Violations of expectation trigger infants to search for explanations

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Abstract

Infants look longer and explore more following violations-of-expectation, but the reasons for these surprise-induced behaviors are unclear. One possibility is that expectancy violations increase arousal generally, thereby increasing infants' post-surprise activity. Another possibility is that infants' exploration reflects the search for an explanation for the surprising event. We tested these alternatives in three experiments. First in Experiment 1 we confirmed that seeing an object violate expectations (by passing through a solid wall) increased infants' exploration of the surprising object compared to a novel object, and compared to when no expectancy violation was seen. Then in Experiment 2 we measured infants' exploration after they saw the same violation event, but then an explanation for the event was provided (the wall was revealed to have a large hole in it). We found that providing this explanation abolished infants' surprise-induced exploration. Furthermore, the longer infants looked at the explanation, the greater their reversal in exploratory preference (i.e., the more they ignored the surprising object and explored the novel object). In Experiment 3 we replicated these effects. These findings demonstrate that preverbal infants both seek and recognize explanations for surprising events.

Keywords: surprise, explanation, violation-of-expectation, infants, exploration

1. Introduction

A central finding in developmental psychology is that infants look longer at impossible than possible events. By just a few months of age, infants exhibit heightened looking when objects behave in ways that adults describe as surprising or impossible, compared to ways that adults find expected. Researchers have leveraged this methodological discovery to characterize pre-verbal expectations across a range of domains (see Spelke & Kinzler, 2007 for a review). As one example from the object domain, Spelke and colleagues showed 2.5-month-old infants a ball roll down a ramp and pass behind a screen, heading towards a wall in its path. The screen was then lifted to reveal either the expected outcome—the ball at rest on the near side of the wall, as though the wall had interrupted its trajectory—or the unexpected outcome—the ball on the far side of the wall, as though it had passed straight through. Infants looked significantly longer at the unexpected outcome, suggesting that they expected the ball to be stopped by the wall (Spelke, Breinlinger, Macomber & Jacobson, 1992). This implicates an early understanding of an important principle of object behavior: that objects respect solidity and cannot pass through one another. Other studies using the violation-of-expectation method reveal that infants have further expectations about objects, including that they continue to exist when hidden (Baillargeon & DeVos, 1991; Baillargeon, Spelke, & Wasserman, 1985), trace spatiotemporally continuous paths (Wilcox, Nadel & Roser, 1996; Aguiar & Baillargeon, 1999), and fall if unsupported (Needham & Baillargeon, 1993).

Other violation-of-expectation findings implicate early knowledge across several additional domains. To highlight a few examples, infants look longer when 5 objects + 5 objects yields 5 objects, compared to when 5 + 5 yields 10, pointing to core knowledge of numerosities (McCrink & Wynn, 2004). Infants look longer when someone reaches for a new object instead of

an object for which they had previously reached, pointing to knowledge of people's goals (Woodward, 1998). And infants look longer when someone approaches an agent who has previously been mean over an agent who has previously been nice, pointing to early knowledge of agents' dispositions (Kuhlmeier, Wynn, & Bloom, 2003).

Results like these tell us that infants notice surprising events across a wide range of entities. But beyond this simple detection, more recent work also suggests that violations-of-expectation also change infants' exploratory behaviors. In one study, 10- to 12-month-old infants saw a solidity event like that described above, and then were offered the opportunity to explore the object from the just-seen event as well as a novel distractor object. Infants who had seen the object accord with their expectations (i.e., be stopped by the wall) generally ignored that object and spent most of their time exploring the distractor, consistent with a preference for novelty. In contrast, infants who had seen the object violate expectations (i.e., pass through the wall) mostly explored the familiar object that had just defied solidity. This shift in exploratory preference was also observed when infants saw violations of object support (an object appearing to float in mid-air) (Stahl & Feigenson, 2015). Similarly, Sim and Xu (2017) showed 13-month-old infants two boxes containing balls of many different colors, from which an experimenter "randomly" drew samples. The sample from one box yielded all identically-colored balls (a surprising outcome, given the population), and the sample from the other yielded multiple colors (an expected outcome, given the population). Later, infants spent more time touching and reaching into the box that had yielded the unexpected sample.

However, the question of *why* violations-of-expectation increase infants' looking and exploration—namely, whether these surprise-induced behaviors have any functional significance, remains unanswered. One possibility is that infants' surprise-induced exploration

reflects a targeted effort to learn from anomalous events. In particular, infants might explore because they are searching for explanations: infants could be examining objects in the service of gaining a better understanding of what just happened, actively seeking information that offers a causal mechanism for the violation just witnessed. Such targeted information-search would be an efficient way to learn about the world, giving infants the opportunity to revise their mental models when faced with contradictory evidence. Support for this view comes from the finding that 11-month-old infants' post-surprise behaviors are linked to the type of object violation seen: infants who saw an object appear to float without support later tended to repeatedly drop the object, whereas infants who saw an object appear to pass through a solid wall repeatedly banged the object (Stahl & Feigenson, 2015). These diverging exploratory actions could reflect infants' drive to explain the particular violation they had observed. However, it is also possible that this violation-action link simply reflects infants' attempt to reproduce the surprising events, without seeking their causes.

