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Short Communication

Minimally counterintuitive stimuli trigger greater curiosity than merely improbable stimuli

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ABSTRACT

Curiosity plays a key role in directing learning throughout the lifespan. Prior work finds that violations of expectations can be powerful triggers of curiosity in both children and adults, but it is unclear which expectation-violating events induce the greatest curiosity and how this might vary over development. Some theories have suggested a U-shaped function such that stimuli of moderate extremity pique the greatest curiosity. However, expectation-violations vary not only in degree, but in kind: for example, some things violate an intuitive theory (e.g., an alligator that can talk) and others are merely unlikely (e.g., an alligator hiding under your bed). Combining research on curiosity with distinctions posited in the cognitive science of religion, we test whether minimally counterintuitive (MCI) stimuli, which involve one violation of an intuitive theory, are especially effective at triggering curiosity. We presented adults ($N = 77$) and 4- and 5-year-olds ($N = 36$) in the United States with stimuli that were ordinary, unlikely, MCI, and very counterintuitive (VCI) and asked which one they would like to learn more about. Adults and 5-year-olds chose Unlikely over Ordinary and MCI over Unlikely, but not VCI over MCI, more often than chance. Our results suggest that (i) minimally counterintuitive stimuli trigger greater curiosity than merely unlikely stimuli, (ii) surprisingness has diminishing returns, and (iii) sensitivity to surprisingness increases with age, appearing in our task by age 5.

1. Introduction

Curiosity is fundamental to learning. The desire to learn directs attention, promotes exploration, and guides theory development (see Gopnik, 2000; Dubey & Griffiths, 2020; Von Stumm, Hell, & Chamorro-Premuzic, 2011; Jirout & Klahr, 2020; Fandakova & Gruber, 2021, for reviews; see Kidd & Hayden, 2015, Liquin & Lombrozo, 2020a, Liquin and Lombrozo, 2020b, and Mills & Sands, 2020). But curiosity is effective because it is selective. What kinds of observations induce the greatest curiosity, and how does this selectivity develop?

One factor that plays a role in prompting curiosity is whether an observation violates expectations (Berlyne, 1966; Perez & Feigenson, 2022; Stahl & Feigenson, 2015). Even young infants seem to have expectations about how the world works and pay more attention to events that violate them. For example, 4.5-month-olds look longer at a block floating unsupported in the air than at a block that is adequately supported, which researchers interpret as evidence that infants expect unsupported objects to fall (Needham & Baillargeon, 1993). A vast developmental literature finds early-emerging expectations in other domains (for a review, see Baillargeon, Li, Gertner, & Wu, 2011), alongside evidence that expectation-violating events can lead to exploration and learning in infancy and beyond (Bonawitz, van Schijndel, Friel, & Schulz, 2012; Legare, Gelman, & Wellman, 2010; Stahl & Feigenson, 2015, 2017, 2019). Similarly, infants attend more to events that are improbable versus probable (Gergely, Nádasdy, Csibra, & Bíró, 1995; Kayhan, Gredebäck, & Lindskog, 2018), and use probabilistic information to make predictions and guide action (e.g., Denison & Xu, 2014; Téglás, Girotto, Gonzalez, & Bonatti, 2007; Xu & Garcia, 2008).

Notably, not all violations of expectation are equal. One important dimension of variation is their extremity. This is often cached out in terms of complexity, uncertainty, or surprisingness, where violations of *moderate* extremity prompt the greatest curiosity (Berlyne, 1966; Loewenstein, 1994). Such accounts can be motivated in terms of the efficiency of learning: directing attention to stimuli that are too simple is unlikely to support learning because such stimuli are already expected or can be assimilated without effort, whereas stimuli that are too extreme are unlikely to support learning because they could be random or too costly to understand (Kidd, Piantadosi, & Aslin, 2012). Evidence

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for an inverted U-shaped function of this form has been found in both explicit measures of curiosity in adults (e.g., Kang et al., 2009) and indirect measures in children, such as looking time (Kidd et al., 2012) and information search (Wang, Yang, Macias, & Bonawitz, 2021).

