# Understanding How Children Change Their Minds

**Elizabeth Bonawitz** Research Statement

Studying the mind of a child provides a unique and powerful way to understand human intelligence. In the course of development, children change their causal beliefs over and over, often moving from a less to more accurate picture of the world. Sometimes this learning is fast and flexible; other times it is protracted and rigid. Sometimes very young infants demonstrate competencies in their understanding that seem to be lacking in much older children. Sometimes children make incredible leaps of insight; other times they seem to irrationally meander from one incorrect belief to the next. And sometimes, learning is most efficient during self-guided play while at other times direct instruction is more efficient. In order to understand how learning is possible, these discrepancies must be reconciled. To this end, my research has focused on four specific questions in causal learning: (1) How do evidence and prior beliefs interact in children's causal learning? (2) What are the early developmental origins of construing events as causal? (3) What are learning algorithms that include appropriate cognitive developmental constraints? (4) What is the role of social information in learning?

To investigate these questions, I take a "domain diverse", "methodologically diverse", and "age diverse" approach. My research draws on multiple domains of children's causal learning such as biological domains (reasoning about illness and psychogenic events), psychology (reasoning about other's minds), forces (balance, magnetism), and artifacts (toys with causal affordances). I use multiple measures (exploratory play, predictions, explanations, looking time measures, and eye-tracking), and, in particular, I use computational modeling to understand how evidence influences learning. Finally, I look at learning across the developmental age range, studying toddlers, preschoolers, early school-aged children, and adults. By exploring multiple domains, combining methodological tools, and assessing learning at many stages of development, I hope to converge on general principles of causal learning as well as understand how specific constraints may influence learning at different ages.

### (1) Interaction of prior beliefs and evidence in causal learning

The theory theory proposes that theories are abstract, defeasible representations of causal structure; it predicts that the child, like the scientist, engages in an ongoing process of hypothesis testing and revision. It also suggests that both existing theories and new evidence shape causal inference and learning; in particular, it provides a means to think about why small amounts of evidence may sometimes support learning but why at other times even very compelling evidence does not overturn beliefs. However, the theory theory does not provide a specific proposal about how new evidence and prior beliefs should interact. Bayesian models and the theory theory can be bridged to investigate what it means for children to take a rational approach to processes that support learning.

In graduate school, in collaboration with my adviser, Laura Schulz, my research program looked at formalizing precisely how prior beliefs and evidence interact to support children's predictions, explanations, and exploratory play. The approach takes the general format of either manipulating observed evidence and controlling for children's prior beliefs, or manipulating children's prior beliefs and controlling for the amount of evidence observed. For example, I have investigated children's exploratory play with a jack-in-the-box (with which children don't have strong beliefs differentiating the possible ways that the toy works), and give different patterns of evidence either deconfounding or not deconfounding these possibilities. I looked at how children's strong differential beliefs about balance interact with evidence to affect their predictions, play, explanations, and learning [12, 19], and I used eye-tracking to show that children with these different beliefs track causal balancing scenes differently [1]. I also looked at how evidence and children's strong beliefs about biological events and psychosomatic illness influence their causal explanations [27], and I developed a training study to further investigate developmental differences in children's learning about psychosomatic events from evidence when they have strong prior beliefs [5, 6]. I investigated how children's prior preference for simpler explanations interacts with increasing evidence for more complex explanations [2, 13]. And, I looked at the role of evidence in guiding children's false belief explanations [7, 22]. I also collaborated on adult studies, considering the role of physical theories on adults' causal inference [23] as well as the role of context in reasoning about causal transmission [25]. By examining situations where children have strong and weak prior beliefs and situations where children observe strong and weak evidence, we can contrast how differences in theories and evidence affect children's predictions, exploration, and explanations; I have used computational frameworks to formalize this interaction [10, 14, 15]. Taken together, this program helps to define the specific role of prior beliefs in constraining and aiding the interpretation of evidence, but I am also working towards a more precise characterization of representational structure in the child's mind and in these frameworks.