There are other reasons to wonder whether infants' surprise-induced exploration has anything to do with explanation-seeking. Surprising events might simply increase infants' overall arousal, which could amplify their subsequent behaviors—including their interaction with objects. One version of this general arousal account seems to be ruled out by the finding that surprise promotes infants to specifically explore the object involved in the surprising event, as opposed to unrelated distractor objects (Stahl & Feigenson, 2015). Still, it might be that arousal motivates infants to engage with familiar entities (e.g., the object from the preceding event), without any top-down goal of seeking specific information. This possibility is consistent with findings that amphetamine-induced arousal increases motor activity in human adults (and mice) without increasing exploration per se (Minassian et al., 2016).

If infants are capable of seeking explanations for surprising events, then one would expect to find evidence that cognition cares about explanations from early in development. This appears to be true by the toddler- to preschool years. By 2- to 5-years of age, children are already asking *why* and *how* questions in their everyday conversations with adults. Their questions are more persistent when they receive non-explanatory responses as opposed to explanations (Callanan & Oakes, 1992; Frazier, Gelman, & Wellman, 2009), and they prefer learning from people who provide non-circular over circular explanations (Corriveau & Kurkul, 2014). Moreover, 3- to 5-year old children can offer their own verbal explanations, and are more likely to do so when objects behave in unexpected ways (Legare, Gelman, & Wellman, 2010). In addition to seeking and producing verbal explanations, preschool-aged children produce exploratory actions in situations where explanations are warranted. They explore more in situations in which it is clear that there is a new causal relation to be learned (Butler & Markman, 2012) and when faced with unexplained or ambiguous events; further, their exploratory behaviors seem targeted to potential explanations of the events (Schulz and Bonawitz, 2007). This ability to generate and test explanations in order to form a causal understanding of the world has been argued to be a central driver of children's learning (Gopnik, 1998; Legare & Clegg, 2014; Wellman, 2011).

Yet, evidence that preverbal infants recognize explanations is surprisingly sparse. One potential indication that they might comes from patterns of null results in some violation-of-expectation studies (Baillargeon, 1994). In one series of studies, 3- and 3.5-month-old infants saw an object pass behind a U-shaped screen (Aguiar & Baillargeon, 2002). Sometimes the U was big enough so that its bottom portion hid the object as it moved from one side to the other, and other times the U was too short, such that the moving object should have been partially

131 visible—but wasn't. Three-month-old infants looked longer at the shorter-U event than the
132 larger-U event, suggesting that they were surprised when the object passed by without being
133 seen. Yet 3.5-month-olds failed to show this elevated looking. The interpretation offered by
134 Baillargeon is that 3.5-month-olds spontaneously generated an explanation for the surprising
135 event: they posited that two identical objects were present—one behind each vertical arm of the
136 U. The event would then be construed as involving an object moving out from behind the left
137 arm of the U and then, after a pause, a second object emerging from behind the right arm.
138 Baillargeon's interpretation is bolstered by her additional finding that when 3.5-month-olds
139 definitively saw that only one object was present prior to the event (because the U-shaped screen
140 was lowered to reveal just a single object, then was raised again), they now looked longer in the
141 shorter-U condition (just like the younger 3-month-olds who were not yet capable of generating
142 an explanation of the event), because the 2-object explanation could no longer account for their
143 observations. Baillargeon (1994) suggests that other null results in violation-of-expectation
144 studies could similarly be caused by infants constructing explanations—if infants faced with
145 surprising events generate explanations on their own, then they may show no difference in
146 looking time to impossible versus possible events (Baillargeon, 1994). Further, Baillargeon
147 suggests that when infants see particular kinds of violations of expectation events, they can use
148 these experiences to refine their expectations about object behavior. When 11- and 12-month-old
149 infants saw an asymmetric object that remained supported without falling, even though only half
150 of it was in contact with the supporting surface underneath and its center of mass dangled over
151 empty space, they initially failed to show surprise. But when infants received a short series of
152 teaching events involving asymmetric objects, they now detected the violation (Baillargeon &
153 DeJong, 2017). According to Baillargeon, infants' new observations led them to construct a more

accurate rule that better accounted for objects' behavior. In a sense, the new rule could be considered to be an explanation—in that it includes a representation of causal factors relevant to interpreting the event.

Although the findings described above could potentially implicate preverbal recognition of explanations, other evidence suggests that infants struggle to recognize explanations for surprising events. For example, Wang & Goldman (2016) found that 12-month-old infants successfully used information that was presented before a surprising event, such that they were able to revise their expectations of the event's outcome. In contrast, when the same information was presented after the event—thereby providing an explanation for what had already happened—infants seemed unable to integrate this new information into their event representation. The distinction between information presented before versus after a surprising event may be critical to thinking about whether infants genuinely represent explanations. When infants have all of the relevant information available to them before an event occurs, they may simply be triggered to represent the event in a different way. For example, in the task described above by Aguiar and Baillargeon (2002), infants in one condition saw the object move back and forth from behind the small U-shaped screen. Although the object was tall enough to protrude above the horizontal portion of the U, it never did; it only emerged from and then disappeared behind the screen's vertical arms. Baillargeon suggests that the 3.5-month-olds in this task formed an explanation for this seemingly impossible event: two objects were present, one behind each vertical arm. This 2-object construal of the event can describe what happened without invoking any expectancy violations. But is it an *explanation*? Seeing an object emerge from behind one arm without having traversed the gap to get there might have automatically caused infants to token a new object representation, such that they now represented the scene as

177 containing two identical objects. Forming this second object representation does not require that
178 infants experienced a state of puzzlement or mental conflict that would require an explanation to
179 resolve. It may merely be an automatic generation of a new object representation, caused by the
180 spatiotemporal evidence in the event.

