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Children with more uncertainty in their intuitive theories seek domain-relevant information

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Abstract

How do changes in learners' knowledge influence information seeking? We showed preschoolers (N = 100) uncertain outcomes for events and let them choose which event to resolve. We found that children who were at immature stages of their intuitive theories were more likely to seek information to resolve uncertainty about an outcome in the related domains, but children with more mature knowledge were not. This result was replicated in a second experiment, but with the nuance that children at intermediate stages of belief development--where the causal outcome would be most ambiguous--were the most motivated to resolve the uncertainty. This effect was not driven by general uncertainty at the framework level, but rather the impact framework knowledge has in accessing uncertainty at the model level. These results are the first to show the relationship between a learning preference and the developmental stage of a child's intuitive theory.

Keywords

Cognitive Development, Active Learning, Information Gain, Intuitive Theories

Statement of Relevance:

Built upon the traditions of information theory and developmental science, our study looks at information gain in the context of children's beliefs – specifically, whether children who are transitioning between beliefs are more motivated to seek information that could support learning. We found that, consistent with the uncertainty reduction account, children with more uncertain beliefs in a domain were more likely to seek information about an outcome in that domain, compared to children with less uncertain beliefs. This work highlights the role of prior beliefs on information seeking, sets the stage for future research using quantitative modeling to provide a comprehensive account of information seeking behavior, and adds to the broader literature on curiosity and theory change.

Introduction

Contrary to the folk belief that children are passive learners, absorbing information that others select for them, a growing body of research has demonstrated that children are drivers of their epistemic development (Schulz, 2012; Saylor & Ganea, 2018). But this picture of active learning poses a critical developmental question: given that there are essentially an infinite number of possible learning opportunities, how does a learner choose what to learn? Here we suggest that one important factor that shapes informational choices is uncertainty in a learner's intuitive theories.

Drivers of children's exploration

Many factors have been proposed to explain children's information seeking preferences. One (unlikely) possibility is that choices about what to learn are essentially random, with all learning opportunities evaluated and sampled with equal probability. Other possibilities point to fairly simple drivers of attention, such as stimulus salience (Berlyne, 1950) or novelty (Mendel, 1965), which might drive learning decisions by low-level attraction to the salient items. Other accounts necessitate more sophisticated representations and faculties of the learner, pointing towards uncertainty reduction as a driver of exploratory preference.

Uncertainty accounts of information seeking require a method to quantify said uncertainty. Recent computational approaches to cognitive development quantitatively describe the learning system in terms of Bayesian Probabilistic models (e.g. Gopnik & Bonawitz, 2015; Gopnik & Wellman, 2012; Tenenbaum et al, 2007; Gopnik & Schulz, 2004). The probabilistic nature of the computational approach quantifies uncertainty in terms of how confidence in hypotheses is distributed. High posterior probability in a single hypothesis reflects less uncertainty than more evenly distributed probability across multiple hypotheses. The uncertainty reduction account predicts that learners' actions are driven by an intrinsic desire to seek information to reduce uncertainty (Gottlieb, Oudeyer, Lopes, & Baranes, 2013).

Uncertainty thus reflects the distribution of belief across different hypotheses. There are two well established empirical cases in which, following some evidence, a learner finds themselves in high states of uncertainty. One source of uncertainty is surprise: when observed evidence conflicts with expectations given a strongly held belief, infants and children explore and learn more (Bonawitz, van Schjindel, Friel, & Schulz, 2012; Legare, Gelman, & Wellman, 2010; Stahl & Feigenson, 2015). Bayesian surprise reflects uncertainty because the probability of the observed evidence was very low under a previously strongly held mental model, and this "balances out" with alternative hypotheses that the evidence supports but were not as likely, which leads to uncertainty across these alternative hypotheses[1]. A different source of uncertainty comes from evidence that fails to disambiguate between a priori equally-likely hypotheses, or "ambiguous evidence". For example, when presented with confounded evidence for the cause and effect in a novel toy where multiple causes are equally likely, children are more likely to engage in exploratory behavior to disambiguate the possible causes (Gweon & Schulz, 2008; Schulz & Bonawitz, 2007).

How might children recognize uncertainty in their own mental model? Even though previous research suggests that explicit meta-cognitive skills do not emerge until later school years, recent research suggests that even preschool-aged children have an internal sense of uncertainty that reflects the subjective difficulty of various tasks, such as judging numerical quantities or emotional expressions (Baer, Gill, & Odic, 2018; Vo, Li, Kornell, Pouget, &

[1] The same holds for a distribution of beliefs.

Cantlon, 2014). Taken together, this past work suggests that children are sensitive to the uncertainty in observed evidence, and are motivated to explore when evidence is surprising or ambiguous with respect to their beliefs. However, less work has investigated how children might choose to explore in the absence of evidence -- when outcomes are left to be predicted. This kind of implicit, internal sense of uncertainty may thus also drive children's exploratory decisions when it comes to choosing what kind of evidence to seek to discern among competing models.

Distinguishing between model and framework levels of uncertainty

In these aforementioned studies of children's exploration to resolve uncertainty, events were uncertain in the context of a particular causal model. However, in addition to the uncertainty at the model level brought directly by the observed evidence, uncertainty can also occur at "higher" levels of representation which have been referred to as intuitive theories or framework theories (Carey 1985; Gopnik & Wellman, 1994; Keil, 1991; Wellman & Gelman, 1992).

