Stable individual differences in infants' responses to violations of intuitive physics

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Infants look longer at impossible or unlikely events than at possible events. While these responses to expectancy violations have been critical for understanding early cognition, interpreting them is challenging because infants' responses are highly variable. This variability has been treated as an unavoidable nuisance inherent to infant research. Here we asked whether the variability contains signal in addition to noise: namely, whether some infants show consistently stronger responses to expectancy violations than others. Infants watched two unrelated physical events 6 mo apart; these events culminated in either an impossible or an expected outcome. We found that infants who exhibited the strongest looking response to an impossible event at 11 mo also exhibited the strongest response to an entirely different impossible event at 17 mo. Furthermore, violation-of-expectation responses in infancy predicted children's explanation-based curiosity at 3 y old. In contrast, there was no longitudinal relation between infants' responses to events with expected outcomes at 11 and 17 mo, nor any link with later curiosity; hence, infants' responses do not merely reflect individual differences in attention but are specific to expectancy violations. Some children are better than others at detecting prediction errors—a trait that may be linked to later cognitive abilities.

cognitive development | infants | prediction | surprise | individual differences

Infants look longer at events that adults judge as impossible or improbable, compared to possible or likely versions of the same events (1). This response to violations of expectation is seen, for example, when objects defy physical principles, like floating in midair (2): when quantities combine in mathematically impossible ways, like when 5 shapes + 5 shapes = 5 (3): and when social agents violate behavioral norms, like taking unnecessarily circuitous paths to goals (4). Results like these suggest that, from the first months of life, infants have expectations about the world around them.

Using looking times to make inferences about infants' perceptual and cognitive capacities has been highly fruitful for psychology and cognitive science. But it has also been challenging, in large part because infants' responses are notoriously noisy, making their data hard to interpret. Infants' behaviors are much more variable than those of adults; not all infants in a sample show violation-of-expectation responses. This variability has typically been treated as unwanted noise. But might infants' noisy responses also contain signal? Although some of the variability in infants' behavior might reflect momentary fluctuations in attention or arousal (i.e., noise unrelated to the focus of the experiment), some might also stem from differences in individuals' ability to detect, or their interest in, surprising events. If so, infants who exhibit stronger violation-of-expectation responses than others may also do so later, and in different contexts. Further, given the importance to learning of forming and evaluating predictions (5, 6), such individual differences, if they exist, might be linked to later variability in children's cognitive abilities. Strikingly, despite demonstrations of individual differences in infants' visual attention, habituation rate, novelty seeking, and exploration efficiency (e.g., refs. 7–9), it remains unknown whether infants stably differ in their ability to form and evaluate predictions.

To find out, we asked whether infants' interest in one impossible event at 11 mo predicted interest in a different impossible event 6 mo later. Sixty-five infants saw a single object solidity event at 11 mo (experiment 1) and a single object support event at 17 mo (experiment 2; Fig. 1). In the solidity event, infants saw an object roll down a ramp and pass behind a screen. A red wall could be seen standing behind the screen, blocking the object's path. The screen then was lifted to reveal the object resting on the wall's near side, as though the wall had stopped it (expected outcome), or its far side, as though it had passed straight through (surprising outcome). In the support event, an object was pushed along a supporting surface. It either was always fully supported (expected outcome) or was pushed completely over the edge yet did not fall (surprising outcome). Infants' looking at these outcomes was measured. Half the infants saw the expected outcome at both time points; half saw the surprising outcome at both time points. To ask whether any observed differences reflected variability specific to expectancy violations, as opposed to general cognitive differences, we measured infants' vocabulary using the Short-form MacArthur Communicative Development Inventories (10). Finally, as an exploratory investigation, at 37 mo we collected parental reports of children's explanation-based curiosity and interest in novelty [using the Interest and Deprivation Young Children Curiosity Scales (11)], and expressive vocabulary [using the Developmental Vocabulary Assessment for Parents (12)] (experiment 3, $n = 50$) (these were collected via parental report because the COVID-19 pandemic precluded in-person testing). An example item from the explanation-based curiosity measure was, "My child devotes considerable effort trying to figure out things that are confusing or unclear." An example from the novelty seeking measure was, "My child is attracted to new things in his/her environment" (*SI Appendix*).

Results

All analyses were performed on log-transformed looking times to account for positive skew (13). As predicted, 11-mo-old infants looked longer overall at surprising than at expected outcomes (6.43 s vs. 4.99 s), t (62) = 2.65, $P = 0.01$, and exhibited longer first looks at surprising than at expected outcomes (4.45 s vs. 2.91 s), t (62) = 2.92, $P < 0.01$. Seventeen-month-old infants also looked marginally longer overall at surprising than at expected outcomes (4.11 s vs. 3.28 s), t (62) = 1.73, $P = 0.09$, and exhibited longer first looks at surprising than at expected outcomes (2.61 s vs. 1.69 s), t (62) = 2.86, $P = 0.01$.

