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Explanation-seeking curiosity in childhood

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Children are known for asking 'why?' — a query motivated by their desire for explanations. Research suggests that explanation-seeking curiosity (ESC) is triggered by first-person cues (such as novelty or surprise), third-person cues (such as a knowledgeable adults' surprise or question), and future-oriented cues (such as expectations about information gain or future value). Once triggered, ESC is satisfied by an adequate explanation, typically obtained through causal intervention or question asking, both of which change in efficiency over development. ESC is an important driver of children's learning because it combines the power of active learning and intrinsic motivation with the value of explanatory content, which can reveal the unobservable and causal structure of the world to support generalizable knowledge.

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Introduction

From early in development, children exhibit curiosity about the properties [1] and names [2–4] of objects, and about visual and auditory patterns [5,6]. Moreover, they often seek *explanations* for their observations, and in so doing construct intuitive theories that equip them to better predict and intervene upon the world [7,8]. Here we focus on children's 'explanation-seeking curiosity' (ESC), which we define as an affective drive state [9] that motivates learning *how* or *why* something is the case [10]. We review recent research addressing two questions: (1) What triggers ESC? And (2) How is ESC satisfied?

Our focus on ESC complements two existing bodies of research. First, research has considered the epistemic power of explanations. Seeking explanations supports learning in young children [10,11], and explanations can drive subsequent exploration [12] and improve metacognition [13]. For example, when prompted to generate explanations (versus report observations) while learning novel causal rules, preschoolers are more likely to learn causal rules that are broad [14], are simple [15], and emphasize internal properties over perceptual similarity [16]; when prompted to explain aspects of a story, 5-year-olds to 6-year-olds are more likely to extract its lesson [17]. However, this research has rarely focused on ESC — the drive state that prompts explanation search.

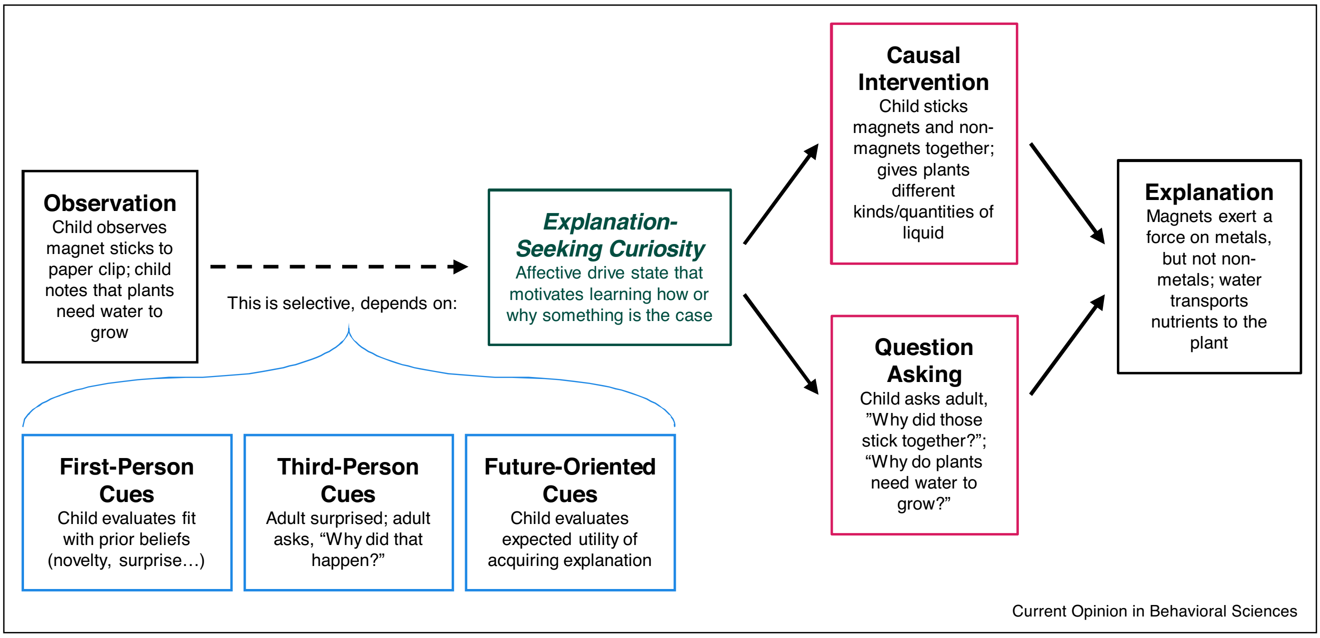
Second, research on curiosity (including developmental prerequisites to experiencing and expressing curiosity [18,19]) has been pursued in many contexts, including active word learning [3] and question asking [20•]. Among other benefits [21,22], there is evidence that curiosity-driven exploration can be as efficient as direct pedagogy for causal learning [23] and lead to better memory for target information [24–29], and that exploration efficiency relates to IQ in young children [30]. However, this work has typically focused on curiosity directed towards non-explanatory targets, such as facts, object labels, or object properties.