Intuitive theories play an essential role in organizing children's basic knowledge about the world, and support the learning of new causal structures (Dunbar & Klahr, 1988). Coherent and abstract intuitive theories afford consistent predictions about the world, and they have been proposed to have a broad explanatory power that other types of knowledge do not have (Gopnik & Wellman, 1994). However, the abstractness of intuitive theories may postulate a special challenge for children's learning, as evidenced by their prolonged learning trajectory compared to the learning of factual outcomes (Carey, 2009; though see Goodman, Tenenbaum, & Ullman, 2011; Bonawitz et al, 2019 for how abstractness may foster learning at the theory level).

Intuitive theories have been formalized in generative computational models (Tenenbaum et al, 2011), guiding the probability of particular causal models under them (e.g. see Schulz, Bonawitz, & Griffiths, 2007). Thus, children can not only have uncertainty at the model level (e.g. whether a particular event caused an outcome), but also at the theory level (e.g. whether types of events in general can even lead to those kinds of outcomes in general).

Evidence can thus help inform different causal models, but will also, in turn, inform the higher level theories at the framework level. An open question is whether children are capable of representing uncertainty at the *theory level* -- whether they (implicitly) recognize the limits of their current frameworks. If given the choice between informing just a causal model versus informing both a causal model and the theory above it, do children prefer the option that informs the theory level as well? Such a preference would only be seen when there was more uncertainty at the theory level, as in less developed knowledge domains.

Theories and models in guiding exploration

Here we ask whether children who are at different transitional stages of understanding in a knowledge domain also differ in their interest in acquiring information in the corresponding domain. Development provides a natural testbed for this potential role of intuitive theory in guiding children's information seeking. There is evidence that children's intuitive theories undergo important growth in the preschool years in numerous domains including biological transmission and contagion (e.g., how people catch a cold; Blacker & LoBue, 2016; Keil et al, 1999), psychosomatic events (e.g., how being scared can cause a stomach ache; Schulz, Bonawitz, & Griffiths, 2007; Bonawitz, Fisher, & Schulz, 2012), and other people's mental states (Theory of Mind; e.g., how other people can have different beliefs from us; Wellman, Fang, & Peterson, 2011).

In the first stage of the study, we measured children's existing knowledge in these three domains, allowing us to classify children as having more immature theories (with higher uncertainty) or more mature theories (with less uncertainty). In the second stage, a few days later, we gave children a "choose-your-own-adventure" storybook that offered each child a forced choice opportunity to learn more about just one outcome. They could receive more information either about the target domain (such as whether one character became ill after prolonged contact with another, contagiously-sick character), or about a domain-irrelevant outcome that does not provide information about a broad, conceptually rich domains of knowledge (such as what of two options the character had for breakfast).

If uncertainty at the model level is influenced by the uncertainty at the theory level, having more uncertainty at the theory level (children with immature theories) should show a preference for the domain-relevant information. This is, because it provides evidence at both levels, making it a more interesting option than the domain-irrelevant outcome that holds uncertainty only at the model level.

Experiment 1

Method

Participants

Fifty children (M_{age} = 4.95 years, *SD* = 0.62, 24 females) participated in this study. A power analysis with an assumed effect size of 0.5 yielded that N = 32 would be sufficient for detecting a significant effect of intuitive theory level (mature vs. immature) with alpha = 0.05, two-tailed, with a power of 0.8. Eleven additional children were excluded from the analyses due to inattention (two children) or a bias to give “yes” or “no” answers (9 children; exclusion criterion: more than 95% of all answers were uniformly “yes” or “no”). Children were recruited from local preschools. Parental consents were acquired prior to children’s participation.

Stimuli

Knowledge Assessment. Children’s existing knowledge in each of the three knowledge domains (Biological Transmission, Psychosomatic Events, and Theory of Mind) were assessed. All questions were adapted from previous assessments of children’s knowledge in each domain (Blacker & LoBue, 2016; Schulz, et al., 2007; Wellman, Fang, & Peterson, 2011). For example, for the Biological Transmission domain, children heard descriptions of scenarios where a character had symptoms of a contagious illness (such as sneezing), and then made contact with a second character. Then children were asked whether the second character would also have the illness. For each question, pictures or puppets were used to facilitate understanding. Additionally, we included attention-check questions that clearly violated basic notions that should have fully developed at the preschool stage, such as asking the child whether someone could just float in mid-air as long as they want without falling down (e.g., Needham & Baillargeon, 1993). These questions allowed us to differentiate children who were not paying attention or were biased to give the same answer to all the questions. The assessment included six questions for each domain and three check questions, resulting in a total of 21 questions. (See SOM-U and OSF: https://osf.io/4nfmk/?view_only=77bc3ecb0d214a809580466b64420a08 for additional details.)

Information Seeking task. The Information Seeking task was based on a "choose-your-own-adventure" paradigm. For each domain, children heard stories about a character experiencing a similar scenario as in the Knowledge Assessment task, intermixed with a domain-irrelevant scenario.