Beyond extremity, however, expectation-violations can also differ in kind (Sim & Xu, 2019; Wang et al., 2021). There is a difference between finding a kangaroo in the streets of Manhattan (an expectation-violating event that is highly unlikely) and finding a kangaroo that can talk (an expectation-violating event that challenges intuitive theories of how the world works). This distinction between events that are merely improbable and those that violate our intuitive theories has been explored in prior work on "minimally counterintuitive" concepts within the cognitive science of religion (Boyer & Ramble, 2001; Norenzayan, Atran, Faulkner, & Schaller, 2006). This work has found that in both adults (Boyer & Ramble, 2001; Nyhof & Barrett, 2001) and children as young as age 7 (Banerjee, Haque, & Spelke, 2013), minimally counterintuitive concepts – concepts that involve a single violation of an intuitive theory (e.g., an alligator that can talk) – are easier to remember and more likely to be shared with others than concepts that are ordinary (e.g., an alligator in a swamp), unlikely (e.g., an alligator under a bed in a city), or have too many theory violations (e.g., an alligator that can talk, walk through walls, and live forever). However, it is unknown whether adults and children are selectively curious about minimally counterintuitive concepts, as well.

Indeed, events that violate intuitive theories might present an especially powerful opportunity for learning, especially for young children. It has long been argued that children possess rich naïve or intuitive theories, and that these theories are key to children's impressive learning and reasoning abilities (e.g., Carey, 1985; Gopnik, 2000; Wellman & Gelman, 1992). Moreover, empirical evidence suggests that children use intuitive theories to interpret new events and guide exploration (Karmiloff-Smith & Inhelder, 1974; Bonawitz et al., 2012). Therefore, a violation of expectations that prompts theory revision could have important downstream consequences for later learning and reasoning. Children are more likely to seek theory-relevant information when their theories are more uncertain (Wang et al., 2021), suggesting that children are motivated to construct accurate theories. However, a systematic investigation of curiosity following theory-relevant violations of expectation compared to curiosity following theory-irrelevant violations of expectations remains to be conducted.

In the present research, we build on prior work positing an inverted U-shaped function governing curiosity, and we combine it with work on intuitive theories and minimally counterintuitive concepts to ask new questions. The answers to these questions will not only refine our understanding of the relation between violations of expectations and curiosity, but also shed light on how curiosity develops. First, we ask: do observations that are moderately expectation violating in the sense that they are minimally counterintuitive trigger the greatest curiosity? If accurate intuitive theories of the world are an especially powerful and generalizable form of knowledge, we might expect children to benefit from attention to (minimally) theory-violating observations as soon as they reliably differentiate the counterintuitive from the merely improbable. We would therefore expect higher levels of curiosity about minimally counterintuitive observations, in contrast to ordinary, unlikely, or very counterintuitive observations.

Second, if this differentiation is observed, when does it develop? Research on the development of the improbable / impossible distinction suggests that this differentiation may begin to emerge around 4 years of age. Shtulman and Carey (2007) found that 4- to 8-year-old children accurately differentiated impossible events from ordinary events, but often reported that improbable events (e.g., finding an alligator under the bed) could not "happen in real life" (see also Williams & Danovitch, 2022). However, Weisberg and Sobel (2012) found that children as young as 4 successfully distinguished impossible from improbable events when asked to continue a story by selecting an appropriate event (see also Bowman-Smith, Shtulman, & Friedman, 2019). While this work has not connected the improbable / impossible distinction to children's curiosity or learning, it motivates the prediction that a preference to learn about minimally counterintuitive stimuli could emerge as early as age 4.

To address our research questions, we presented 4-year-olds, 5-year-olds, and adults in the U.S. with pairs of events, and we asked them which they would like to learn more about. We operationalized curiosity in this form for two reasons: first, it tapped into facets of curiosity likely to direct exploration and learning, and second; it gave us a behavioral measure that did not depend upon children's understanding of the word "curiosity" or their metacognitive ability to report on it. However, to ensure that our measure about a desire to learn corresponded to the experience of curiosity (at least for adults), we had one group of adults complete the same measure as children and another group explicitly report curiosity.

Crucially, the events that participants could learn more about were either ordinary, unlikely, minimally counterintuitive, or very counterintuitive, as defined by prior research in the cognitive science of religion. This variation allowed us to investigate how different kinds of expectation-violation map onto the posited inverted U-shaped function for curiosity, and specifically determine whether minimally counterintuitive observations maximally pique children's and adults' curiosity.