181 Explanation has been defined in multiple ways (Lombrozo, 2006), but one version
182 involves the ability to observe an object or event that conflicts with a prior model of the world,
183 represent this conflict, and then use subsequent information to resolve the conflict. For this
184 definition, the distinction between the ability to use information available before a surprising
185 event (such that the event is never perceived as surprising) versus after a surprising event (to
186 explain away the surprising apparent conflict) is critical. With respect to this definition, it
187 remains an open question whether infants recognize explanations.

188 In the present work we sought to address the open question of whether infants can use
189 new evidence to explain a previously observed violation-of-expectation event. We hypothesized
190 that if surprise-induced exploration reflects the search for an explanation, then if offered a
191 plausible explanation for the surprising event, infants' post-surprise exploration should cease.
192 We tested this hypothesis in three experiments. First, in Experiment 1, we attempted to replicate
193 the finding that surprise propels infants to explore. We showed 11-month-old infants a physical
194 event that either culminated in an expected outcome (that accorded with constraints on object
195 solidity), or a nearly identical event that culminated in a surprising outcome (that violated
196 constraints on solidity). Based on previous findings (Baillargeon et al., 1985; Spelke et al., 1992;
197 Stahl & Feigenson, 2015), we anticipated that when then given the chance to explore the object
198 from the event versus a novel distractor, infants who had seen the violation would show a
199 heightened preference to explore the target object. Next, in Experiment 2, we asked what would

happen if infants were offered an explanation for the surprising event. Infants saw the same surprising solidity violation as in Experiment 1, but then were given new information that offered a plausible explanation for what had just happened. If surprise simply increases infants' arousal and motivation to engage with the object from the surprising event, then infants in Experiment 2 should show the same heightened exploration as infants in Experiment 1. Alternatively, if infants' exploration reflects the search for an explanation for the anomalous event, then receiving an explanation should abolish any surprise-induced exploration. Finally, in Experiment 3, we replicated Experiment 2 with an independent sample of infants.

2. Experiment 1

Although hundreds of studies find that infants look longer at surprising than expected outcomes, to date only a few published studies report that surprise also triggers infants to explore more (Sim & Xu, 2017; Stahl & Feigenson, 2015). Therefore, in Experiment 1 we first sought to replicate the finding that surprise enhances infants' exploration. Eleven-month-old infants saw a solidity event modeled on that by Spelke et al. (1992), in which an object rolled down a ramp and passed behind a screen, heading towards a wall in its path. The event either culminated in an expected outcome (the object appeared to have been stopped by the wall) or a surprising outcome (the object appeared to have passed straight through the wall). We predicted that infants would subsequently explore the object more when it had been involved in the surprising event as opposed to the expected one.

2.1 Method

2.1.1 Participants

Forty full-term 11-month-old infants participated (mean age: 11 months, 13 days; range: 10 months, 12 days to 13 months, 4 days); eighteen were girls. Data from nine additional infants were excluded for fussiness (3), parent interference (1), failing to look at the event outcome (4; see below), or failing to engage in any object exploration at all (1). Written informed consent was obtained from parents prior to participation, and infants received a small gift (book, stuffed toy) to thank them for their participation.

2.1.2 Stimuli

Infants saw two objects during the course of the study, chosen to be easy discriminable in terms of basic level kind and low level visual features: a blue and red toy truck and a green and red ball. The truck measured 12 x 8 centimeters and the ball measured 8 centimeters in diameter. Half of the infants saw the truck serve as the Target Object and the ball as the Distractor Object, and half saw the reverse.

2.1.3 Procedure

Infants sat in a highchair one meter from a puppet stage. Parents sat out of view behind them and were instructed to remain silent throughout the study.

Familiarization Event. The study started with a trial designed to familiarize infants to the stage and the Target Object. The experimenter, out of view behind the stage, raised the stage curtain to reveal a black ramp (120 cm long) slanting downward from the stage's far left. At the opposite end of the stage, on the far right, stood a grey wall (30 cm high x 25 cm wide). Next infants saw the experimenter reach in from above and place a black screen on stage, facing infants, so that the screen partially occluded the ramp and the path from the ramp to the wall (Figure 1). The experimenter then said "Look at this!" as she reached down from above, holding the Target Object (e.g., truck), and waved it for 5 seconds to draw infants' attention before

placing it at the top of the ramp. She said, “Watch this!” and released the object so that it rolled down the ramp and behind the occluding screen. The experimenter then said, “Look at this!” as she reached down and removed the screen, revealing the Target Object resting against the grey wall on the far right side of the stage. After five seconds, the experimenter lowered the stage curtain and the Familiarization trial was considered complete.