We designed the books to investigate children's preference to learn about future outcomes (where such predictions have some uncertainty). The books were designed such that the two alternative domain-irrelevant event outcomes were a priori equally likely and the details in the storybook failed to provide any clues as to what the outcome might be. Because this option was domain irrelevant, resolving the uncertainty at the model level would not provide additional evidence to inform children's developing theories.

The alternative option for the child was to learn more about the domain-relevant event. This event was, in principle, designed similarly to disambiguate between two outcomes that were a priori equally likely based on the content of the storybook. Because this option was domain relevant, resolving uncertainty at the model level (what happened to this particular character) would also serve to provide additional evidence at the theory-level (e.g. a data-point that confirms or denies a theory of contagion). However, children's interest in the provided evidence in this target domain may differ based on the development of their intuitive theory in the domain. For example, compared to children who are still developing an understanding of contagion and illness and may have more uncertainty at the theory-level, children with a mature understanding may have less uncertainty about the relation between encountering someone sick and becoming sick oneself, and are therefore less interested in uncovering the domain-relevant outcome in the specific context of the book.

For the Biological Transmission domain, a character with a cold (Harper) played with a friend (Devin) (domain-relevant), and also talked about what to have for breakfast the next morning (domain-irrelevant). At the end of the storybook, participants were asked to make a choice about what they wanted to find out, either domain-relevant information, (i.e., whether Devin caught a cold - yes or no), or domain-irrelevant information, (i.e., what - of two options - they had for breakfast).

For the Theory of Mind domain, a character's sister moved one of his toys in secret (domain-relevant), and the doorbell rang (domain-irrelevant). At the end of the storybook, participants were asked to choose whether they wanted to find out where (of two locations) the character would look for his toy, or whether they wanted to find out who (of two possible friends) was at the door.

For the Psychosomatic domain, children learned about a character doing different kinds of activities during the day, and ended up having both a tummy-ache (domain-relevant) and a sore foot (domain-irrelevant). At the end of the book, children could choose to learn about what caused the character's tummy-ache (whether being worried or eating tofu caused the tummy-ache), or sore foot (whether running on a hard surface or tight shoes caused the sore foot).

Procedure

The Knowledge Assessment and Information Seeking task were administered on two separate visits, between two and nine days apart (M_{interval} = 4.39 days). During each visit, children were individually tested in a quiet classroom in their preschool. The order of the question/answer options was counterbalanced across participants.

Results

Overall, children showed similar performance on the Knowledge Assessment as in previous research for each domain. Children on average answered 3.74 (*SD* = 2.01) out of six questions correctly for Biological Transmission, 2.86 (*SD* = 1.57) for Psychosomatic Events, and 2.12 (*SD* = 1.94) for Theory of Mind. Paired t-tests revealed significant differences in performance across the three knowledge domains, ts > 2, ps < .02, suggesting that questions in different domains differ in difficulty significantly.

Because questions in different domains differ in difficulty on average, we analyzed children's knowledge level categorically by performing a median-split on children's Knowledge Assessment Performance for each knowledge domain. This produced a group of children with more mature theories and a group of more immature theories for each domain (Figure 1). Overall, children with mature intuitive theories showed no preference for the two alternative choices in the Information Seeking question (48% choosing domain-relevant information, CI: [40%, 62%]). Critically, we predicted that children with more immature theories -- who stand to learn something at the theory-level from the domain-relevant events -- might thus prefer domain-relevant events. Indeed, results revealed that 67% of children with immature intuitive theories preferred the domain-relevant information over the domain-irrelevant information (CI: [54%, 78%]).

Next, we asked what factors contributed to children's choice patterns in the Information Seeking question. We used the lme4 package in R (Bates et al., 2012) to perform a generalized linear mixed-effects model (GLMM) of the relationship between Theory Level and Information Seeking choice (with a logistic link). As fixed effects, we entered Theory Level, Knowledge Domain, and Age (without interaction term) into the model. As random effects, we had intercepts for participants. P-values were obtained by likelihood ratio tests of the full model with the effect in question against the model without the effect in question. This analysis revealed a significant effect of Theory Level, $\chi^2(1) = 4.54$, $p = .033$, $\beta = -.77$. There was no effect of Knowledge Domain ($\chi^2(1) = .35$, $p = .55$, $\beta = .13$) or Age ($\chi^2(1) = .16$, $p = .69$, $\beta = -.12$).

Discussion

The current results showed that children who were at an immature stage of understanding showed more interest in domain-relevant information, compared to children who reached a more mature understanding of each respective domain. What is driving this exploratory preference: is it theory-level immaturity or theory-level uncertainty? The Knowledge Assessment measure used in Experiment 1 was designed to roughly categorize children based on whether they had more developed theories of each domain. However, the questions did not differentiate children with a lack of theory from children with uncertainty in their intuitive theory. It is possible that children only start to recognize the limits in their framework knowledge after establishing a baseline understanding of the causal relations in the domain, which help to highlight ambiguous contexts as they are encountered. A related possibility is that children may develop from confidence in an incorrect earlier theory to confidence in a later correct theory -- critically passing through a stage where there is uncertainty between the two (e.g. Goodman et al, 2006). This account also suggests that there will be a time of maximal uncertainty when the alternative theories are approximately equally likely; this “liminal” stage is in fact when learners will most benefit from additional data. To ask whether theory-immaturity or theory-uncertainty drove children’s information seeking behavior, we need a finer measure of theory development.