2. Method

This study was approved by the Institutional Review Board at Princeton University (#11566). All data and research materials are available at https://osf.io/sqm5c/?view_only=eea1394cd79b4fb4b655a9a80e9afcca. Data were analyzed using R, version 4.1.3 (R Core Team, 2021).

2.1. Participants

2.1.1. Children

Participants were 36 4- and 5-year-old children (18 female, 18 male, 18 4-year-olds, 18 5-year-olds, mean age = 59 months, SD = 7) recruited from a database of local participants in the U.S..[1] Due to the COVID-19 pandemic, the first twenty participants were tested in-person and the remaining sixteen were tested via video-conferencing. All participants were native or fluent English speakers. Informed consent was obtained from participants' parents. Children who participated in-person received a small gift for their participation and their parents received $10; parents of children who participated virtually received a $10 Amazon gift card.

2.1.2. Adults

Participants included 77 adults recruited via Amazon Mechanical Turk. An additional five respondents were excluded for failing an attention check (described below). Participants were paid $0.63 for a 5-min experiment. Participation was restricted to workers in the United States who had completed at least 500 prior tasks with a 95% approval rating.

2.2. Materials

To construct stimuli, we selected six items from each of three domains: biological (e.g., an alligator), physical (e.g., a statue), and psychological (e.g., a woman; see Table 1 for samples, and https://osf.

[1] Because our study involved two proximate age groups and a within-subjects design that gave us multiple data points per child, we opted for a target sample of 36, with 18 participants per age group, after consulting sample sizes used in similar studies (Shtulman & Carey, 2007; Weisberg & Sobel, 2012; Banerjee, Haque, & Spelke, 2013). However, this decision was not based on an estimated effect size and formal power analysis.

Table 1
Examples of each type of item.

	Ordinary	Unlikely	MCI	VCI
Biological	a tree that's as tall as a house that has a first floor and a second floor	a rose that can grow to be more than five feet tall	a pig that won't die even if it never gets any food or water	a creature that can see or hear things no matter how far away they are, and it can move those things using its mind
Physical	a toy train that comes with a plastic railroad track you can build yourself	a basket made out of bread that's shaped to look like a basket with a handle	a statue of a lion that can turn into a real lion	a statue of a person that can read your mind and understand you if you talk to it
Psychological	a man who can speak and understand Spanish	a dancer who can spin and spin in fast circles a whole 30 times without stopping	a woman who can make her hair grow longer just by just wishing it	a kid who can eat lightning for breakfast and live forever

io/sqm5c/?view_only=eea1394cd79b4fb4b655a9a80e9afcca for all stimuli). Each item was represented with an image, and associated with a description that was either Ordinary (no theory violations and not statistically infrequent, e.g., "an alligator in a swamp that swims in the water and walks through the grass"), Unlikely (no theory violations but statistically infrequent, e.g., "an alligator hiding under a bed in a house in a big city"), Minimally Counterintuitive (MCI; one theory violation, e.g., "an alligator that can talk just like a human can talk"), or Very Counterintuitive (VCI; two theory violations, e.g., "an alligator that can talk like a human and also walk through walls"). The domains, items, and theory violations were based on previous research on MCI concepts (especially Banerjee et al., 2013; see also Barrett, 2000; Boyer & Ramble, 2001; Nyhof & Barrett, 2001; Shtulman & Carey, 2007).

This resulted in 72 different item descriptions (6 items from each of 3 domains, with 4 versions per item). These item descriptions were paired to create three contrast types: Ordinary vs. Unlikely, Unlikely vs. MCI, and MCI vs. VCI. Each pair contained two distinct items from the same domain (see Fig. 1). A complete stimulus set contained nine pairs total, crossing contrast type (Ordinary vs. Unlikely, Unlikely vs. MCI, and MCI vs. VCI) with domain (biological, physical, psychological). We created six different stimulus sets with different pairings, such that across participants, each item (e.g., the alligator) appeared an equal number of times in each position of each contrast.