Solidity Event. All infants next saw a single test event. The experimenter raised the curtain to reveal the ramp, the far grey wall, and the black occluding screen, all in the same positions they had been in during the Familiarization event. In addition, there was now a bright red wall (35 cm high x 25 cm wide) interrupting the path from the ramp to the far grey wall; the top of this red wall could be clearly seen protruding 13 cm above the top of the occluding screen (Figure 1). The experimenter drew infants’ attention to the visible portion of the red wall, saying “Look at this!” as she pointed to and tapped it for two seconds before withdrawing her hand from the stage. Next the experimenter reached back into the stage holding the Target Object, said, “Watch this!” and released the object at the top of the ramp so that it rolled down and disappeared behind the screen. After approximately five seconds she said, “Look at this!” as she removed the screen, revealing the final position of the Target Object. For infants in the Expected condition, the Target Object was revealed on the near side of the red wall—consistent with the red wall having stopped the object (Figure 1, Panel 3A). For infants in the Surprising condition, the Target Object was revealed on the far side of the red wall—consistent with the object having passed straight through (Figure 1, Panel 3B). Infants’ looking at the outcome was measured for 10 seconds. Because we were interested in how infants’ exploration would change as a consequence of which outcome infants saw, we excluded from analysis any infants who did not look at the outcome for at least 2 seconds (4 infants). After 10 seconds the experimenter said

“Look at this!” as she picked up and rotated the red wall so infants could see its front face (which had previously not been visible). She placed the wall facing infants on the left side of the stage, and infants’ looking was measured for 20 seconds (Figure 1, Panels 4A & 4B). After 20 seconds had elapsed, the experimenter lowered the stage curtain.

Figure 1. Schematic of Experiment 1. The experimenter released the Target Object at the top of the ramp (Panel 1). The Target Object rolled down the ramp and disappeared behind an occluding screen, above which a bright red wall could be seen (Panel 2). The screen was then removed, revealing either the Target Object on the near side of the red wall (Expected condition, Panel 3A) or on the far side (Surprising condition, Panel 3B). After 10 s the experimenter rotated the red wall so infants could see its front face (Panels 4A & 4B).

Exploration Phase. Immediately following the Test Event the experimenter emerged from behind the stage holding the Target Object (e.g., truck) and a novel Distractor Object (e.g., ball), one in each hand. She said, “Look at these!” and placed both objects on the high-chair tray (with left-right placement counterbalanced across infants). Then she returned behind the stage so that

she was out of infants' view. The objects remained on the high chair tray for 30 seconds, during which infants' visual and manual exploration of the objects was recorded for later coding.

All videos were coded offline by two trained observers; each observer coded the videos of 60% of the participants; 20% of videos were coded by both. Inter-observer reliability was .95 for infants' visual exploration and .94 for manual exploration.

2.2 Results

We first asked whether infants detected the solidity violation. We found that infants in the Surprising condition looked significantly longer at the event outcome ($M = 7.42$ sec, $SD = 2.35$ sec) than infants in the Expected condition ($M = 5.41$ sec, $SD = 1.64$ sec; $t(38) = -3.13$, $p < .01$, $CI [-3.31, -.71]$), confirming the results of many previous studies.

Next we asked whether the type of outcome infants saw affected their subsequent exploration. We first computed each infant's visual exploration preference score by subtracting the time spent visually exploring the novel Distractor Object from the time spent visually exploring the familiar Target Object, and each infant's manual exploration preference score by subtracting the time spent touching the Distractor Object from the time spent touching the Target Object. Then we asked whether these exploration preference scores differed across conditions. A 2 x 2 ANOVA with Condition (Surprising or Expected Outcome) and Object Type (truck or ball as Target Object) as between-subjects factors revealed a significant main effect of Condition on infants' visual exploration, $F(1, 36) = 5.85$, $p = .02$, $\eta^2 = .14$, no main effect of Object Type, and no interaction between Condition and Object Type. Infants who had seen the Surprising outcome of the solidity event preferred to visually explore the familiar Target Object ($M_{preference} = 4.50$, $SEM = 1.57$, $CI [1.18, 7.76]$), a preference that differed from chance, $t(1, 19) = 2.84$, $p = .01$). In contrast, infants who saw the Expected outcome slightly preferred to explore the novel

Distractor ($M_{preference} = -1.59$, $SEM = 1.93$, $CI [-5.64, 2.45]$, although this tendency did not differ from chance, $t(1, 19) = .82$, $p = .42$. For manual exploration, we observed no main effect of Condition, $F(1, 36) = .00$, $p = .98$, $\eta^2 = .00$, a main effect of Object Type, $F(1, 36) = 23.01$, $p = .00$, $\eta^2 = .39$, and no interaction between Condition and Object Type. The effect of Object Type was driven by infants' overall preference to touch the ball, regardless of which outcome they had seen. Unlike infants' visual exploration, infants' manual exploration did not significantly differ across the two conditions (Surprising Outcome $M_{preference} = 1.70$, $SEM = 3.70$, $CI [-3.57, 6.97]$; Expected Outcome $M_{preference} = 2.38$, $SEM = 2.76$, $CI [-3.71, 6.89]$), $F(1, 36) = .001$, $p = .98$, $\eta^2 = .00$.