Given the epistemic power of explanation and the learning benefits of curiosity, ESC is poised to be an especially important driver of children's learning. While it is yet unclear precisely how ESC diverges from other forms of curiosity [31••,32] or fits into existing taxonomies for curiosity [e.g. Ref. 33], ESC is unique in its ability to drive the discovery of *unobservables* and *causal structure* — important foundations for generalizable knowledge. For these reasons, the study of ESC is likely to lead to important insights about how (young) human learners come to know so much about the world given limited evidence, time, and cognitive resources, with potential implications for education and for the development of artificial learners [34,35], as well.

What triggers explanation-seeking curiosity?

Children encounter far more unexplained observations than they have the time or resources to pursue as targets of inquiry. In fact, there is evidence that merely lacking information is insufficient to trigger information search: in one study, 5-year-olds to 9-year-olds explored following some types of underinformative evidence, but not others (though this may in part stem from a developing capacity to recognize whether evidence is informative) [36]. Thus, both theoretically and perhaps empirically, we have reason to believe that ESC is selective, and that additional cues make some unexplained observations call out for explanation more strongly than others [37,38]. We review three categories of cues: first-person cues, third-person cues, and future-oriented cues (Figure 1). The evidence

Figure 1



Model of explanation-seeking curiosity, including cues that trigger it (first-person cues, third-person cues, and future-oriented cues), and two methods by which it is satisfied (causal intervention and question asking).

for these cues comes from studies of ESC as well as studies of curiosity more broadly; we discuss the potentially unique triggers of ESC in the Conclusions section.

First-person cues

First-person cues, such as surprise and novelty [39], are those that relate unexplained information to an individual's epistemic state. We refer to these cues as first-person because observations are not intrinsically surprising or novel; they are surprising or novel with respect to a set of expectations or prior experiences. Indeed, recent research has clarified the first-personal (subjective) nature of these cues. Infants preferentially explore objects that violate their expectations, whether those expectations are formed on the basis of core knowledge [27], inferred rules [40], or probabilistic information [41,42]. Furthermore, infants' exploration after an expectation violation may be specifically geared towards uncovering an explanation for that violation [43].

One proposal is that curiosity is piqued not by maximally surprising or novel information, which may be too far beyond a learner's grasp, but by *moderately* surprising or novel information, which presents the best opportunity for learning [44]. Infants preferentially direct their visual attention to patterns that are moderately predictable [5, see also Ref. 6]. However, this 'moderate information gap' hypothesis has been studied primarily in adult populations [e.g. Ref. 45], and has not been applied to ESC.

Third-person cues

Third-person cues rely on social information from others. For example, infants use others' surprised expressions to guide visual exploration [46], and preschoolers spend more time exploring a novel toy after viewing an experimenter's surprised expression while playing with it [47]. Adults can also highlight information through the use of *pedagogical questions*: questions with answers that are known to the asker, but posed to facilitate learning [48]. After a pedagogical question from a knowledgeable teacher, children spend more time playing with a novel toy and discover more of its functions [49•]. However, relying on knowledgeable others can also suppress exploration — direct pedagogy decreases preschoolers' exploration and learning of non-target information [50], and preschoolers (though not elementary schoolers) forgo exploration of counterintuitive claims offered by reliable sources [51].

Future-oriented cues

Future-oriented cues concern expectations about how acquiring information will serve the learner in the future. In one task, 4-year-olds to 5-year-olds were more likely to explore unknown rewards over known rewards only when the unknown rewards would inform future choices [52]. While this could be explained by reward-seeking behavior (and not curiosity), there is evidence that 4-year-olds to 5-year-olds explore a causal system more than older children and adults, but fail to efficiently exploit their knowledge to gain rewards (EG Liquin *et al.*, unpublished) [see also 53–55]. These findings cast doubt on reward pursuit as the sole motivation behind children's future-oriented exploration. Furthermore, children sometimes pursue information that may be relevant for future action even when this information will not impact immediate reward: in one study, children displayed greater curiosity about counterfactual outcomes that were under their control, relative to outcomes they could not have caused [56••].

Future-oriented cues are in tension with approaches that define curiosity as the pursuit of information as an end in itself [e.g. Ref. 44]. In fact, in both adults [57] and non-human animals [58], curiosity has been operationalized as costly information-seeking without immediate benefit. We propose that curiosity is defined by the phenomenological *experience* of pursuing information for its own sake, even in cases where the psychological *function* of this experience is instrumental. The willingness to pursue information with no immediate benefit is good evidence that such a phenomenology is present. However, adults report experiencing curiosity even when instrumental goals are at play, and this reported curiosity is in part guided by the future utility of information [31••,59–61]. Our model predicts the same for young children (and potentially for many non-human animals), but direct evidence for this claim will require moving away from paradigms that rely on exploration as an index of curiosity, and towards paradigms that more directly measure the phenomenology of curiosity.

How is explanation-seeking curiosity satisfied?

ESC can be satisfied when the child acquires what they judge to be an adequate explanation. Children prefer explanations that are simple [62] and general [63•], and that contain a moderate amount of detail [64] that is explanatorily relevant [65,66•]. Children also prefer teleological explanations (which appeal to function or purpose) [67,68] and explanations that appeal to properties inherent to the thing being explained [69], though these preferences decrease across development. When children receive a non-explanatory response rather than an explanatory response, they are more likely to re-ask their original question [70] (though children's reactions to explanatory and non-explanatory responses are moderated by socioeconomic status [71,72] and age [73]). The perceived quality of a provided explanation predicts subsequent explanation-seeking behavior, as well [74••].