2.3. Procedure

2.3.1. Procedure for children

All children were tested in individual sessions with an experimenter. For in-person sessions, children sat next to the experimenter and viewed the survey on a laptop. For virtual sessions, the experimenter's screen displaying the survey was shared via video-conferencing. Children were told: "We're going to look through a book of lots of different things. It has a lot of cool stuff in it. You're going to get to see two things at a time, and you'll get to pick one of those things to learn about."

All children then received the same practice trial, in which two images – a blue present and a red present – appeared side-by-side. The order of the images was randomized for all stimuli. Participants were told, "Here is a blue present and here is a red present," then asked, "Which one do you want to learn more about, the blue present or the red present?". After children made a choice, they were told that they would learn more about the present they chose at the end of the game and were asked if they had any questions before continuing.

Children then saw nine pairs of images presented serially in a random order, corresponding to one of the six stimulus sets (to which they were randomly assigned). For each pair, the experimenter introduced each item then asked which one the child wanted to learn more about (see Fig. 1).

After completing the task, children were asked if they still wanted to learn about the items they chose. If they said yes, the experimenter provided additional information about the items.

2.3.2. Procedure for adults

Adults completed a task nearly identical to children's, with the following exceptions. Adults completed an online survey accessed via Qualtrics. Like the child participants, adult participants were introduced to the task, completed the practice question, then saw nine pairs of items, selected from the same six stimulus sets as children. However, there were two versions of the adult survey. In one version, adults were asked the same question as children: "Which one do you want to learn more about?" In the other, adults were asked, "Which one are you more curious about?" We included both versions to bolster the inference that the question about learning, which we judged more natural for children, effectively tracked the experience of curiosity. At the end of the task, if participants opted to learn more about the items they chose, the next screen showed additional information.

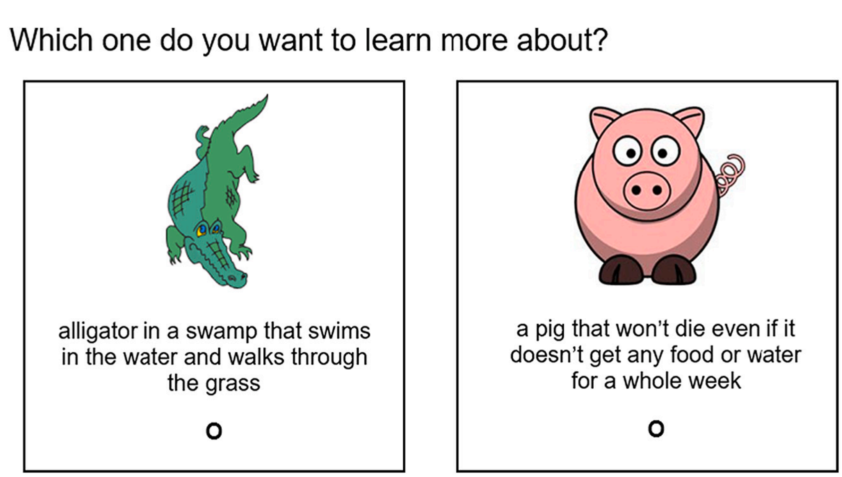

Fig. 1. Example stimuli shown to participants. The item on the left is "Ordinary," while the item on the right is "Unlikely".

3. Results

Our analytic approach to these data was to fit multilevel models containing all variables of interest. These models were compared to reduced models (excluding particular variables) using likelihood ratio tests. We report the results from the best fit models.

We first compared adults' responses when they were asked which item they wanted to learn more about to their responses when they reported curiosity (collapsing across contrast types). There was no significant difference between the model including question type and the model excluding it ($\chi^2(1) = 1.81$, $p = .18$), so the results reported below collapse across this variable. We also tested whether children's responses were affected by video-conferencing versus being in-person. We found no significant difference between the model including this variable and the model excluding it ($\chi^2(1) = 0.29$, $p = .59$), so these results were collapsed. Finally, we found no significant difference between the model including stimulus set and the model excluding it ($\chi^2(5) = 5.48$, $p = .36$), so these results were also collapsed.

Next, we tested our main question: are minimally counterintuitive observations especially powerful triggers of curiosity? If so, we would expect children and adults to be more eager to learn about MCI over Unlikely, and also more eager to learn about MCI over VCI. In addition, we would expect children and adults to be more eager to learn about Unlikely over Ordinary.