The current results also raised a second question: How does theory change influence information seeking behavior? Specifically, are children's preferences for domain-relevant information driven by a general motivation to learn about the domain or by a more specific sensitivity to context-dependent uncertainty[2]? One possibility is that children's information seeking was driven by a *general* interest in the domain (which might support refining their developing intuitive theories). This predicts that children with more immature/uncertain understanding in each knowledge domain would not only prefer domain-relevant information in specific story contexts, but also prefer domain-relevant information in general, even when it does not relate to uncertainty about a specific situation. Alternatively, children's information seeking may be driven by their motivation to resolve uncertainty that arises in specific contexts. This motivation to explore may thus be triggered by observing uncertainty at the model level, which then highlights uncertainty at the theory-level. This suggests that causal ambiguity that arises in specific contexts may be a necessary motivating factor for such rational information seeking to support theory change.

To test these possibilities, we designed Experiment 2 with several goals in mind. First, we sought to replicate the findings from Experiment 1. Second, we aimed to distinguish between an account that points to mere immaturity as a driver of information seeking from an account that more clearly points to uncertainty. Third, we aimed to test whether children's information seeking is driven by a general interest in domain-relevant information, regardless of its context.

Experiment 2

Method

[2] We thank an anonymous reviewer for raising this question.

Participants

Fifty children (M_{age} = 4.82 years, *SD* = 1.03, 26 females) participated in this study. Two additional children were excluded from the analyses due to sibling interference during the testing session. Children were recruited through online platforms including a lab database and the platform ChildrenHelpingScience.com. All participants were tested online via video conferencing. Parental consents were acquired through an online consent form prior to children's participation.

Stimuli

Knowledge Assessment. We sought to better characterize children's pre-existing intuitive theory by including more questions overall as well a more diverse set of questions. We chose to focus on the domain of Biological Transmission for Experiment 2, because it best afforded a diverse range of questions probing children's causal understanding. In addition to sickness prediction questions similar to Experiment 1, we also included questions that measure children's avoidance preference and their knowledge about causal mechanisms of contagion. Children's understanding of Biological Transmission was assessed by a battery of seven questions. Each question was described with pictures and animations to facilitate comprehension. Two of these questions were similar to the prediction questions in Experiment 1. Children were read descriptions of a character with flu symptoms, and then were asked whether hugging or playing with this character can make someone sick. Two additional questions probed children's avoidance preference to a sick character (e.g., whether they should hug or wave them). For each question, children had two alternative choices, and they were scored either as 1 (correct) or 0

(incorrect).

Three additional questions assessed children's understanding of the causal mechanism of biological transmission. Children were read descriptions of a character with flu symptoms. But critically, this sick character interacted with three originally healthy characters. The degree of interaction between the sick character and the healthy characters varied along the following dimensions: 1) duration of exposure (i.e., how long they stay together in the same closed space), 2) physical proximity (i.e., how far they sit next to each other), and 3) number of potential germ transfers (i.e., how many intermediate contacts are between the contaminated hand and the individual). For each of these questions, children were asked which of the three originally healthy characters was most likely to be sick later following each type and degree of exposure. For each question, one of the characters always had no actual contact with the sick character (scored as 0), another one had moderate contact with the sick character (scored as 1), and the third character had the most contact with the sick character (scored as 2).

The total score ranges from 0 to 10 for the entire Knowledge Assessment. (See SOM-U and OSF: https://osf.io/4nfmk/?view_only=77bc3ecb0d214a809580466b64420a08for additional details.)

Information Seeking task. The Information Seeking task was similarly designed as the Biological Transmission domain in Experiment 1. A character with a cold (Jesse) played volleyball with another character (Max). At the end of the storybook, participants were asked to make a choice about what they wanted to find out, either domain-relevant information, (i.e., whether Max caught a cold), or domain-irrelevant information, (i.e., whether Max made the volleyball team).

General Information Question. Additionally, children were asked which domain they wanted to learn more about in general, either domain-relevant (i.e., how all kinds of people get sick), or domain-irrelevant (i.e., how all kinds of people play volleyball).

Procedure

The Knowledge Assessment and Information Seeking task were administered on the same day, with the Knowledge Assessment preceding the Information Seeking task. The order of the question/answer options was counterbalanced across participants.

Results

Median split results

First we asked whether we replicated the findings from Experiment 1, that children with mature intuitive theories showed no preference for the two alternative choices in the Information Seeking question, whereas children with more immature theories prefer domain-relevant events. Children on average scored 7.42 (SD = 2.34) out of 10 on the Knowledge Assessment. We performed a median-split based on children's Knowledge Assessment scores. Results revealed that only 58% of children with mature intuitive theories chose the domain-relevant information (binomial exact test p = .65, CI: [33%, 80%]), whereas 68% of children with immature intuitive theories preferred the domain-relevant information over the domain-irrelevant information (binomial exact test p = .07, CI: [49%, 83%]). Although these results are not statistically significant, they broadly replicated the findings of Experiment 1.

Next, we asked whether a similar pattern of preference exists in children's interest in the knowledge domain in general. We analyzed children's preference for the final follow-up general information question (how all kinds of people get sick vs. how all kinds of people play volleyball). Neither group showed any preference for the domain-relevant information (mature: 63%, p = .36, CI: [42%, 78%]; immature: 61%, p = .28, CI: [38%, 84%]).