Often, children are not simply offered an explanation, but must solicit an explanation, reason their way to one, or discover one for themselves. Children have many tools for eliciting information — such as pointing [4,75–77] and social referencing [78] — but these are unlikely to elicit specifically explanatory information. *Causal intervention* and *question asking*, by contrast, are likely to be especially useful for the pursuit of explanations because they allow the learner to infer causal relations [79,80] and inquire about unobservable entities [81] (Figure 1).

Causal intervention

Effective causal intervention in pursuit of explanations relies on the ability to perform informative experiments: typically, interventions that isolate a single causal variable and control confounds. Early research suggested that children's ability to design informative experiments is limited until adolescence [82], but recent research has demonstrated that preschool-aged children choose interventions that disambiguate causal structure [83], use conjectured explanations to inform their later exploration [84], and selectively deploy different exploratory actions based on their relative informativeness for the task [85•]. Older children selectively deviate from controlled experiments in contexts where testing multiple variables at once is more efficient [86]. In more complex tasks, however, 3-year-olds to 6-year-olds fail to spontaneously create disambiguating interventions after receiving evidence that disconfirms their expectations [87]. Instead, they use intervention strategies like the 'positive test strategy,' which privileges positive evidence consistent with a single target hypothesis [87–89]. However, some have argued that a positive test strategy could be quite useful in some contexts [90] or given particular learning goals [91].

Question asking

Causal intervention is not appropriate in all circumstances; unobservable entities (e.g. germs) and inaccessible entities (e.g. the moon) cannot be readily manipulated, and thus question asking may be the only way for children to learn about explanations involving these entities. Indeed, by the age of six, children ask fact-seeking questions about unobservable entities but directly explore observable entities [92].

Children begin asking questions before the age of two, and the proportion of questions that are explanation-seeking increases with development, peaking around age three [93]. While children begin to direct questions to appropriate sources in preschool [20•,52,94], children's ability to ask maximally informative questions to solve a specified problem continues to develop during the preschool years and beyond. In one set of studies [95], 3-year-old to 5-year-old children were asked to identify the most informative question to discover the explanation for an event. With increasing proficiency with age, children preferred questions that targeted an individual explanation when that explanation was more likely than others, but chose questions that eliminated several candidate explanations when all were equally likely. Other studies using similar methods have also shown age-related improvements in question-asking efficiency [96–98, but see Ref. 99], and that question efficiency can be influenced by certain structural supports [96].

To summarize, children use both causal intervention and question asking to seek explanations, with both strategies improving in efficiency over the preschool and early elementary school years, and with the former continuing to develop through adolescence. Additional research will be required to link these exploratory behaviors to the drive states that motivate them over development, and to identify whether and when these behaviors are triggered by first-person, third-person, or future-oriented cues. For example, in tasks that involve seeking rewards, there are age-related changes in the extent to which exploration is random (the result of decision noise) or systematic (directed towards uncertainty) [54,100], and in tasks that involve learning about categories, children direct their exploration differently from adults [101]. Future research is needed to determine how and why exploration that is motivated by curiosity and directed at acquiring explanations changes (in quantity or in nature) across development.

Conclusions

Combining the motivational drive of curiosity with the epistemic power of explanations, explanation-seeking curiosity is likely to be an important driver of children's learning, especially when it comes to the unobservable and causal structure of the world captured by intuitive theories. We reviewed evidence that very young children are selective in their ESC and preferentially seek explanations when cued by first-person cues, third-person cues, and future-oriented cues. Children's ability to seek explanations also develops, with causal intervention and question asking playing critical roles.

While much of our analysis is based on studies of actual learners, many of the papers we review argue that fully rational learners *should* explore when a relevant cue is present, or that exploration *should* be pursued in a particular way to resolve uncertainty, typically using Bayesian approaches. Bayesian models have provided a powerful method for understanding active learning in development, but additional questions arise when combining these individual analyses into a single model: How should a rational learner weigh competing cues to curiosity against each other? How should a rational learner choose between question asking, causal intervention, and other available behaviors? And how do actual learners navigate these problems? Answering these questions will require building more complex models, designing more sophisticated experiments, and better characterizing children's exploration in real-world environments [78,94,102–105,106•,107]. Ultimately, however, these efforts will improve our understanding of learning throughout the lifespan.

Future research may also provide insight into whether and how we should expect ESC to diverge from other forms of curiosity. Explanation search often involves consultation with and deference to experts [108,109], suggesting third-person cues may be especially powerful in triggering ESC. Additionally, the future-oriented cues that trigger ESC may focus on unique criteria — for example, how likely it is that the received information will constitute a 'good' explanation [31••]. Finally, satisfaction methods may differ: for example, causal intervention is more likely than pointing to elicit explanatory information.

