Children's Rational Exploration

Elizabeth Baraff Bonawitz & Laura Schulz

MIT Department of Brain and Cognitive Sciences
77 Massachusetts Avenue, Bldg. 46-4005
Cambridge, MA 02139
liz_b@mit.edu, lschulz@mit.edu

Abstract

Very young children have remarkably sophisticated causal knowledge about the world, yet relatively little is known about the process of causal learning. In this paper we provide a Bayesian model of how the interaction of prior theories and evidence can lead to ambiguity in competing causal hypotheses; we suggest that children seek to resolve such ambiguities through active exploration. In Experiment 1, we look at the model with respect to children's causal judgments. In Experiments 2 and 3, we show that children selectively engage in exploration when evidence is formally ambiguous with respect to their prior theories. We suggest that children's play is rational with respect to this model and that children's active exploration of causal ambiguities might generate evidence that could support theory formation and theory change.

Children's Causal Reasoning

Very young children have remarkably sophisticated causal knowledge about the world in a variety of domains. Children reason about the causes of mental states such as beliefs and desires (e.g. see Wellman, 1990), in the domain of physics, they reason about object properties and forces (e.g. Bullock, Gelman, & Baillargeon, 1982; Shultz, 1982) and with respect to their naïve biology, they reason about causes pertaining to illness and growth (Gelman & Wellman, 1991; Kalish, 1996).

Many researchers have suggested that children's causal knowledge can be characterized as intuitive theories: abstract, coherent, defeasible representations of causal structure (Carey, 1985; Gopnik & Meltzoff, 1997; Wellman, 1990; Keil, 1989). However, despite the importance of theories for children's predictions, explanations, counterfactual reasoning, and exploration, relatively little is known about the processes responsible for this kind of causal learning.

Some researchers have suggested that children's naive theories might be instantiated in domain-specific modules, or innate concepts in core domains, (Carey & Spelke, 1994; Keil, 1995). For example, some researchers have argued that we have core knowledge about objects, agents, and number (Carey & Spelke, 1994). However, other researchers have emphasized the role of domain-general learning mechanisms, such as sensitivity to patterns of statistical evidence. Of the few studies that have directly compared domain-specific and domain-general causal learning, some have suggested that both adults and children privilege domain-specific information over domain-general evidence, (Ahn, Kalish, Medin, & Gelman, 1995; Bullock, Gelman & Baillargeon, 1982; Shultz, 1982). By contrast, other research suggests that children can use domain general learning mechanisms (such as the conditional probability of events) to override domain boundaries (e.g. Schulz.& Gopnik, 2004).

Because previous research has focused on cases when evidence either overwhelmingly favored a domain inappropriate cause (suggesting the strength of domain general arguments), or cases when theories were strongly instantiated and little counter-evidence was available (suggesting the strength of prior theories), little work has demonstrated a graded interaction between the two. However, in previous research (Bonawitz, Griffiths, & Schulz, 2006; Schulz, Bonawitz, & Griffiths, in press), we proposed a formal model that suggested how prior knowledge and statistical updating may interact in cases when children are presented with ambiguous evidence. Our model is applicable both to cases when children have strong prior knowledge and cases when they do not.

In this paper, we will argue that both domain-specific theories and statistical evidence play an important role in children's causal inferences. In particular, we will describe scenarios in which the interaction of prior knowledge and evidence leads to ambiguity between two potential candidate causes. First we will describe how ambiguity arises and is reflected in children's causal inferences. Then, we will suggest that in these cases of ambiguity, it is more optimal to explore than in cases when a single likely causal hypothesis is strongly favored. We will suggest that, although children may not construct carefully controlled experiments, their spontaneous exploration reflects sensitivity to these formal instances of ambiguity and is thus rational with respect to our model. We suggest that this sophistication in exploratory play is one mechanism that can allow children to 'construct' new knowledge and support the processes involved in theory change.

Within and Cross-Domains Causal Reasoning

We set up a scenario where there were two potential candidate causes that a priori where equally plausible to explain a recurring event. However, evidence accumulated such that one cause always recurred with the effect, but the other causes were always novel. Thus, it became increasingly plausible that the recurring variable was the likely cause. We were interested in whether or not preschoolers could reason about this type of ambiguous statistical evidence.