Exploring "liminal" children

We next explored the possibility that findings in Experiment 1 were driven by uncertainty at the theory-level, rather than mere immaturity of the theory. The more sensitive Knowledge Assessment measure in Experiment 2 was designed to allow us to detect more subtle changes in children's theory-development. Specifically, we looked at whether the above results could be better accounted for a model where children are split into three theory groups instead of two. We used children's performance on the Knowledge Assessment as a proxy for their actual theory level. Children were categorized into three (roughly) equal-sized groups based on their Knowledge Assessment scores (using the cut_number function in the ggplot2 package in R, Wickham, 2016). Children that scored between 1 and 6 were categorized as the earlier theory group (N=17), children that scored 7 or 8 were the liminal group (N=20), and children that scored 9 or 10 were the later theory group (N=13). The prediction is that if information seeking is driven by uncertainty, then, in fact, the group that should most prefer to learn about the domain-relevant outcome are the children at the intermediate stage, who are in the process of transitioning between pre- and post-mature theories and thus have greatest uncertainty between the two. As illustrated in Figure 2, this analysis revealed that neither children in the early theory group (53%; binomial exact test p = 1, CI: [28%, 77%]) nor the later theory group (53%; binomial exact test p = 1, CI: [25%, 81%]) showed any preference for the domain-relevant option. In contrast, 80% children in the liminal group chose the domain-relevant option (binomial exact test p = .01, CI: [56%, 94%]).

To explore the second question of whether liminal children's choices are driven by a general preference to seek out domain-general information or whether interest is triggered by uncertainty from a specific context, we looked at children's responses on the final, follow-up general information question. We did not find any significant preference in children's response for this general information question, ps > .26 (Figure 2). When categorizing children into three age groups, we did not find any preference for the domain-relevant option in any age group, ps > .21. While a null result must be interpreted with caution, this result provides tentative support for the claim that children were choosing the domain relevant option to resolve uncertainty at the model level (though mediated by their theories) rather than because they have some general interest in the domain-relevant content, independent of context.

General Discussion

The current study investigated how children's existing intuitive theory influences their information seeking behavior. Across two experiments, we found that children who were at immature stages of understanding showed more interest in domain-relevant information, suggesting that children are sensitive to uncertainty at the theory level and use it to guide their information seeking spontaneously. The more sensitive measures employed in Experiment 2 further reveal that results are best explained by an uncertainty account: children at an intermediate stage of intuitive theory were most motivated to explore domain-relevant information. Such a finding is consistent with a rational account of information seeking -- with learners driving additional data under maximum uncertainty.

What drives the relation between children's theory level and their information seeking behavior? Children with a more uncertain intuitive theory may be interested in any domain-relevant information that can inform their theory development. Alternatively, information seeking may be triggered by uncertainty at the model level, which is influenced by children's theory-level uncertainty. Our follow-up experiment suggests that when there is no immediate model-level uncertainty to resolve, children's general interest in a knowledge domain cannot be accounted for by their theory level. These results, combined with the main results, suggest that children's information seeking is not driven by a context-independent general interest to refine their intuitive theory. Instead, children seek information the most when it helps resolve their uncertainty in a specific context, which informs learning at both the model and theory levels.

The exploratory analysis in Experiment 2 is consistent with a Goldilocks's Effect of information seeking behavior (Kidd, Piantadosi, & Aslin, 2012; 2014), but importantly demonstrates the role of intuitive theories. All children evaluated the same stories and outcomes, but we found that only children with intermediate levels of understanding preferred to learn more about the domain-relevant information. This highlights the important role of theory development in our models of active learning and information seeking.

Our research also connects to a broader literature on curiosity, and our results dovetail with a celebrated "knowledge-gap" account of curiosity, which has been proposed to arise from the "perception of a gap in knowledge and understanding" (Loewenstein, 1994). The increased information seeking in children with early knowledge state suggests that children may recognize the gap in their own knowledge and be more curious about relevant content that can help them close this gap, as has been demonstrated for learning at the model level (e.g. see Ruggeri, Lombrozo, Griffiths, & Xu, 2016). This kind of recognition and curiosity may facilitate the slow and difficult process of theory change in childhood, but it remains to be shown whether children's information seeking behavior is causally related to actual learning outcomes. The current results are consistent with the idea that a gap in knowledge can drive exploration in general. However, children differ in their metacognitive skills (Baer Gill, & Odic, 2018) and their rate of learning and conceptual change (Zaitchik, Iqbal, & Carey, 2014). Therefore, it remains unknown what role children's ability to monitor the uncertainty in their own knowledge, versus the amount of gap (or rate of change) in their knowledge, plays in children's information seeking behavior.

Inspired by information processing theories of learning the current study presented a novel demonstration of how a learner's knowledge state at the theory-level influences information seeking in the relevant domain. Quantitative modeling of expected information gain, quantification of uncertainty in a learner's intuitive theories, and the relationship with children's actual behavior would be an important next step to provide a comprehensive account of children's information seeking behavior. Fortunately, we can recognize our own theories of learning are incomplete, and so, like the children in our studies, we are driven to continue to explore them.