Lastly, research on decision making under risk [110] and on how costs are weighed against the benefits of information gain [53–55,111] will shed light on when we can expect children to pursue their curiosity. With adults, it has been proposed that information is itself rewarding, and that curiosity motivates learners to obtain this reward [112–114]. In settings where children are more exploratory than adults [53–55], do children find information more rewarding than adults, or are the costs associated with exploration less steep for young learners? If explanatory information is indeed especially powerful for learning, do learners find the satisfaction of ESC especially rewarding, and correspondingly experience stronger curiosity towards explanatory targets?

Despite these open questions, recent research has dramatically deepened our understanding of children's ESC. Through question asking and exploration, children actively pursue information that helps them make sense of the world, and they do so with increasing proficiency over the course of development. Motivated by explanation-seeking curiosity, children come to know not just *what* events and phenomena they can expect to encounter, but *why* such events and phenomena occur — providing a powerful means for prediction, intervention, and understanding.

Conflict of interest statement

Nothing declared.

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References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Smith LB, Jayaraman S, Clerkin E, Yu C: **The developing infant creates a curriculum for statistical learning**. *Trends Cogn Sci* 2018, **22**:325-336.

2. Carvalho PF, Vales C, Fausey CM, Smith LB: **Novel names extend for how long preschool children sample visual information**. *J Exp Child Psychol* 2018, **168**:1-18.

3. Jimenez S, Sun Y, Saylor MM: **The process of active word learning**. In *Active Learning from Infancy to Childhood: Social Motivation, Cognition, and Linguistic Mechanisms.* Edited by Saylor MM, Ganea PA. Springer International Publishing; 2018:75-93.

4. Lucca K, Wilbourn MP: **The what and the how: information-seeking pointing gestures facilitate learning labels and functions**. *J Exp Child Psychol* 2019, **178**:417-436.

5. Kidd C, Piantadosi ST, Aslin RN: **The Goldilocks effect: human infants allocate attention to visual sequences that are neither too simple nor too complex**. *PLoS One* 2012, **7**:e36399.

6. Kidd C, Piantadosi ST, Aslin RN: **The Goldilocks effect in infant auditory attention**. *Child Dev* 2014, **85**:1795-1804.

7. Bonawitz E, Ullman TD, Bridgers S, Gopnik A, Tenenbaum JB: **Sticking to the evidence? A behavioral and computational case study of micro-theory change in the domain of magnetism**. *Cogn Sci* 2019, **43**:e12765.

8. Gopnik A: **Explanation as orgasm and the drive for causal knowledge: the function, evolution, and phenomenology of the theory formation system**. In *Explanation and Cognition.* Edited by Keil FC, Wilson RA. The MIT Press; 2000:299-323.

9. Kidd C, Hayden BY: **The psychology and neuroscience of curiosity**. *Neuron* 2015, **88**:449-460.

10. Lombrozo T: **Explanation and abductive inference**. In *Oxford Handbook of Thinking and Reasoning.* Edited by Holyoak KJ, Morrison RG. Oxford University Press; 2012:260-276.

11. Lombrozo T: **Explanatory preferences shape learning and inference**. *Trends Cogn Sci* 2016, **20**:748-759.

12. Danovitch JH, Mills CM: **Understanding when and how explanation promotes exploration**. In *Active Learning from Infancy to Childhood: Social Motivation, Cognition, and Linguistic Mechanisms.* Edited by Saylor MM, Ganea PA. Springer International Publishing; 2018:95-112.

13. Mills CM, Keil FC: **Knowing the limits of one's understanding: the development of an awareness of an illusion of explanatory depth**. *J Exp Child Psychol* 2004, **87**:1-32.

14. Walker CM, Lombrozo T, Williams JJ, Rafferty AN, Gopnik A: **Explaining constrains causal learning in childhood**. *Child Dev* 2017, **88**:229-246.

15. Walker CM, Bonawitz E, Lombrozo T: **Effects of explaining on children's preference for simpler hypotheses**. *Psychon Bull Rev* 2017, **24**:1538-1547.

16. Walker CM, Lombrozo T, Legare CH, Gopnik A: **Explaining prompts children to privilege inductively rich properties**. *Cognition* 2014, **133**:343-357.

17. Walker CM, Lombrozo T: **Explaining the moral of the story**. *Cognition* 2017, **167**:266-281.

18. Ronfard S, Bartz DT, Cheng L, Chen X, Harris PL: **Children's developing ideas about knowledge and its acquisition**. In *Advances in Child Development and Behavior.* Edited by Benson JB. Elsevier; 2018:123-151.

19. Sobel DM, Letourneau SM: **Curiosity, exploration, and children's understanding of learning**. In *Active Learning from Infancy to Childhood: Social Motivation, Cognition, and Linguistic Mechanisms.* Edited by Saylor MM, Ganea PA. Springer International Publishing; 2018:57-74.

20. • Ronfard S, Zambrana IM, Hermansen TK, Kelemen D: **Question-asking in childhood: a review of the literature and a framework for understanding its development**. *Dev Rev* 2018, **49**:101-120
Comprehensively reviews the research on question initiation, formulation, expression, and response evaluation between infancy and elementary school. Discusses potential sources of individual differences.