However, because we also wanted to investigate processes that might underlie genuine instances of theory change, we chose a second context in which children's theories are both robust and distinct from adult theories. Considerable research has shown that children's causal reasoning respects domain boundaries, (Carey, 1985; Estes, Wellman, & Woolley, 1989; Hatano & Inagaki, 1994). In particular, some researchers have suggested that children respect an ontological distinction between mental phenomena and bodily/physical phenomena, (Notaro, Gelman & Zimmerman, 2001). So while adults accept that some events (e.g., psychosomatic phenomena) can cross the mental/physical divide, preschoolers typically deny that psychosomatic reactions are possible (e.g., they deny that feeling frustrated can cause a headache or that feeling embarrassed can make you blush). We were interested in how preschool children would interpret formal patterns of evidence suggesting the presence of a psychosomatic cause in light of a strong initial belief in domain boundaries.

Theory-based Bayesian Model of Children's Causal Inferences

Bayesian inference provides a natural framework in which to consider how prior knowledge and data interact. In work by Bonawitz, Griffiths, & Schulz (2006), and Schulz, Bonawitz, & Griffiths, (*in press*), we model children's causal inferences in a framework with two critical components. First, we assume that children's judgments are the result of a Bayesian inference, comparing children's prior beliefs about a potential model of the world (hypothesis) to the probability of observing the data given the hypothesis. Second, we assume that these hypotheses are generated by a causal theory. This Bayesian model captures the two critical components of children's reasoning: their ability to update their beliefs given new evidence, and the soft constraints imposed by their prior knowledge.

To capture children's reasoning in the task, we model their inferences as weighing the probability of one candidate explanation over another. That is, children are explicitly asked in the task, "Why does {character} have {symptom}? Is it because of {Explanation 1} or is it because of {Explanation 2}?" We model the probability that the child chooses Explanation 1 as

$$(1) \qquad \frac{P(\text{Explanation 1} \mid D)}{P(\text{Explanation 1} \mid D) + P(\text{Explanation 2} \mid D)}$$

which directly contrasts the two potential explanations given the data, D, observed. The probability of each possible explanation given the data is computed by summing over all causal models that are consistent with the explanation. This is formalized as:

$$(2) \qquad P(\text{Explanation 1} \mid D) = \sum_{h \in H} P(\text{Explanation 1} \mid h) P(h \mid D)$$

where h is a hypothesis as to the underlying causal structure, and H is the space of all hypotheses. We represent hypothetical causal structures as causal graphical models (Pearl, 2000; Spirtes, Glymour, & Schienes, 1993), consisting of a graphical structure indicating the causal relationships among a set of variables, where nodes are variables and relationships are indicated by arrows from cause to effect, and a set of conditional probability distributions giving the probability that each variable takes on a particular value given the values of its causes. We assume that the probability of the explanation given a particular causal structure h is 1/k, where k is the set of candidate causes that are present and possess a direct causal link with the effect in h.

The probability of a particular causal structure given the data is expanded via Bayes rule as

$$(3) \qquad P(h \mid D) \propto P(D \mid h) P(h)$$

where P(h) is the prior probability of a particular causal structure, implementing the constraints imposed by the prior knowledge of the learner, and P(D|h) is the "likelihood", indicating the probability of the data D under the causal model h. The precise values of these two probabilities are determined by the causal theory entertained by the observer.

Generating Causal Models from a Causal Theory

An important notion in developmental psychology is the idea that children have rich causal theories of the world. As proposed by Tenenbaum and Niyogi (2003) and Tenenbaum, Griffiths, and Niyogi (2007), we model the theory that guides the inferences made by children in our task as a simple scheme for generating causal graphical models. In this scheme, we allow for several types of domains. Causes are likely to have relationships with their domain-related effects, however, we also allow a small probability that a cause from one domain can lead to an effect in another domain. This framework theory provides a simple recipe for generating the space of causal graphical models that could describe a particular situation. The prior probability associated with each model is simply its probability of being generated by the theory. The process of generating a model breaks down into four steps:

1. Represent all possible causes and all possible effects as a set of nodes in a causal graphical model.

2. For each cause and effect in the same domain, generate a causal relationship (an arrow) between the corresponding nodes with probability p.
3. For each cause and effect in different domains, generate a causal relationship (an arrow) between the corresponding nodes with probability q.
4. Specify the conditional probability distribution for the effects given their causes.