Action Editor

Marc J. Buehner

Editor

D. Stephen Lindsay

Author Contributions

EB developed the study concept. JW, YY, EB contributed to the study design. Testing and data collection were performed by JW, YY, CM. JW performed the data analysis and interpretation under the supervision of EB. JW and EB drafted the manuscript, and YY and CM provided critical revisions. All authors approved the final version of the manuscript for submission.

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Reference

Baer, C., Gill, I. K., & Odic, D. (2018). A domain-general sense of confidence in children. *Open Mind*, *2*(2), 86-96.

Bates, D., Maechler, M., Bolker, B., Walker, S., Christensen, R. H. B., Singmann, H., ... & Scheipl, F. (2012). Package 'lme4'. *CRAN. R Foundation for Statistical Computing, Vienna, Austria*.

Berlyne, D. E. (1950). Stimulus intensity and attention in relation to learning theory. *Quarterly Journal of Experimental Psychology*, *2*(2), 71-75.

Blacker, K. A., & LoBue, V. (2016). Behavioral avoidance of contagion in childhood. *Journal of experimental child psychology*, *143*, 162-170.

Bonawitz, E., Fischer, A., & Schulz, L. (2012). Teaching 3.5-year-olds to revise their beliefs given ambiguous evidence. Journal of Cognition and Development, 13(2), 266-280.

Bonawitz, E., Ullman, T. D., Bridgers, S., Gopnik, A., & Tenenbaum, J. B. (2019). Sticking to the Evidence? A Behavioral and Computational Case Study of Micro-Theory Change in the Domain of Magnetism. Cognitive Science, 43(8), e12765.

Bonawitz, E. B., van Schijndel, T. J., Friel, D., & Schulz, L. (2012). Children balance theories and evidence in exploration, explanation, and learning. *Cognitive psychology*, *64*(4), 215-234.

Carey, S. (1985). *Conceptual change in childhood*. MIT press.

Carey, S. (2009). The Origin of Concepts.*Oxford series in cognitive developmen*t, 3. New York, NY, US: Oxford University Press.

Gopnik, A., & Bonawitz, E. (2015). Bayesian models of child development. *Wiley Interdisciplinary Reviews: Cognitive Science,* 6(2), 75-86.

Gopnik, A., & Wellman, H. M. (1994). The theory theory. *Mapping the mind: Domain Specificity in Cognition and Culture*, 257.

Gopnik, A., & Wellman, H. M. (2012). Reconstructing constructivism: Causal models, Bayesian learning mechanisms, and the theory theory. *Psychological Bulletin*, 138(6), 1085.

Goodman, N. D., Baker, C. L., Bonawitz, E. B., Mansinghka, V. K., Gopnik, A., Wellman, H., ... & Tenenbaum, J. B. (2006). Intuitive theories of mind: A rational approach to false belief. *Proceedings of the Twenty-eighth Annual Conference of the Cognitive Science Society*, 6. Vancouver, Canada: Cognitive Science Society.

Goodman, N. D., Ullman, T. D., & Tenenbaum, J. B. (2011). Learning a theory of causality. *Psychological Review*, 118(1), 110.

Gottlieb, J., Oudeyer, P. Y., Lopes, M., & Baranes, A. (2013). Information-seeking, curiosity, and attention: computational and neural mechanisms. *Trends in Cognitive Sciences*, *17*(11), 585-593.

Gweon, H., & Schulz, L. E. (2008). Stretching to learn: Ambiguous evidence and variability in preschoolers' exploratory play. In B. C. Love, K. McRae, & V. M. Sloutsky (Eds.), *Proceedings of the 30th Annual Conference of the Cognitive Science Society* (pp. 570-574). Austin, TX: Cognitive Science Society.

Gweon, H., & Schulz, L. (2011). 16-month-olds rationally infer causes of failed actions. *Science*, *332*(6037), 1524-1524.

Horst, J. S., Samuelson, L. K., Kucker, S. C., & McMurray, B. (2011). What's new? Children prefer novelty in referent selection. *Cognition*, *118*(2), 234-244.

Keil, F. C. (1991). The emergence of theoretical beliefs as constraints on concepts. *The epigenesis of mind*, 237-256.

Keil, F. C., Levin, D. T., Richman, B. A., & Gutheil, G. (1999). Mechanism and explanation in the development of biological thought: The case of disease. *Folkbiology*, 285-319.

Kidd, C., Piantadosi, S. T., & Aslin, R. N. (2012). The Goldilocks effect: Human infants allocate attention to visual sequences that are neither too simple nor too complex. *PloS One*, *7*(5).

Kidd, C., Piantadosi, S. T., & Aslin, R. N. (2014). The Goldilocks effect in infant auditory attention. *Child Development*, *85*(5), 1795-1804.

Legare, C. H., Gelman, S. A., & Wellman, H. M. (2010). Inconsistency with prior knowledge triggers children's causal explanatory reasoning. *Child Development*, *81*(3), 929-944.

Lieder, F., & Griffiths, T. L. (2020). Resource-rational analysis: understanding human cognition as the optimal use of limited computational resources. *Behavioral and Brain Sciences*, *43*.

Loewenstein, G. (1994). The psychology of curiosity: A review and reinterpretation. *Psychological Bulletin*, *116*(1), 75.