### (2) Foundations of causal learning: agency, causal language, & spatial contact

By investigating the interaction of causal theories and evidence, I also became interested in seeing what events children initially construe as causal. Human beings may be unique among animals in having a single representation ("causal knowledge") that encodes what is common across causal relationships that do not involve the actions of agents and the relationship between agent actions and outcomes. While adults live in a world rife with causal connections, there are substantial constraints on toddlers' ability to infer that predictive relations (events that co-occur, that are associated with each other) might support effective manipulation (acting on 'A' may bring about 'B'). My collaborators and I found that toddlers, unlike preschoolers, needed extra information in order to move directly from observation to action: toddlers only represented the events in our studies as causal when a dispositional agent initiated the observed events, the observed events involved direct contact relations, or the observed events were described with causal language [4, 11]. If infants in general fail to treat non-agentive predictive relations as relations that support intervention, this might help explain why infants can understand a concept based on their pattern of looking time behavior and yet older children fail on very closely matched action paradigms. In follow-up studies, we looked at whether toddlers' failures are due merely to the difficulty of initiating interventions or to more general constraints on the kinds of events they represent as causal [24]. The results suggest that such gaps might not reflect mere failures of performance (e.g., due to the increased complexity of acting vs. looking) but genuine constraints on children's causal representations. A challenge for future work involves connecting infants' proficiencies in specific causal domains to representations that are later developing in these domains.

### (3) Formally connecting "algorithmic" to "computational" levels

My work has been motivated in part by recent advances in machine learning and cognitive science that suggest that people often act in ways consistent with optimal Bayesian models. However, it would be impossible for any system to enumerate and test every hypothesis in succession, so how can children carry out what appear to be these intractable Bayesian computations? As a post-doctoral fellow, I have worked in collaboration with Tom Griffiths and Alison Gopnik to test the "Sampling Hypothesis", derived from techniques in machine learning, which asserts that children's inferences (and associated explanations and predictions) are made via a process that resembles sampling from a probability distribution. The Sampling Hypothesis has recently been suggested as a way to model the inferences of adult learners [8, 9], but it also provides some insight into informal observations of child learners [3, 18, 21]. An approach that starts with rational inference and provides an account of how such inference may be approximated—by generating samples – may help explain how young learners search through and evaluate a space of hypotheses and why variability in children's explanation and predictions is to be expected. The Sampling Hypothesis also has the potential to reconcile approaches that stress rational inference with approaches that stress the relative difficulty children (and adults) have with generating correct beliefs; it can thus explain why the specific responses that children do generate may be less than optimal. These algorithms depend on specific hypotheses about cognitive constraints and make different predictions depending on the degree to which the system is taxed. Thus, they also provide a means to unite other developmental changes (e.g. cognitive limitations, attentional, motivational, emotional changes) with modeling approaches that have previously been unable to capture these factors. Ongoing work is contrasting specific sampling algorithms and demonstrating how these algorithms connect to computational level analysis.

### (4) Role of social factors in causal learning

Most recently, I have been interested in understanding how social information shapes learning. Two competing intuitions animate longstanding debates over children's learning: that children learn primarily from helpful, informative others (through testimony or "direct instruction"), and that, especially in the early years, children learn chiefly through their own active exploration of the environment ("constructivist" or "discovery learning"). The tension between learning from others and from self-guided exploration might stem in part from a principled trade-off at the heart of pedagogical learning. Teaching produces an inductive bias that constrains children's hypothesis space for better and for worse: in promoting rapid and efficient learning of target material, pedagogical instruction necessarily limits the range of hypotheses children consider. Motivated by computational analyses, and in collaboration with Patrick Shafto, I have looked at how teaching affects exploration and discovery. We found that preschoolers in a pedagogical condition focused almost exclusively on the demonstrated target function in their exploratory play; by contrast, following an interrupted pedagogical demonstration, a naïve 'accidental' demonstration, or no demonstration, children explored broadly [17]. We also showed that children only extend this assumption for those who are likely to have similar beliefs: Children limit their exploration both after direct instruction to themselves and after overhearing direct instruction given to another child; they do not show this constraint after observing direct instruction given to an adult or after observing a non-pedagogical intentional action [16]. In another project, we found an increase in exploration when category labels provided by a teacher conflicted with objects' causal properties [28]. My collaborators and I have also found that children's ability to prove that one hypothesis is true and another false (an ability generally thought to require formal education) significantly improves in a social context in which hypotheses are construed as people's beliefs [20]. These projects are a first step in understanding the powerful role of social factors in constraining children's exploration and inferences about causal properties, as well guiding their interpretation of evidence. In my current work, I am looking at how putting children in the teaching role helps them reason about evidence, deception, and other people's minds.

### Conclusions

Many dichotomies exist in development, such as: the sophisticated and rapid inferences children sometimes make versus the protracted period that some belief revision takes; the divide between looking and acting; the "Bayesian" behavior of even very young children versus the intractability of such computations; and the benefits of direct instruction versus self-guided play. My work has sought to explain these dichotomies by examining the factors that make learning possible. My goal is to bridge detailed empirical evidence and formal theory to explain the successes and "failures" of children's causal learning. Ultimately, I believe this will help us understand learning in general and thus human intelligence.

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