21. van Schijndel TJ, Jansen BR, Raijmakers ME: **Do individual differences in children's curiosity relate to their inquiry-based learning?** *Int J Sci Educ* 2018, **40**:996-1015.

22. Gottfried AE, Preston KSJ, Gottfried AW, Oliver PH, Delany DE, Ibrahim SM: **Pathways from parental stimulation of children's curiosity to high school science course accomplishments and science career interest and skill**. *Int J Sci Educ* 2016, **38**:1972-1995.

23. Sim ZL, Xu F: **Learning higher-order generalizations through free play: evidence from 2- and 3-year-old children**. *Dev Psychol* 2017, **53**:642-651.

24. Bernacki ML, Walkington C: **The role of situational interest in personalized learning**. *J Educ Psychol* 2018, **110**:864-881.

25. Fandakova Y, Gruber M: **States of curiosity and interest enhance memory differently in adolescents and in children**. *Dev Sci* 2020:e13005.

26. Ruggeri A, Markant DB, Gureckis TM, Bretzke M, Xu F: **Memory enhancements from active control of learning emerge across development**. *Cognition* 2019, **186**:82-94.

27. Stahl AE, Feigenson L: **Observing the unexpected enhances infants' learning and exploration**. *Science* 2015, **348**:91-94.

28. Stahl AE, Feigenson L: **Expectancy violations promote learning in young children**. *Cognition* 2017, **163**:1-14.

29. Stahl AE, Feigenson L: **Violations of core knowledge shape early learning**. *Top Cogn Sci* 2019, **11**:136-153.

30. Muentener P, Herrig E, Schulz L: **The efficiency of infants' exploratory play is related to longer-term cognitive development**. *Front Psychol* 2018, **9**:635.

31. •• Liquin EG, Lombrozo T: **A functional approach to explanation-seeking curiosity**. *Cogn Psychol* 2020, **119**:101276
Characterizes explanation-seeking curiosity in adults. Finds that explanation-seeking curiosity is potentially distinct from fact-seeking curiosity, is associated with subsequent information-seeking behavior, and is related to potential triggers capturing fit with prior knowledge, expectations about future learning, and expectations about future export.

32. Schwitzgebel E: **Children's theories and the drive to explain**. *Sci Educ* 1999, **8**:457-488.

33. Berlyne DE: **A theory of human curiosity**. *Br J Psychol* 1954, **45**:180-191.

34. Oudeyer P-Y: **What do we learn about development from baby robots?** *Wiley Interdiscipl Rev Cogn Sci* 2017, **8**:e1395.

35. Oudeyer P-Y: **Computational theories of curiosity-driven learning**. In *The New Science of Curiosity.* Edited by Gordon G. Nova Science Publishers; 2018:43-72.

36. Busch JTA, Legare CH: **Using data to solve problems: children reason flexibly in response to different kinds of evidence**. *J Exp Child Psychol* 2019, **183**:172-188.

37. Wong W, Yudell Z: **A normative account of the need for explanation**. *Synthese* 2015, **192**:2863-2885.

38. Grimm SR: **Explanatory inquiry and the need for explanation**. *Br J Philos Sci* 2008, **59**:481-497.

39. Berlyne DE, Frommer FD: **Some determinants of the incidence and content of children's questions**. *Child Dev* 1966, **37**:177-189.

40. Wang S, Zhang Y, Baillargeon R: **Young infants view physically possible support events as unexpected: new evidence for rule learning**. *Cognition* 2016, **157**:100-105.

41. Sim ZL, Xu F: **Infants preferentially approach and explore the unexpected**. *Br J Dev Psychol* 2017, **35**:596-608.

42. Sim ZL, Xu F: **Another look at looking time: surprise as rational statistical inference**. *Top Cogn Sci* 2019, **11**:154-163.

43. Perez J, Feigenson L: **Violations of expectation trigger infants to search for explanations**. *PsyArXiv preprint* 2020 http://dx.doi.org/10.31234/osf.io/eahjd.

44. Loewenstein G: **The psychology of curiosity: a review and reinterpretation**. *Psychol Bull* 1994, **116**:75-98.

45. Kang MJ, Hsu M, Krajbich IM, Loewenstein G, McClure SM, Wang JT, Camerer CF: **The wick in the candle of learning: epistemic curiosity activates reward circuitry and enhances memory**. *Psychol Sci* 2009, **20**:963-973.

46. Wu Y, Gweon H: **Surprisingly unsurprising! Infants' looking time at probable vs. improbable events is modulated by others' expressions of surprise**. *PsyArXiv preprint* 2019 http://dx.doi.org/10.31234/osf.io/8whuv.

47. Wu Y, Gweon H: **Preschoolers jointly consider others' expression of surprise and common ground to decide when to explore**. *PsyArXiv preprint* 2019 http://dx.doi.org/10.31234/osf.io/ckh6j.

48. Yu Y, Bonawitz E, Shafto P: **Pedagogical questions in parent–child conversations**. *Child Dev* 2019, **90**:147-161.

49. • Yu Y, Landrum AR, Bonawitz E, Shafto P: **Questioning supports effective transmission of knowledge and increased exploratory learning in pre-kindergarten children**. *Dev Sci* 2018, **21**:e12696
Introduces 'pedagogical questioning' as a tool for teaching children target information without decreasing their exploration of non-target information, in contrast to direct instruction. Provides a tool for introducing information without hampering curiosity.