Mendel, G. (1965). Children's preferences for differing degrees of novelty. *Child Development*, 453-465.

Munakata, Y., Casey, B. J., & Diamond, A. (2004). Developmental cognitive neuroscience: progress and potential. *Trends in Cognitive Sciences*, *8*(3), 122-128.

Ruggeri, A., Lombrozo, T., Griffiths, T. L., & Xu, F. (2016). Sources of developmental change in the efficiency of information search. Developmental Psychology, 52(12), 2159.

Saylor, M. M., & Ganea, P. A. (Eds.). (2018). *Active Learning from Infancy to Childhood: Social Motivation, Cognition, and Linguistic Mechanisms*. Springer.

Schulz, L. E., & Bonawitz, E. B. (2007). Serious fun: preschoolers engage in more exploratory play when evidence is confounded. *Developmental Psychology*, *43*(4), 1045.

Schulz, L. E., Bonawitz, E. B., & Griffiths, T. L. (2007). Can being scared cause tummy aches? Naive theories, ambiguous evidence, and preschoolers' causal inferences. *Developmental Psychology*, *43*(5), 1124.

Schulz, L. E., & Gopnik, A. (2004). Causal learning across domains. *Developmental Psychology*, *40*(2), 162.

Schulz, L. E., Hooppell, C., & Jenkins, A. C. (2008). Judicious imitation: Children differentially imitate deterministically and probabilistically effective actions. *Child Development*, *79*(2), 395-410.

Stahl, A. E., & Feigenson, L. (2015). Observing the unexpected enhances infants' learning and exploration. *Science*, *348*(6230), 91-94.

Tenenbaum, J. B., Kemp, C., Griffiths, T. L., & Goodman, N. D. (2011). How to grow a mind: Statistics, structure, and abstraction. *Science*, 331(6022), 1279-1285.

Vo, V. A., Li, R., Kornell, N., Pouget, A., & Cantlon, J. F. (2014). Young children bet on their numerical skills: metacognition in the numerical domain. *Psychological Science*, *25*(9), 1712-1721.

Wellman, H. M., Fang, F., & Peterson, C. C. (2011). Sequential progressions in a theory-of-mind scale: Longitudinal perspectives. *Child development*, *82*(3), 780-792.

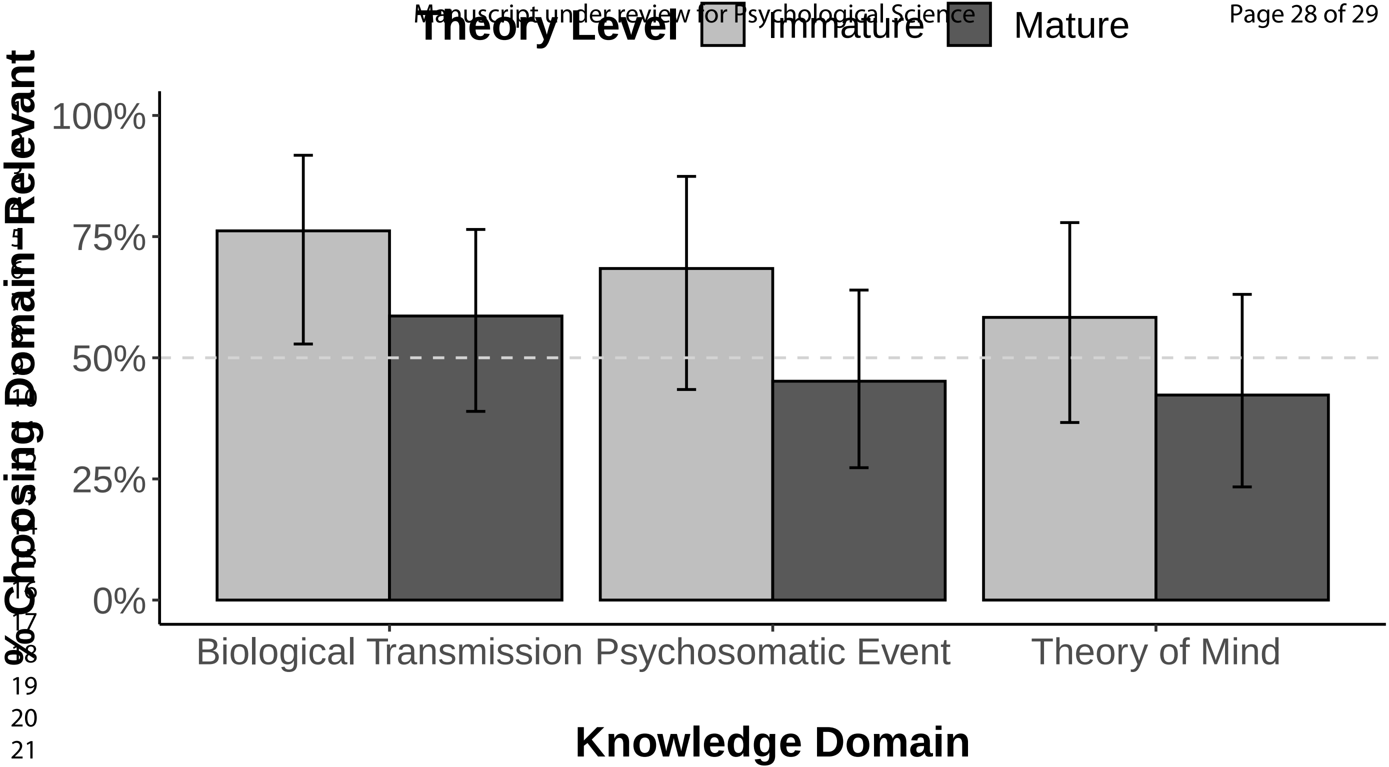
Wickham H (2016). *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York. ISBN 978-3-319-24277-4, https://ggplot2.tidyverse.org.