For infants in the surprising condition, outcome looking at 11 mo (at a toy that appeared to have passed through a wall) significantly

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Fig. 1. At 11 mo, infants saw an object roll down a ramp and appear to have been stopped by a wall (expected outcome) or to have passed straight through (surprising outcome). At 17 mo, infants saw an object fully supported by a block (expected outcome) or pushed over the edge without falling (surprising outcome).

predicted outcome looking at 17 mo (at a different toy that appeared to hover in midair), r (38) = 0.38, P = 0.02 (Fig. 2). This relation held when the effects of age and vocabulary at 17 mo were partialled out, r (35) = 0.38, P = 0.03. Critically, there was no relation between outcome looking at 11 and 17 mo for infants in the expected condition, r (26) = –0.12, P = 0.54 (Fig. 2). This suggests that the stable individual differences observed for infants in the surprising condition do not merely reflect differences in visual attention or overall stimulus engagement.

Finally, exploratory analyses revealed that infants' looking at a surprising outcome at 17 mo predicted explanation-based curiosity at 3 y, controlling for age and vocabulary, r (28) = 0.38, P = 0.05, whereas it was unrelated to novelty seeking, r (28) = 0.00, P = 0.99. Infants' looking at an expected outcome at 17 mo was unrelated to later curiosity, r (22) = 0.37, P = 0.11, or novelty seeking, r (22) = 0.00, P = 0.99.

Discussion

Here we show that some infants respond more to expectancy violations than others, consistently over development and across event types. The discovery of this signal opens the door to future work in at least three key areas.

First, our findings raise the question of whether individual differences in infants' responses to expectancy violations impact later development. Children's learning is enhanced immediately following an expectancy violation (5). Combined with the results

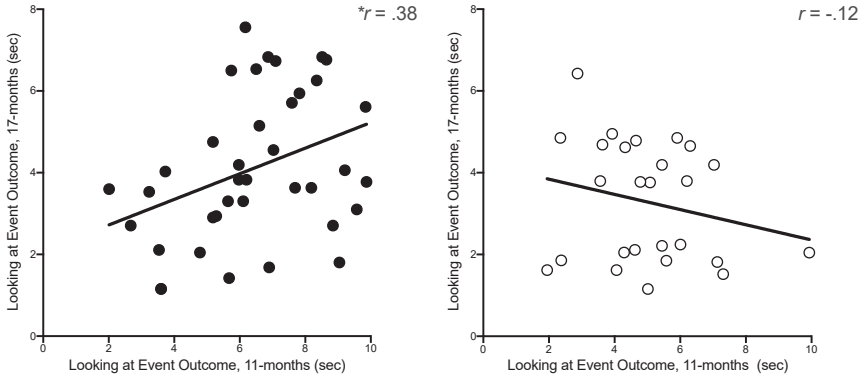

Fig. 2. Relation between looking at event outcomes at 11 and 17 mo for infants who saw surprising (*Left*) and expected (*Right*) outcomes. *P < 0.05.

of our longitudinal study, this points to the possibility that some children not only respond more to violations but also learn better from them. More work is needed to examine this and other potential consequences of these early individual differences. Second, our findings highlight the question of how infants' variable responses to expectancy violations arise in the first place. These differences may be rooted in biology, prior experience, or both, and could directly reflect cognitive differences among infants, or differences in infants' temperament or emotional regulation (14). Finally, the scope of the individual differences we observed remains unknown—for example, do infants who respond most to physical object violations also respond most to violations of expectations about how other social agents will act? Individual differences in infants' rates to encode socially relevant information are linked with later reasoning about others' mental states (15). Whether this variability also leads some infants to respond more to violations of social expectations, and, if so, whether these individual differences are related to infants' object violation responses, as observed in the present work, has yet to be discovered.

The proposal that infants have expectations about aspects of the world from early in development sometimes is taken to imply that early cognition is invariant. However, unlike experiments designed to investigate cognitive capacities at the group level, our findings highlight important variability in infants' basic expectations about the world—variability that has previously been treated as noise.

Materials and Methods

Participants. Sixty-five infants participated in experiment 1 at 11 mo (M = 11.55 mo, range = 10.15 to 14.01, SD = 0.93) and again in experiment 2 at 17 mo (M = 17.09 mo, range = 15.18 to 19.25, SD = 1.03); 29 were girls. When children were 3 y old (M = 36.92 mo, range = 27.18 to 48.16, SD = 6.41), parents of 50 of them returned completed experiment 3 questionnaires. This study was approved by the Johns Hopkins University Homewood Internal Review Board. Parents gave written informed consent at each time point. More methods can be found in *SI Appendix*.

Data Availability. The dataset has been deposited in Harvard Dataverse (https://doi.org/10.7910/DVN/MH2K8N).

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