50. Bonawitz E, Shafto P, Gweon H, Goodman ND, Spelke E, Schulz L: **The double-edged sword of pedagogy: instruction limits spontaneous exploration and discovery**. *Cognition* 2011, **120**:322-330.

51. Ronfard S, Chen EE, Harris PL: **The emergence of the empirical stance: children's testing of counterintuitive claims**. *Dev Psychol* 2018, **54**:482-493.

52. Bonawitz E, Bass I, Lapidow E: **Choosing to learn: evidence evaluation for active learning and teaching in early childhood**. In *Active Learning from Infancy to Childhood: Social Motivation, Cognition, and Linguistic Mechanisms.* Edited by Saylor MM, Ganea PA. Springer International Publishing; 2018:213-231.

53. Blanco NJ, Sloutsky V: **Systematic exploration and uncertainty dominate young children's choices**. *PsyArXiv preprint* 2019 http://dx.doi.org/10.31234/osf.io/72sfx.

54. Schulz E, Wu CM, Ruggeri A, Meder B: **Searching for rewards like a child means less generalization and more directed exploration**. *Psychol Sci* 2019, **30**:1561-1572.

55. Sumner E, Li AX, Perfors A, Hayes B, Navarro D, Sarnecka BW: **The exploration advantage: children's instinct to explore allows them to find information that adults miss**. *PsyArXiv preprint* 2019 http://dx.doi.org/10.31234/osf.io/h437v.

56. •• FitzGibbon L, Moll H, Carboni J, Lee R, Dehghani M: **Counterfactual curiosity in preschool children**. *J Exp Child Psychol* 2019, **183**:146-157
Finds that 4-year-olds to 5-year-olds pursue post-decision information about alternative courses of action, preferentially after negative outcomes and for alternatives they could have pursued. Suggests that children's curiosity is selective to particular types of stimuli and potentially geared towards understanding undesirable outcomes that could be prevented in the future.

57. Lau JKL, Ozono H, Kuratomi K, Komiya A, Murayama K: **Shared striatal activity in decisions to satisfy curiosity and hunger at the risk of electric shocks**. *Nat Hum Behav* 2020 http://dx.doi.org/10.1038/s41562-020-0848-3.

58. Wang MZ, Hayden BY: **Monkeys are curious about counterfactual outcomes**. *Cognition* 2019, **189**:1-10.

59. Dubey R, Griffiths TL: **A rational analysis of curiosity**. In In *Proceedings of the 39th Annual Conference of the Cognitive Science Society*. Edited by Gunzelmann G, Howes A, Tenbrink T, Davelaar EJ. *Proceedings of the 39th Annual Conference of the Cognitive Science Society* Cognitive Science Society; 2017:307-312.

60. Dubey R, Griffiths TL: **Reconciling novelty and complexity through a rational analysis of curiosity**. *Psychol Rev* 2020, **127**:455-476.

61. Dubey R, Griffiths TL, Lombrozo T: **If it's important, then I am curious: a value intervention to induce curiosity**. In In *Proceedings of the 41st Annual Conference of the Cognitive Science Society*. Edited by Goel AK, Seifert CM, Freksa C. *Proceedings of the 41st Annual Conference of the Cognitive Science Society* Cognitive Science Society; 2019:282-288.

62. Bonawitz EB, Lombrozo T: **Occam's rattle: children's use of simplicity and probability to constrain inference**. *Dev Psychol* 2012, **48**:1156-1164.

63. • Johnston AM, Sheskin M, Johnson SGB, Keil FC: **Preferences for explanation generality develop early in biology but not physics**. *Child Dev* 2018, **89**:1110-1119
Finds that children prefer explanations at higher levels of generality in biology by age 5 (e.g. explaining a property of an individual bear by appealing to a property of all animals, rather than a property of all bears or that individual bear), but in physics by age 11. Suggests that ESC may be satisfied by different explanations across development.

64. Frazier BN, Gelman SA, Wellman HM: **Young children prefer and remember satisfying explanations**. *J Cogn Dev* 2016, **17**:718-736.

65. Chu J, Schulz L: **Cognitive pragmatism: children flexibly choose between facts and conjectures**. In In *Proceedings of the 40th Annual Conference of the Cognitive Science Society.* Edited by Rogers TT, Rau M, Zhu X, Kalish CW. *Proceedings of the 40th Annual Conference of the Cognitive Science Society* Cognitive Science Society; 2018:226-231.

66. • Johnston AM, Sheskin M, Keil FC: **Learning the relevance of relevance and the trouble with truth: evaluating explanatory relevance across childhood**. *J Cogn Dev* 2019, **20**:555-572
Investigates whether children evaluate explanations by whether they are relevant to an explanatory goal, rather than merely by their truth. Children as young as 4 years old can select a relevant explanation as more helpful than an irrelevant but true explanation; however, the ability to identify relevant explanations in isolation improves across childhood. Suggests that the criteria for satisfying ESC may change across development.