2.3 Experiment 1 Discussion

The results of Experiment 1 suggest that surprise motivates infants to explore. Infants who saw an object violate the principle of solidity visually explored that object significantly more than infants who saw the same object behave in an expected way. This replicates the results of previous studies (Sim & Xu, 2017; Stahl & Feigenson, 2015), and suggests that violations-of-expectation are not only detected by infants, but also change their subsequent information-seeking behavior.

However, it remains unknown why surprise triggers infants' exploration. One possibility is that surprise-induced exploration merely reflects arousal. On this account, surprise straightforwardly increases infants' engagement with surprising objects, resulting in enhanced exploration (Experiment 1 in the present work; Sim & Xu, 2017; Stahl & Feigenson, 2015) and learning (Stahl & Feigenson, 2015). Alternatively, infants' exploration might reflect the search for an explanation for the surprising event. If explanation-seeking is what surprise motivates infants to explore, then providing them with an explanation following a surprising event might

be expected to abolish surprise-induced exploration. Previous research finds a related pattern of behavior in preschool-aged children, who stop asking causal questions once they have received an explanation from an adult, but persist following non-explanations (Frazier, Wellman, & Gelman, 2009).

To find out whether preverbal infants recognize explanations, in Experiment 2 we showed a new group of infants the surprising solidity event from Experiment 1. As before, infants saw a moving object apparently pass through a red wall and come to rest on the wall's far side. Then, also as before, the experimenter rotated the wall so that infants could see its front face. However, this time, rotating the wall revealed that it contained an opening large enough for the object to have passed through — thereby providing a plausible explanation for the surprising event (i.e., the object passed through the hole). If infants' surprise-induced exploration reflects the search for an explanation, then seeing the wall with the opening in it should decrease infants' subsequent exploration, relative to that exhibited by infants in Experiment 1 who received no such explanation.

3. Experiment 2

3.1 Method

3.1.2 Participants

Twenty 11-month-old infants participated (mean age: 11 months, 9 days; 8 girls; range: 11 months, 5 days to 13 months, 24 days). Data from seven additional infants were excluded for fussiness (2), parent interference (1), failing to look at the event outcome (3), or failing to engage in any object exploration (1).

3.1.3 Procedure

354 Infants first saw a Familiarization trial as in Experiment 1. All infants then saw the same
 355 solidity event as infants in the Surprising condition of Experiment 1: a Target Object was placed
 356 at the top of the ramp and then released so that it rolled down and passed behind the occluding
 357 screen, above which the red wall protruded. The experimenter then lifted the screen to reveal that
 358 the object had come to rest on the far side of the wall, as though it had passed through it. As in
 359 Experiment 1, infants had 10 seconds to view this surprising outcome. Then the experimenter
 360 reached down and picked up and rotated the red wall, placing it so that its front face was visible
 361 to infants. Whereas in Experiment 1 the red wall was revealed to be solid (Figure 2, Panel 4A),
 362 in Experiment 2 the red wall was revealed to have a large opening in its face (Figure 2, Panel
 363 4B). Infants' looking was measured during the 20 seconds that followed.

364 The exploration phase that followed was as in Experiment 1. The experimenter emerged
 365 holding the Target Object (e.g., truck) and a novel Distractor Object (e.g., ball), said, "Look at
 366 these!" and placed both objects on the high-chair tray. Infants had 30 seconds to explore the
 367 objects.

368 **Figure 2.** Schematic of Experiment 2. The experimenter released the Target Object at the top of
 369 the ramp (Panel 1). The Target Object rolled down the ramp and disappeared behind an
 370

occluding screen, above which a bright red wall protruded (Panel 2). The screen was then removed, revealing the Target Object resting on the far side of the red wall (Panel 3). After 10 s the experimenter rotated the red wall. Whereas infants in the Surprising condition of Experiment 1 saw that it was solid (Panel 4A), infants in Experiment 2 saw that the red wall contained a large opening (Panel 4B).

3.2 Results

We first asked whether infants in Experiment 2 detected the solidity violation by comparing their looking during the 10 seconds following the event outcome to that of infants in the Expected condition of Experiment 1. Infants in Experiment 2 looked significantly longer ($M = 6.77$ seconds, $SD = 1.46$ seconds) than infants in the Expected condition of Experiment 1 ($M = 5.41$ seconds, $SD = 1.64$ seconds; $t(38) = -2.76, p = .01, CI [-2.36, -.36]$). In contrast, infants in Experiment 2 and infants in the Surprising condition of Experiment 1 ($M = 7.42$ sec, $SD = 2.35$ sec) looked equally ($t(38) = 1.05, p = .30, CI [-.61, 1.90]$). Hence infants in Experiment 2 detected the solidity violation.

