *and* effective support to identify the relevant feature, 3.5-month-olds identify the feature *height* for constructing an explanation, but the anomaly prevents them from proceeding further in EBL, as it does with 6.5-month-olds.

Together, this big picture supports the idea that infants in the first few months are provided with two powerful mechanisms to learn about physical events: SL and EBL. At both ages, infants gave at least some evidence that these mechanisms *could* be simultaneously available to them, allowing infants to engage in one or both depending on the limitations of their cognitive resources and the nature of the task. SL allows young infants to find patterns in otherwise arbitrary physical events. On the other hand, EBL requires infants to build a candidate rule for the events being observed, linking current learning with their background knowledge. The interplay between rule construction and background knowledge in young infants echoes the interplay between concept construction and prior knowledge in older children and adults (e.g., Barrett, Abdi, Murphy, & Gallagher, 1993; Murphy & Medin, 1985; Williams & Lombrozo, 2013; Wisniewski & Medin, 1994). This aspect of EBL also aligns with the Bayesian learning account.

From the causal reasoning perspective, the Bayesian account (e.g., Gopnik & Tenenbaum, 2007; Gopnik & Wellman, 2012; Griffiths, Sobel, Tenenbaum, & Gopnik, 2011) stresses two components for rule learning: (a) the pattern of the data being observed—the likelihood, and (b) the prior probability of a given hypothesis—the priors. Guided by these two parameters, learners search for the most likely hypothesis and put it to test. The hypothesis-testing process may involve several iterations, bringing learners closer to identifying the rule instantiated by the examples observed. Although Bayesian learning can be viewed as similar to SL in that it also addresses the roles of data structure and probabilities, this account endows a prominent role to rational expectations. The *a priori expectations* about what is likely to be true should drive learners' search for probable hypotheses toward certain directions. When these directions are consistent with the rule being learned, the *a priori expectations* would enhance rule learning. On the flip side, when the rule being learned contradicts the *a priori expectations*, holding such expectations will likely impede rule learning (Gopnik, Griffiths, & Lucas, 2015; Lucas, Bridgers, Griffiths, & Gopnik, 2014). The present results on 6.5-month-olds' difficulty in constructing an explanation for anomalous events could be taken to support the role of *a priori expectations* in Bayesian learning. However, it is unclear how Bayesian learning would account for the individual differences in the 6.5-month-olds and for the priming results with the 3.5-month-olds. Theory bridging—integrating Bayesian learning and EBL—could provide important insights into the roles and processes of causal reasoning and hypothesis testing in infants' learning about physical events.

9.1. Reconciling apparent contradictions

Prior research on physical reasoning in infancy has shown that without deliberate teaching or priming, infants typically fail to detect violations involving the variable height in covering events until they are about 12 months. For example, 9-month-olds failed to notice the violation of an event in which an object became fully hidden beneath a cover that was shorter than the object (Wang et al., 2005) and would search for a toy under a cover that was too short to hide it (Wang & Kohne, 2007). It could be seen as surprising that 6.5- and even 3.5-month-olds in the present experiments were sensitive to the anomaly of the teaching events (which involved covering). However, older infants' failure to notice the violation in a covering event reflects their failure to include height information in the representations of covering events (e.g., Wang et al., 2005; Wang & Goldman, 2016; Wang & Mitroff, 2009). In contrast, the 3.5- and 6.5-month-old infants' sensitivity to the anomaly of the teaching events in the present experiments reflects the interference of core knowledge with the construction of an anomalous explanation. Infants who were affected by the interference in the present research (and subsequently failed to notice the inconsistency in test) must have attended to the feature *height* at least partially, but such attention should be differentiated from the ability to reason about relative heights of a cover and object by infants at 12 months. Thus, 9-month-olds' failure to reason about relative heights in covering events does not contradict 3.5- and 6.5-month-olds' sensitivity to core knowledge about objects in the present experiments—these two sets of findings reflect two different processes.

Another seemingly contradictory finding concerns the 6.5-month-olds' looking-time distribution during the teaching trials. Recall that infants who responded to the anomalous teaching events with sustained attention noticed the inconsistency in test. In contrast, infants whose looking times dropped considerably were affected by the anomaly and missed the inconsistency in test. Thus, *sustained* looking could be mapped onto infants' *insensitivity* to the anomaly, whereas *reduced* looking could be mapped onto infants' *sensitivity* to the anomaly. This mapping appeared contradictory to the widely observed pattern that infants typically respond with prolonged looking when they detect an anomaly of a physical event. For example, a myriad of research has shown that infants as young as 2.5 months respond to events that violate basic object principles with prolonged looking (e.g., Aguiar & Baillargeon, 2002; Cheries et al., 2008; Luo & Baillargeon, 2005; Wang et al., 2005; Spelke, 1994; Spelke & Hespous, 2001; Stahl & Feigenson, 2015).