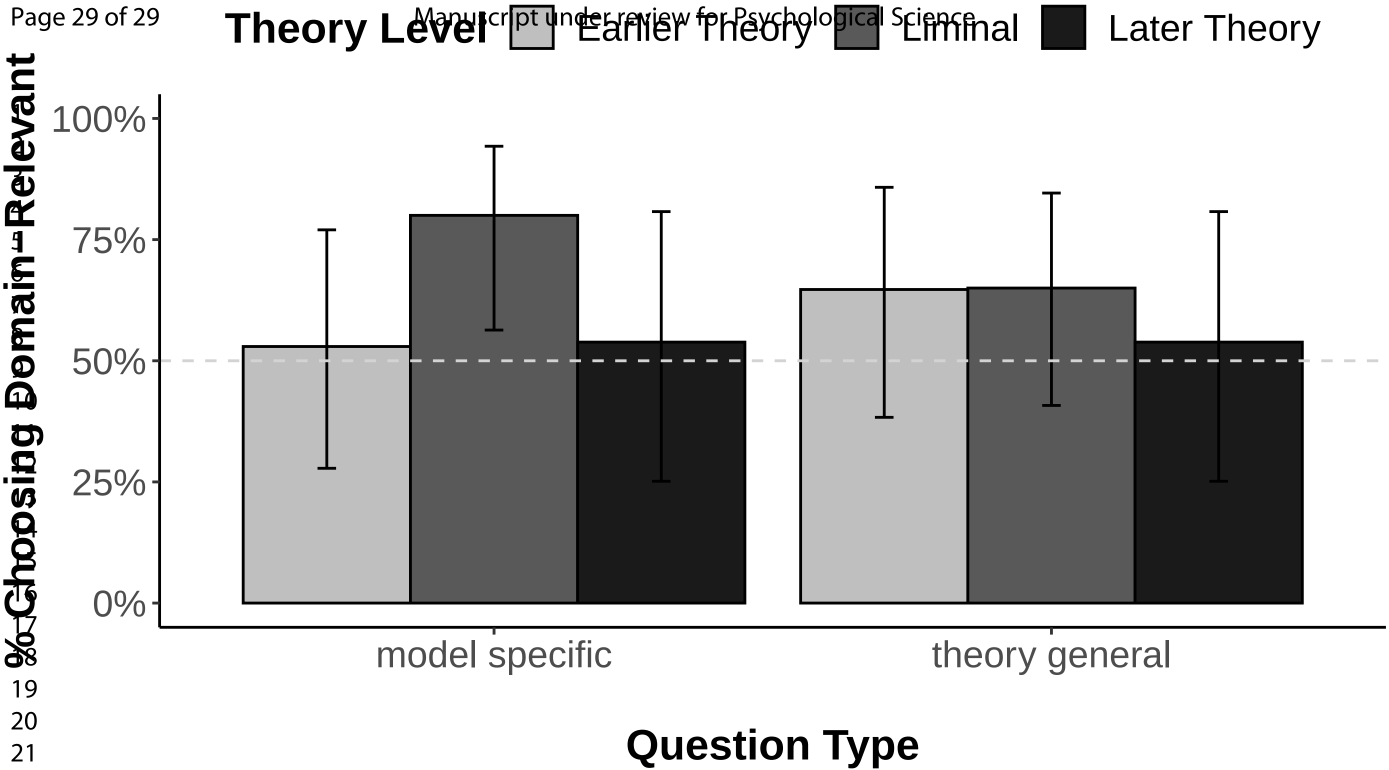
Zaitchik, D., Iqbal, Y., & Carey, S. (2014). The effect of executive function on biological reasoning in young children: An individual differences study. *Child Development*, *85*(1), 160-175.

Figure Captions

Figure 1. Percentage of children choosing to seek information in the target domain in the Information Seeking task for each knowledge domain, grouped by their theory level based on the Knowledge Assessment. Error bars represent confidence intervals of proportions based on exact binomial tests.

Figure 2. Percentage of children choosing to seek information in the target domain at the model-level (i.e., find out whether Max was sick or made the team) and theory-level (i.e., learn more about germs or volleyball in general) Information Seeking task in Experiment 2, grouped by their theory level based on the Knowledge Assessment. Error bars represent confidence intervals of proportions based on exact binomial tests.


Theory Level
Immature
Mature
% Choosing Domain-Relevant
100%
75%
50%
25%
0%
Biological Transmission
Psychosomatic Event
Theory of Mind
Knowledge Domain


Theory Level
Earlier Theory
Liminal
Later Theory
% Choosing Domain-Relevant
100%
75%
50%
25%
0%
model specific
theory general
Question Type