Next we examined infants' exploration, first computing visual and manual exploration preference scores as described in Experiment 1 (i.e., exploration of Target Object minus exploration of Distractor Object). Because we hypothesized that infants' exploration following a surprising event would depend on whether they had seen a plausible explanation for the event, we compared the exploration preference scores of infants in Experiment 2 with those of infants in the Surprising condition of Experiment 1 who had seen the same event but without the explanation. A 2 x 2 ANOVA with Condition (Surprising Outcome without Explanation in Experiment 1 or Surprising Outcome with Explanation in Experiment 2) and Object Type (truck

or ball as Target Object) as between-subjects factors revealed a main effect of Condition on infants' visual exploration, $F(1, 36) = 5.20, p = .03, \eta^2 = .13$. Infants who had received an explanation for a surprising event visually explored the target object significantly less ($M_{preference} = -.95, SEM = 1.77, CI [-4.35, 2.46]$) than infants who received no explanation, ($M_{preference} = 4.50, SEM = 1.57, CI [1.06, 7.87]$), $t(1, 38) = 2.29, p = .03, CI [-10.21, -.62]$. There was no main effect of Object Type, nor any interaction between Condition and Object Type. For manual exploration, although infants in Experiment 2 who had received an explanation for the surprising event explored less ($M_{preference} = -4.50, SEM = 4.48, CI [-11.39, 2.39]$) than those in Experiment 1 who received no explanation ($M_{preference} = 1.70, SEM = 3.70, CI [-5.19, 8.59]$), the ANOVA revealed no main effect of Condition $F(1, 36) = 1.66, p = .21, \eta^2 = .04$. There was a significant main effect of Object Type, $F(1, 36) = 19.09, p = .00, \eta^2 = .35$, again driven by infants' tendency to manually explore the ball, and no interaction between Condition and Object Type.

Did seeing a plausible explanation make infants treat a surprising event like an expected event? We next compared the visual exploration preferences of infants in Experiment 2 to those of infants in the Expected condition of Experiment 1. A 2 x 2 ANOVA with Condition (Surprising Outcome with Explanation in Experiment 2 or Expected Outcome in Experiment 1) and Object Type (truck or ball as Target Object) as between-subjects factors found no main effect of Condition on infants' visual exploratory preferences, $F(1, 36) = .08, p = .78, \eta^2 = .00$, no main effect of Object Type, and no interaction between Condition and Object Type. As predicted, infants visually explored equally after receiving an explanation for a surprising outcome ($M_{preference} = -.95, SEM = 1.77, CI [-4.73, 2.83]$) and after seeing an expected outcome ($M_{preference} = -1.59, SEM = 1.93, CI [-5.49, 2.10]$, Figure 3). For manual exploration, the ANOVA also revealed no main effect of Condition, $F(1, 36) = 1.96, p = .17, \eta^2 = .05$, a main

effect of Object Type, $(1, 36) = 19.09, p = .00, \eta^2 = .35$, and no Condition by Object Type interaction. Infants manually explored equally after seeing a surprising event accompanied by an explanation ($M_{preference} = -4.50, SEM = 4.48, CI [-10.73, 1.73]$) and after seeing an expected event ($M_{preference} = 2.38, SEM = 2.76, CI [-4.66, 7.86]$).

Figure 3. Visual exploration preference scores (looking to Target Object – looking to Distractor Object) in Experiments 1 and 2. Errors bars reflect SEM. * $p < .05$.

Finally, as a further test of whether explanations drove infants' exploratory behavior, we examined individual differences in infants' looking times and their possible link to subsequent exploration. Because we had hypothesized that seeing an explanation for a surprising event would abolish surprise-induced exploration, we also predicted that the longer infants looked at the explanation (i.e., the red wall with the opening in it), the less they would subsequently explore the Target Object. That is, the more infants processed the explanation, the less drive they should have to explore. We used linear regression to examine the relationship between the duration of infants' looking at the wall with the opening in it and their later preference to visually

explore. We found that the longer infants in Experiment 2 looked at the wall with the opening, the more they preferred to explore the novel Distractor Object, $R^2 = .23$, $F(1, 18) = 5.28$, $p = .03$ (Figure 4A). No such relationship was found among infants in either condition of Experiment 1, for whom the red wall offered no explanatory information (Surprising condition of Experiment 1, $R^2 = .00$, $F(1, 18) = .00$, $p = .99$) (Figure 4B); Expected condition of Experiment 1, $R^2 = .01$, $F(1, 18) = .08$, $p = .78$).

Figure 4. Relationship between infants' visual exploration preference and looking at the rotated wall in Experiment 2, in which the rotated wall provided an explanation for the solidity violation (Panel A), and in the Surprising Outcome condition of Experiment 1, in which the wall offered no explanation (Panel B).

A similar pattern was seen for infants' manual exploration, although this was not statistically significant, $R^2 = .10$, $F(1, 18) = 1.96$, $p = .17$. For infants in the Surprising condition of Experiment 1, looking at the solid red wall was unrelated to manual exploration preference R^2

= .02, $F(1, 18) = .31$, $p = .59$. Similarly, for infants in the Expected condition of Experiment 1, looking at the red wall was unrelated to manual exploration, $R^2 = .03$, $F(1, 18) = .54$, $p = .47$.

4. Experiment 3

The main finding from Experiment 2 was that seeing an explanation for a violation-of-expectation event eliminated infants' exploration of the object that had behaved surprisingly. In Experiment 3 we sought to replicate this effect with a new sample of infants, to examine the robustness of this effect.