First, we tested whether adults and children were more likely to choose the more surprising item within each contrast (see Fig. 2). Overall, adults reliably chose Unlikely over Ordinary ($M = 2.10$ out of 3, $t = 6.01$, $p < .001$) and MCI over Unlikely ($M = 2.12$, $t = 6.09$, $p < .001$), but not VCI over MCI ($M = 1.64$, $t = 1.37$, $p = .17$). Children only reliably chose MCI over Unlikely ($M = 1.83$, $t = 2.58$, $p = .01$; Unlikely vs. Ordinary: $M = 1.78$, $t = 1.74$, $p = .09$; VCI vs. MCI: $M = 1.56$, $t = 0.41$, $p = .68$). Adults were also more likely than children to choose the more surprising item overall ($\beta = -0.22$, $p = .05$). However, our final model retained contrast type and age group, but not their interaction.

Next, we tested developmental changes within children. The best fit model retained age in months as a fixed effect. This regression coefficient was significant ($b = 0.03$, 95% CI [0.00, 0.05], $p = .02$), suggesting that as children's age in months increased, they were more likely to choose the more surprising item. When we divided children's data into two age groups, we found that like adults, 5-year-olds reliably chose Unlikely over Ordinary ($M = 2.06$, $t = 2.23$, $p = .04$) and MCI over Unlikely ($M = 2.11$, $t = 3.42$, $p = .003$), but not VCI over MCI ($M = 1.67$, $t = 1.03$, $p = .32$). In contrast, 4-year-olds were at chance for each contrast (Unlikely vs. Ordinary: $M = 1.50$, $t = 0.00$, $p = 1.00$; MCI vs. Unlikely: $M = 1.56$, $t = 0.33$, $p = .74$; VCI vs. MCI: $M = 1.44$, $t = 0.26$, $p = .80$).

4. Discussion

Which is a stronger trigger of curiosity: a rose that can grow to be five feet tall, or a rose that can disappear and reappear in different spots in the garden? The present work shows that in our sample, adults and children as young as 5 years are more curious about events that minimally violate their theories of the world than those that are merely unlikely, but no more curious about those with multiple intuitive violations than those with only one. While 4-year-olds were equally curious about all item types in this task, by age 5 children exhibited a preference for learning about events that are not merely unlikely, but impossible.

This work has a number of implications and raises new questions for research on curiosity and learning. First, while prior work has posited an inverted U-shaped function such that curiosity is maximally piqued by stimuli that are neither too simple nor too complex (e.g., Kidd et al., 2012), this study introduces the qualitative distinction between improbability and impossibility as a potential guide to the peak of this function. Minimally counterintuitive observations plausibly offer the best opportunity for revising inaccurate intuitive theories of the world, challenging misconceptions while offering what might be an optimal level of discrepancy (Kinney & Kagan, 1976) or an appropriately-sized "information gap" (Loewenstein, 1994). While prior work has investigated how violations-of-expectation drive information-seeking with the goal of refining intuitive theories (e.g., Legare et al., 2010; Stahl & Feigenson, 2017; Wang et al., 2021), they often do not distinguish how different kinds of expectation-violations differentially impact learning. Since MCI events are easier to remember and more likely to be shared with others than ordinary or VCI events (Banerjee et al., 2013; Boyer & Ramble, 2001; Nyhof & Barrett, 2001), we predict that they could also be good catalysts for learning.

Importantly, the present research did not investigate children's or adults' learning from expectation violations – only their curiosity following such violations. Prior work shows that theory-violating events not only spark exploration, but also promote learning. For example, children more readily learn novel words associated with theory-violating events, compared to words associated with expected events (Stahl & Feigenson, 2015, 2017), perhaps because of heightened attention to the theory-violating object. We would expect to find similar results in our paradigm – curiosity about MCI events should also enhance learning about those events. However, it remains to be tested whether curiosity promotes learning regardless of the target of curiosity (e.g., whether it is ordinary, unlikely, MCI, or VCI), or whether curiosity selectively promotes learning of theory-relevant information.