In the present research, the reduced looking in the 6.5-month-olds may reflect the impediment that occurs when basic object principles flag the anomaly of the teaching events and interfere with explanation construction, whereas the sustained looking suggests that the infants experience no such impediment. In the previous research, infants' prolonged looking at physical events that violate basic object principles reflects heightened attention to a found inconsistency (similar to the heightened attention of infants in the present experiments to the found inconsistency in test). Thus, the reduced looking resulted from an obstructed process of building an explanation does not contradict the prolonged looking resulted from detecting a violation or inconsistency—these two sets of findings also reflect two different processes.

9.2. Considering EBL contributors

The lack of engagement in EBL in the 3.5-month-olds has been attributed to their difficulty identifying the key feature that distinguishes the contrastive outcomes of the teaching events. One potential explanation for the 3.5-month-olds' difficulty relates to *working memory* limitations. Perhaps, the complexity of the teaching events in the present research exceeds 3.5-month-olds' working memory capacity. Infants at 3.5 months may have difficulty tracking multiple objects, hand movement, and relative positioning of the cover and object, all the while searching for a critical feature that distinguishes the outcomes of the teaching events. This possibility is supported by prior research that shows the significant development of working memory in infants at the age of 5 to 6 months (e.g., Reznick, 2009; Reznick et al., 2004). When primed to shift attention to the critical feature, the 3.5-month-olds proceeded further in EBL and responded to the test events in a manner more similar to the 6.5-month-olds.

Experience may also play a role in infants' ability to search for the object feature, thus contributing to EBL. At 3.5 months, infants learn that height is a relevant variable for occlusion events but not for other types of events (e.g., Hespos & Baillargeon, 2006; Wang, 2011). At 6.5 months, infants nearly learn that height is also a relevant variable for containment events, as research showed that infants readily reason about relative heights in containment events at about 7.5 months (e.g., Hespos & Baillargeon, 2001; Wang, 2011). With occlusion and containment events being prevalent in everyday life, it is plausible that 6.5-month-olds who readily attend to object height for these events would identify height as the key feature to build an explanation for the teaching events more quickly than 3.5-month-olds who have less experience.

The ability to track various aspects of a teaching event and compare across events could also potentiate infants' search for the relevant feature. Thus, *comparison* also contributes to EBL. Recall that in the different-height condition of Experiment 4 wherein the 3.5-month-olds engaged further in EBL after watching a display that prompted comparison of object height. This finding provided support for the contribution of comparison to EBL. In addition, comparison could potentiate EBL by accelerating the detection of contrastive outcomes. Moreover, learning about physical events that are more variable and unorganized in everyday life would involve detecting a *relational* commonality in seemingly unrelated examples (e.g., Ferry, Hespos, & Gentner, 2015). The 6.5-month-olds in the present experiments could have built a candidate rule that shared the *relational* attribute of physical rules that infants would build in everyday life. If this was the case, infants should recognize that, regardless of the absolute heights of the cover and object, shorter covers should always fully hide objects whereas taller covers should always partly hide objects. Conversely, the 6.5-month-olds in the present experiment could have built an *entity* rule that narrowly linked the short cover to one particular outcome (e.g., unable to see object) and the tall cover to the other particular outcome (e.g., seeing the bottom 10-cm portion of the object). The results that infants only applied the candidate rule to the same object lend support for the entity rule that narrowly linked particular conditions to particular outcomes. Future research can address this question by presenting varying outcomes in teaching events such that the portion of the object visible under the cover varies across trials, thus requiring infants to extract a relational commonality.

The discussion so far underscores the need to consider three potential contributors for EBL: working memory (e.g., Kibbe, 2015; Moher, Tuerk, & Feigenson, 2012; Reznick, 2009), experience (e.g., Wang & Onishi, 2017), and comparison (e.g., Markman & Gentner, 2000; Gentner & Holyoak, 1997; Gentner et al., 2007; Waxman & Klibanoff, 2000). Future research can specify their roles in EBL, for example, by manipulating working-memory demand imposed by the task, by providing infants additional experience with the target feature, and by varying the contextual support for comparison (e.g., using exemplars that are well aligned versus poorly aligned), while keeping other aspects of the teaching events constant. Such investigations shall provide insight into the interplays between these potential contributors and EBL.

10. Concluding remarks

The present research showed that even when encountering an unusual set of data such as anomalous physical events that contradict basic object principles, young infants engage in SL and are capable of extracting the regularity instantiated by the events observed. It also showed that infants at both 3.5 and 6.5 months are capable of further engaging in EBL to construct a candidate rule for the events observed, as long as the necessary support is provided.

Both SL and EBL play an important role in young infants' learning about physical events. SL makes it possible for young infants to extract patterns from the rich information provided to them, whereas EBL prevents infants from constructing a rule that contradicts their current knowledge and allows infants to build a coherent understanding of the physical world. Thus, young infants' approach to learning about physical events is adaptive and flexible, with more than one pathway to learning. At both 3.5 and 6.5 months, infants may engage in SL only or further engage in EBL. Which pathway is prioritized over the other depends on the limitations of cognitive resources and the nature of the task at hand.

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