4.1 Method

4.1.2 Participants

Twenty 11-month-old infants participated (mean age: 11 months, 4 days; 7 girls; range: 10 months, 3 days to 12 months, 26 days). Data from two additional infants were excluded for fussiness (1) and parent interference (1).

4.1.3 Procedure

The procedure was exactly as in Experiment 2.

4.2 Results

First we asked whether infants in Experiment 3 detected the solidity violation by comparing their looking times to the event outcome to those of infants who had seen an expected outcome in Experiment 1. Infants in Experiment 3 looked significantly longer ($M = 6.53$ seconds, $SD = 1.64$ seconds) than infants in the Expected condition of Experiment 1 ($M = 5.41$ seconds, $SD = 1.64$ seconds; $t(38) = -2.12$, $p = .04$, $CI [-2.17, -.52]$). In contrast, infants in Experiment 3 looked at the outcome for a similar duration as infants in the Surprising condition

of Experiment 1, $t(38) = 1.39$, $p = .17$, $CI [-.41, 2.20]$, and infants in Experiment 2, $t(38) = .49$, $p = .62$, $CI [-.76, 1.25]$, affirming that infants in Experiment 3 detected the solidity violation.

Next we examined infants' visual and manual exploration preference scores. A 2 x 2 ANOVA examining the effects of Condition (Surprising Outcome with Explanation in Experiment 3 or Surprising Outcome with no Explanation in Experiment 1) and Object Type (truck or ball as Target Object) on infants' visual exploration revealed a main effect of Condition, $F(1, 36) = 4.22$, $p = .047$, $\eta^2 = .11$, no effect of Object Type, and no interaction between Condition and Object Type. Infants visually explored less in Experiment 3 after seeing a surprising outcome accompanied by an explanation ($M_{preference} = -.54$, $SE = 2.01$, $CI [-4.04, 2.95]$) than in Experiment 1 after seeing the same surprising outcome but without any explanation ($M_{preference} = 4.50$, $SE = 1.57$, $CI [.97, 7.96]$). For manual exploration, the ANOVA revealed no main effect of Condition, $F(1, 36) = .46$, $p = .50$, $\eta^2 = .01$, a main effect of Object Type, $F(1, 36) = 42.25$, $p = .00$, $\eta^2 = .54$, and no Condition by Object Type interaction. Infants showed a significant tendency to manually explore the ball regardless of whether or not they had been provided an explanation for the surprising event.

To ask whether infants treated a surprising event accompanied by an explanation as an expected event, we compared the visual exploration of infants in Experiment 3 to that of infants in the Expected Outcome condition of Experiment 1. A 2 x 2 ANOVA with Condition (Surprising Outcome with Explanation in Experiment 3 or Expected Outcome in Experiment 1) and Object Type (truck or ball as Target Object) as between-subjects factors revealed no effect of Condition, $F(1, 36) = .18$, $p = .67$, $\eta^2 = .01$, no effect of Object Type, and no interaction between these. For manual exploration, a 2 x 2 ANOVA with Condition (Surprising Outcome with Explanation in Experiment 3 or Expected Outcome in Experiment 1) and Object Type

(truck or ball as Target Object) as between-subjects factors revealed no effect of Condition, $F(1, 36) = .60, p = .44, \eta^2 = .02$, a main effect of Object Type, $F(1, 36) = 50.74, p = .00, \eta^2 = .59$ (with infants again preferring to manually explore the ball), and an interaction between Condition and Object Type, $F(1, 36) = 4.58, p = .04, \eta^2 = .11$.

Finally, because infants in Experiments 2 and 3 saw identical events, we combined the two samples to empower a more robust analysis of potential individual differences. First we confirmed that overall exploration preferences did not differ between infants in these two experiments. A 2 x 2 ANOVA with Condition (Experiment 2 or Experiment 3) and Object Type (truck or ball as Target Object) as between-subjects factors found no main effect of Condition, $F(1, 36) = .03, p = .87, \eta^2 = .00$ on infants' visual exploration. There was a main effect of Object Type on infants' visual exploration, $F(1, 36) = 6.03, p = .02, \eta^2 = .14$, whereby infants visually explored the ball more than the truck, but no Condition by Object Type interaction, $F(1, 36) = .56, p = .46, \eta^2 = .02$. Similarly, a 2 x 2 ANOVA with Condition (Experiment 2 or Experiment 3) and Object Type (truck or ball as Target Object) as between-subjects factors found no main effect of Condition, $F(1, 36) = .68, p = .41, \eta^2 = .02$, on infants' manual exploration. As in the other experiments there was a main effect of Object Type on infants' manual exploration, $F(1, 36) = 34.12, p = .00, \eta^2 = .49$, but no Condition by Object Type interaction, $F(1, 36) = .61, p = .44, \eta^2 = .02$. Given this lack of differences between Experiments 2 and 3, we collapsed the two so that we could examine individual differences in the larger sample of 40 infants. Collapsed across Experiments 2 and 3, we found that longer infants looked at the explanation (the rotated wall with the hole in it), the more they preferred to visually explore the novel Distractor Object, $R^2 = .11, F(1, 38) = 4.84, p = .03$ (Figure 5A). The same pattern was observed for infants' manual exploration, $R^2 = .16, F(1, 38) = 6.99, p = .01$ (Figure 5B). The longer infants looked at

the explanation for the surprising solidity event, the more time they spent playing with the novel distractor object.