67. Kelemen D: **Why are rocks pointy? Children's preference for teleological explanations of the natural world**. *Dev Psychol* 1999, **35**:1440-1452.

68. Lombrozo T, Bonawitz EB, Scalise NR: **Young children's learning and generalization of teleological and mechanistic explanations**. *J Cogn Dev* 2018, **19**:220-232.

69. Cimpian A, Steinberg OD: **The inherence heuristic across development: systematic differences between children's and adults' explanations for everyday facts**. *Cogn Psychol* 2014, **75**:130-154.

70. Frazier BN, Gelman SA, Wellman HM: **Preschoolers' search for explanatory information within adult-child conversation**. *Child Dev* 2009, **80**:1592-1611.

71. Kurkul KE, Corriveau KH: **Question, explanation, follow-up: a mechanism for learning from others?** *Child Dev* 2018, **89**:280-294.

72. Ünlütabak B, Nicolopoulou A, Aksu-Koç A: **Questions asked by Turkish preschoolers from middle-SES and low-SES families**. *Cogn Dev* 2019, **52**:100802.

73. Woolley JD, Cornelius CA: **Wondering how: children's and adults' explanations for mundane, improbable, and extraordinary events**. *Psychon Bull Rev* 2017, **24**:1586-1596.

74. •• Mills CM, Sands KR, Rowles SP, Campbell IL: **"I want to know more!": children are sensitive to explanation quality when exploring new information**. *Cogn Sci* 2019, **43**:e12706
Finds that lower subjective ratings of explanation quality predict greater subsequent information search between the ages of 7 and 10 years. Supports a deprivation theory of curiosity, where learners experience curiosity when they judge that they lack information.

75. Begus K, Southgate V: **Infant pointing serves an interrogative function**. *Dev Sci* 2012, **15**:611-617.

76. Begus K, Southgate V: **Curious learners: how infants' motivation to learn shapes and is shaped by infants' interactions with the social world**. In *Active Learning from Infancy to Childhood: Social Motivation, Cognition, and Linguistic Mechanisms.* Edited by Saylor MM, Ganea PA. Springer International Publishing; 2018:13-37.

77. Lucca K, Wilbourn MP: **Communicating to learn: infants' pointing gestures result in optimal learning**. *Child Dev* 2018, **89**:941-960.

78. Schieler A, Koenig M, Buttelmann D: **Fourteen-month-olds selectively search for and use information depending on the familiarity of the informant in both laboratory and home contexts**. *J Exp Child Psychol* 2018, **174**:112-129.

79. Muentener P, Bonawitz E: **The development of causal reasoning**. In *The Oxford Handbook of Causal Reasoning.* Edited by Waldmann MR. Oxford University Press; 2017.

80. Woodward JF: *Making Things Happen: A Theory of Causal Explanation*. Oxford University Press; 2003.

81. Harris PL, Koenig MA: **Trust in testimony: how children learn about science and religion**. *Child Dev* 2006, **77**:505-524.

82. Kuhn D, Amsel E, O'Loughlin M, Schauble L, Leadbeater B, Yotive W: *The Development of Scientific Thinking Skills*. Academic Press; 1988.

83. Lapidow E, Walker CM: **Informative experimentation in intuitive science: children select and learn from their own causal interventions**. *Cognition* 2020, **201**:104315.

84. Legare CH: **Exploring explanation: explaining inconsistent evidence informs exploratory, hypothesis-testing behavior in young children**. *Child Dev* 2012, **83**:173-185.

85. • Ruggeri A, Swaboda N, Sim ZL, Gopnik A: **Shake it baby, but only when needed: preschoolers adapt their exploratory strategies to the information structure of the task**. *Cognition* 2019, **193**:104013

Reports that children trained on a novel exploratory action (shaking a box to determine its contents) preferentially deploy this action when it is needed to reduce uncertainty. Suggests early developing competencies underlying the design of effective causal intervention.

86. Jones A, Bramley NR, Gureckis TM, Ruggeri A: **Changing many things at once sometimes makes for a good experiment, and children know that**. *PsyArXiv preprint* 2020 http://dx.doi.org/10.31234/osf.io/9qv5y.

87. Köksal-Tuncer Ö, Sodian B: **The development of scientific reasoning: hypothesis testing and argumentation from evidence in young children**. *Cogn Dev* 2018, **48**:135-145.

88. Nussenbaum K, Cohen AO, Davis Z, Halpern D, Gureckis T, Hartley C: **Causal information-seeking strategies change across childhood and adolescence**. *PsyArXiv preprint* 2019 http://dx.doi.org/10.31234/osf.io/qukac.

89. Meng Y, Bramley N, Xu F: **Children's causal interventions combine discrimination and confirmation**. In In *Proceedings of the 40th Annual Conference of the Cognitive Science Society.* Edited by Rogers TT, Rau M, Zhu X, Kalish CW. *Proceedings of the 40th Annual Conference of the Cognitive Science Society* Cognitive Science Society; 2018:762-767.

90. Navarro DJ, Perfors AF: **Hypothesis generation, sparse categories, and the positive test strategy**. *Psychol Rev* 2011, **118**:120-134.