It is also important to recognize that our MCI and VCI stimuli consisted of events that *violate* accurate scientific theories (for example, a talking alligator is impossible in the real world), posing a prima facie challenge to the idea that attention to the counterintuitive supports learning. Indeed, we expect that curiosity about a talking alligator might not be the most direct route to an accurate understanding of contemporary biology. That said, our study helps clarify a general mechanism of learning that is likely to be beneficial when learners receive representative observations from the natural world, versus those constructed to be theory violating in the lab. In the course of development, children often hold scientifically inaccurate theories (e.g., that the sun revolves around the earth, Shtulman & Valcarcel, 2012), rendering some real-world observations counterintuitive. In such cases, inaccurate theories could potentially be revised through curiosity directed toward counterintuitive evidence: evidence that points away from a current misconception and to a more accurate theory. When such evidence is *minimally* counterintuitive, it may be more learnable from the child's current theoretical position.

Notably, we did not find that very counterintuitive events triggered greater curiosity than minimally counterintuitive events, challenging the idea that curiosity favors *maximum* complexity or uncertainty. However, we also failed to find a reliable preference to learn about counterintuitive events with one theory violation over counterintuitive events with two theory violations. It remains an open question whether such a preference might emerge if more numerous (or more dramatic) intuitive violations were introduced. Banerjee et al. (2013) found that 7–9 year-olds showed better memory for concepts with one or two theory violations, relative to either none or three, suggesting that two violations may still fall within the cognitive optimum that maximally triggers curiosity in children. That said, "number" of theory violations is unlikely to be the right metric for mapping curiosity – indeed, single violations of physical theories vary in their interestingness and surprisingness to adults (Lewry, Curtis, Vasilyeva, Xu, & Griffiths, 2021), and therefore might elicit different levels of curiosity as well. Offering a more formal characterization of this axis remains an important question for future research, as does the relation between the effects of curiosity documented here and those for memory documented in prior work on minimally counterintuitive concepts.

Why do 5-year-olds, but not 4-year-olds, exhibit a preference to learn about minimally counterintuitive stimuli? One possibility is that this developmental change reflects a growing understanding of the distinction between improbability and impossibility, which young children