Figure 5. Relationship between infants’ looking at an explanation for a surprising solidity event and their (A) visual exploration preference and (B) manual exploration preference (B), collapsed across Experiments 2 and 3.

5. General Discussion

Here we find that long before they can ask or answer “why” questions, infants seek and recognize explanations for anomalous events. In our first experiment, we confirmed that 11-month old infants who saw an object violate a principle of typical object behavior (by passing through a solid wall) significantly increased their tendency to explore that object, relative to infants who saw a closely matched event in which the object accorded with expectations (replicating previous work; Stahl & Feigenson, 2015). Then, in Experiment 2, we showed that

this surprise-induced exploration reflected infants' search for an explanation: when provided with a plausible reason for the surprising event, infants' exploratory preference disappeared, causing them to treat the previously surprising event like an expected one. We replicated these findings in Experiment 3. Our results suggest that infants' surprise-induced exploratory activity is not triggered ballistically by violation events, and does not merely reflect heightened arousal. Instead, infants appear to be actively searching for explanatory information, such that when that information is found, exploration returns to baseline.

We also saw that infants' ability to recognize explanations for objects' surprising behavior differed among individuals. As a group, infants in Experiments 2 and 3 who had seen an explanation for the surprising event showed no significant exploratory preference—they spent roughly equal amounts of time playing with the object from the surprising event and the novel distractor. However, closer inspection revealed that some of these infants in fact had a strong preference to explore the target object, whereas others had a strong preference to explore the distractor. Critically, which preference infants exhibited was predicted by how long they looked at the explanation for the surprising event: infants who looked at the explanation longest showed the greatest tendency to ignore the previously surprising object and explore the distractor (that is, showed a reverse preference relative to infants in Experiment 1 who received no explanation). The source of these individual differences remains an important direction for future study. An intriguing possibility is that infants differed in their ability to recognize the wall with the hole in it as a satisfying explanation for the surprising event, and/ or in their desire to find an explanation for an expectancy violation in the first place. While previous studies have found stable individual differences in the rate of infants' habituation and in their interest in perceptual novelty (Bornstein & Sigman, 1986; Colombo, Coldren, & Freese, 1991; Fagan, 1984), little is

known about the possibility of individual differences in infants' ability to detect violations of expectation (but see Perez & Feigenson, 2019a, 2019b) or in their ability to recognize explanations for such violations (as in the present work). Our findings therefore highlight the study of individual differences in response to violations, and their potential impact on later cognition, as an important avenue for future research.

A related issue is the degree to which the explanations infants sought and recognized in our experiments are like those that have been studied in older children and adults. Violations and explanations that can be represented using the core knowledge systems that are available to preverbal infants and nonverbal animals (Carey, 2009; Spelke & Kinzler, 2007) may or may not be linked to the verbally articulated explanations sought by older children, often to account for more complex phenomena and involving explanations that would be harder to uncover through a process of individual discovery (e.g., "Why is the sky blue?" "How do bees grow their babies?" (Chouinard, Harris, & Maratsos, 2007)). One approach to begin characterizing the relationship between explanation-seeking in infancy and explanation-seeking in later childhood is to examine individual differences over time—for example, asking whether infants who are most interested in explanations for surprising events later become children who search most persistently for verbal explanations. If these are linked, this could implicate the existence of a stable trait—one potentially related to the constructs of curiosity or "desire for understanding" that have been explored in older children and adults (e.g., Berlyne, 1966; Litman, Hutchins, & Russon, 2005; Loewenstein, 1994; Mussel, 2010), and which might even be measurable early in life.

The present research also raises the question of whether infants represent some explanations as better than others. To illustrate, imagine four different explanations for the solidity violation in the present study: one where the red wall is revealed to contain a large

opening that is plenty wide enough for the object to have passed through, another where the red wall contains an opening barely wider than the object itself, a third where the red wall contains an opening considerably narrower than the object, and finally one where the red wall contains a wide opening but on its top surface (as in a U) rather than its base. These scenarios vary in the likelihood that they can provide an adequate explanation for the surprising event of the ball passing through the wall. Would infants' interest in these explanations, and their change in subsequent exploratory behavior after seeing these explanations, decrease as a function of the explanations' goodness? Adults are sensitive to such variations in "explanatory power," where information is said to have more explanatory power as it renders observations less and less surprising (Colombo, Bucher, & Sprenger, 2017; Schupbach & Sprenger, 2011). Older children too are sensitive to explanatory power, in that they recognize explanations that, because of their circularity, are wholly unsatisfying (Baum, Danovitch, & Keil, 2008; Castelain, Bernard, & Mercier, 2018). However, infants' ability to represent degrees of explanation remains to be explored.

In summary, our findings demonstrate that infants do not merely detect surprising events, they also use surprise as inspiration to seek explanations. Starting in the first year of life, young learners leverage differences between what they predict and what they observe to motivate the gathering of new evidence and the revision of their beliefs. Whereas the ability to test explanations in a systematic way, and to generate novel explanations, likely undergoes considerable development during later childhood, the basic capacity to search for and recognize explanations is functional early in life.

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