91. Lapidow E, Walker CM: **The search for invariance: repeated positive testing serves the goals of causal learning**. *Language and Concept Acquisition from Infancy Through Childhood*. Springer; 2020:197-219.

92. Fitneva SA, Lam NH, Dunfield KA: **The development of children's information gathering: to look or to ask?** *Dev Psychol* 2013, **49**:533-542.

93. Chouinard MM: **Children's questions: a mechanism for cognitive development**. *Monogr Soc Res Child Dev* 2007, **72**:1-129.

94. Choi K, Lapidow E, Austin J, Shafto P, Bonawitz E: **Preschoolers are more likely to direct questions to adults than to other children (or selves) during spontaneous conversational act**. In In *Proceedings of the 40th Annual Conference of the Cognitive Science Society.* Edited by Rogers TT, Rau M, Zhu X, Kalish CW. *Proceedings of the 40th Annual Conference of the Cognitive Science Society* Cognitive Science Society; 2018:220-225.

95. Ruggeri A, Sim ZL, Xu F: **"Why is Toma late to school again?" Preschoolers identify the most informative questions**. *Dev Psychol* 2017, **53**:1620-1632.

96. Kachergis G, Rhodes M, Gureckis T: **Desirable difficulties during the development of active inquiry skills**. *Cognition* 2017, **166**:407-417.

97. Ruggeri A, Lombrozo T: **Children adapt their questions to achieve efficient search**. *Cognition* 2015, **143**:203-216.

98. Ruggeri A, Lombrozo T, Griffiths TL, Xu F: **Sources of developmental change in the efficiency of information search**. *Dev Psychol* 2016, **52**:2159-2173.

99. Meder B, Nelson JD, Jones M, Ruggeri A: **Stepwise versus globally optimal search in children and adults**. *Cognition* 2019, **191**:103965.

100. Somerville LH, Sasse SF, Garrad MC, Drysdale AT, Abi Akar N, Insel C, Wilson RC: **Charting the expansion of strategic exploratory behavior during adolescence**. *J Exp Psychol Gen* 2017, **146**:155-164.

101. Foster-Hanson E, Moty K, Cardarelli A, Ocampo JD, Rhodes M: **Developmental changes in strategies for gathering evidence about biological kinds**. *Cogn Sci* 2020, **44**:e12837.

102. Bilal D, Gwizdka J: **Children's query types and reformulations in Google search**. *Inf Process Manag* 2018, **54**:1022-1041.

103. Danovitch JH: **Growing up with Google: how children's understanding and use of internet-based devices relates to cognitive development**. *Hum Behav Emerg Technol* 2019, **1**:81-90.

104. Lovato SB, Piper AM: **Young children and voice search: what we know from human-computer interaction research**. *Front Psychol* 2019, **10**:8.

105. Wade S, Kidd C: **Cross-cultural differences in the influence of peers on exploration during play**. *Cogn Sci* 2018, **42**:3050-3070.

106. • Willard AK, Busch JT, Cullum KA, Letourneau SM, Sobel DM, Callanan M, Legare CH: **Explain this, explore that: a study of parent–child interaction in a children's museum**. *Child Dev* 2019, **90**:e598-e617

Manipulated whether parents were directed to encourage exploration, encourage explanation, or behave as normal in a gear exhibit in a children's museum. Children of parents who were prompted to encourage exploration spent more time connecting gears, while children of parents who were prompted to encourage explanation spent more time spinning gears and discussing gear mechanisms. Underscores the importance of studying ESC in real-world environments.

107. Callanan MA, Legare CH, Sobel DM, Jaeger GJ, Letourneau S, McHugh SR, Willard A, Brinkman A, Finiasz Z, Rubio E *et al.*: **Exploration, explanation, and parent–child interaction in museums**. *Monogr Soc Res Child Dev* 2020, **85**:7-137.

108. Keil FC, Stein C, Webb L, Billings VD, Rozenblit L: **Discerning the division of cognitive labor: an emerging understanding of how knowledge is clustered in other minds**. *Cogn Sci* 2008, **32**:259-300.

109. Wilkenfeld DA, Plunkett D, Lombrozo T: **Depth and deference: when and why we attribute understanding**. *Philos Stud* 2016, **173**:373-393.

110. Rosenbaum GM, Hartley CA: **Developmental perspectives on risky and impulsive choice**. *Philos Trans R Soc B* 2018, **374**:20180133.

111. Rowles SP, Mills CM: **"Is it worth my time and effort?": How children selectively gather information from experts when faced with different kinds of costs**. *J Exp Child Psychol* 2019, **179**:308-323.

112. Gruber MJ, Ranganath C: **How curiosity enhances hippocampus-dependent memory: the Prediction, Appraisal, Curiosity, and Exploration (PACE) framework**. *Trends Cogn Sci* 2019, **23**:1014-1025.

113. Marvin CB, Shohamy D: **Curiosity and reward: valence predicts choice and information prediction errors enhance learning**. *J Exp Psychol Gen* 2016, **145**:266-272.

114. Murayama K, FitzGibbon L, Sakaki M: **Process account of curiosity and interest: a reward-learning perspective**. *Educ Psychol Rev* 2019, **31**:875-895.