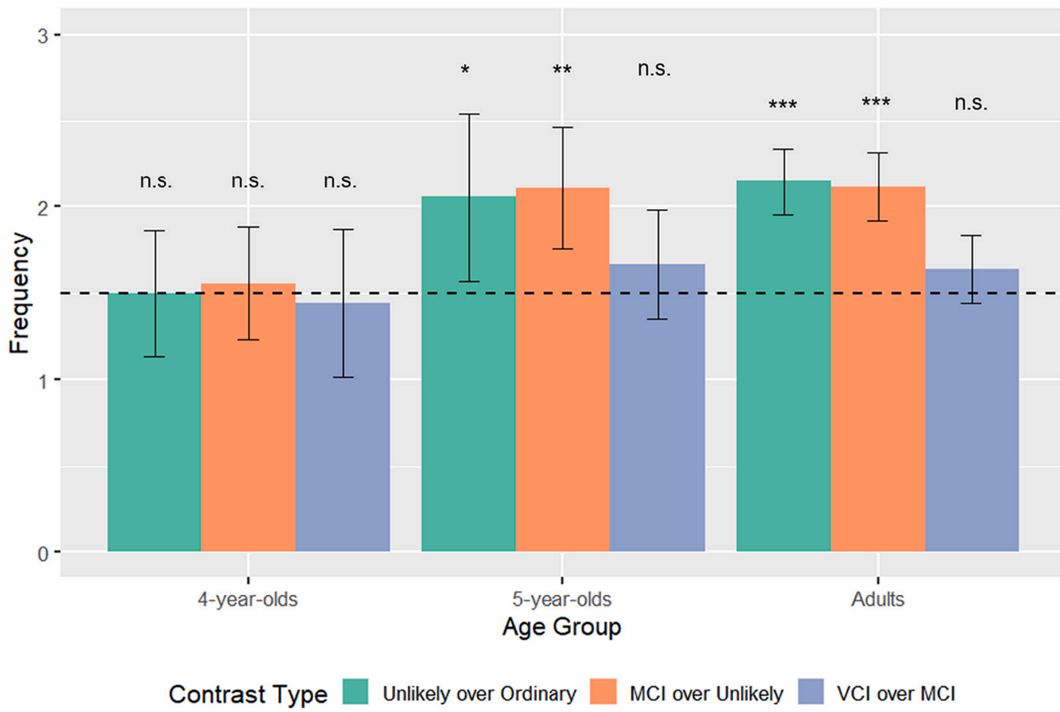

Fig. 2. Frequency of choosing the more surprising item in each contrast by age group (out of three trials). Dotted line represents chance responding (1.5 out of 3 trials), and asterisks indicate significant departures from chance (***$p < .001$, **$p < .01$, *$p < .05$, n.s. $p > .05$). Error bars indicate 95%-CI.

seem to appreciate in the context of some tasks (e.g., Weisberg & Sobel, 2012), but not others (e.g., Shtulman & Carey, 2007). Our findings contribute to this literature in revealing that by age 5, children differentiate the merely unlikely from the impossible in their explicit preferences to learn more. However, it remains puzzling that 4-year-olds in our task (and in Shtulman & Carey, 2007) failed to do so, given that even infants are able to differentiate likely from unlikely events (e.g., Gergely et al., 1995; Kayhan et al., 2018) and possible from impossible events (e.g., Baillargeon et al., 2011; McCrink & Wynn, 2004), as measured with looking time. It may be relevant that infant studies often present babies with "live" impossible events, whereas studies with older children instead describe those events.[2] Another possibility is that implicit measures reveal earlier differentiation than explicit measures, such as reported desire to learn more.

Yet another possibility is that 4-year-olds in our task responded at chance because the task was too demanding or otherwise confusing. Specifically, our stimuli were brief descriptions of an event accompanied by an image; it may be that only by age 5 are children able to process the image and description into an integrated event representation with the potential to elicit surprise. While our stimuli had the advantage of being brief to keep children's attention and allowing us to more closely match information across conditions, future work could use stories, videos, or even live events (as in many infant studies). Additionally, since our study used a forced-choice design, it is unclear whether 4-year-olds were very curious about every item, not curious at all about any item, or somewhere in between. Future work would benefit from incorporating additional measures of children's curiosity (see Jirout & Klahr, 2012).

Finally, this research must be considered in its cultural context: participants were adults living in the United States and children living primarily in or near Princeton, NJ. We predict that children and adults would be most curious about minimally counterintuitive events, regardless of cultural upbringing. However, the content of their intuitive theories – and hence what kinds of events (minimally) violate those theories – is likely to vary (e.g., Busch, Watson-Jones, & Legare, 2018; Watson-Jones, Busch, Harris, & Legare, 2017; Xu & Coley, 2022), especially in later childhood as their theories are more strongly shaped by culture (e.g., Shtulman, Foushee, Barner, Dunham, & Srinivasan, 2019; Zhao et al., 2021). Future work should explore whether and how the content and consequences of curiosity-triggering events are influenced by cultural and other contextual factors.

While raising important questions for future research, this study takes crucial steps toward understanding the development of curiosity. Specifically, it combines prior theories of curiosity (violations of expectation and an inverted U-shaped function), ideas from the cognitive science of religion (minimally counterintuitive concepts), and accounts of intuitive theory development (the improbability/impossibility distinction) to provide a novel illustration of how curiosity develops: by age 5, we are most curious about events that violate our theories of how the world works, at least in small ways.

Author note

Data and materials are open and available online at https://osf.io/sqm5c/?view_only=eea1394cd79b4fb4b655a9a80e9afcca. This study was approved by the IRB at Princeton University (#1156). A subset of this work was submitted in partial completion of requirements for senior independent work at Princeton University by author S.G. The authors declare no conflicts of interest in this work.

CRediT authorship contribution statement

Casey Lewry: Formal analysis, Investigation, Writing – original draft, Visualization, Project administration. **Sera Gorucu:** Formal analysis, Investigation, Resources, Writing – review & editing. **Emily G. Liquin:** Formal analysis, Investigation, Resources, Writing – review & editing, Project administration. **Tania Lombrozo:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Supervision, Funding acquisition.

[2] We thank a reviewer for raising this possibility.

Data availability

Data is publicly available in the OSF repository.

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