Model Predictions The predictions of the model given this pattern of evidence are represented in Figure 1. We implemented our intuition of relatively low cross-domain probability by setting q = .1 and set a higher within-domain probability of p = .4. Importantly, the model demonstrates the shift between favoring the within-domain candidate cause at baseline to favoring the cross-domain candidate cause after evidence. We conducted an experiment to test the predictions of this model.

Children's Causal Inferences

The goal of this experiment was to look at whether or not children would also be able to integrate domain-general learning with their strong domain-specific priors. Thirty-two four and five-year-olds (range = 4;0 to 5;11, M = 5;0) participated. Children were randomly assigned to either a Baseline Condition or an Evidence Condition.

Two picture storybooks were used as the stimuli. Both books featured events occurring over a week, starting on Monday and ending on Sunday so children received 7 'days' of evidence. The Within Domain storybook featured a deer who liked to run in different places. The deer got itchy spots on his legs every morning. Evidence was presented such that A&B→E; A&C→E; A&D→E, etc. The recurring candidate cause (A) was running through cattails, the other cause varied (e.g., running through a meadow, a garden, etc.) (To show that the effect was not always present, the deer ran through different places in the afternoons and never got itchy spots). The Cross Domain book was identical except that it featured a bunny rabbit who got a tummy ache in the mornings (but not the afternoons). Feeling scared was the recurring cause; the other candidate cause varied among types of food Bunny ate (e.g., cheese, a sandwich, etc.) Two sets of each book were created to counterbalance the order of events.

Each child was read both the within- and cross-domains storybook (order was counterbalanced) in a quiet location. In the Evidence Condition, children were asked at the end of the story, "Why does [Bambi/ Bunny] have [itchy spots/tummy ache]? Is it because of [running in the garden/eating a sandwich] or because of [running in the cattails/feeling scared]?" Children in the Baseline Condition saw the same storybooks, only the Monday-Saturday events were not included, and the story went straight to the final, Sunday page.

Children's Results Preliminary analysis revealed no order effects. In the Baseline Condition, children chose at chance between the candidate causes in the within-domain

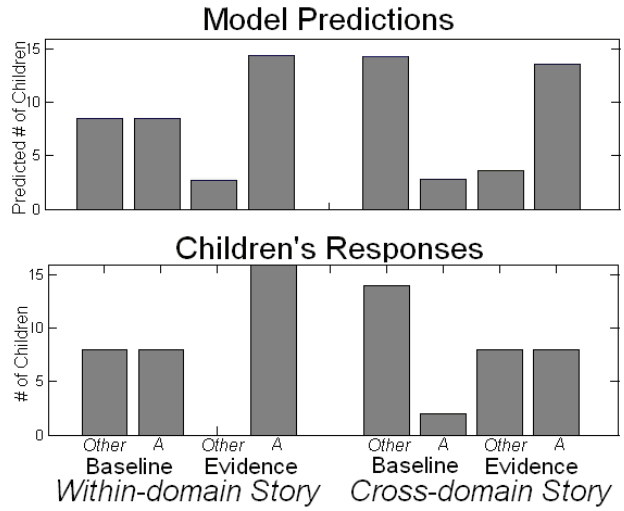

Figure 1: Model predictions and results of Children's experiment when reasoning about candidate causes within domain and cross-domains in baseline and evidence conditions.

storybook and almost always chose the domain-appropriate variable (food) in the cross-domains storybook. Children were significantly more likely to identify A as the cause in the Evidence Condition than at Baseline in both the within-domain and cross-domains storybooks (within-domain: 2 (1, N = 32) = 10.67, p < .01; cross-domains: 2 (1, N = 32) = 5.23, p < .05). However, children were less likely to choose A in the cross-domains storybook than in the within-domain storybook, (2 (1, N = 32) = 10.67, p < .01).

As shown in Figure 1, our model accurately predicted children's responses. The model gives correct relative weights to the variables at baseline in both the within-domain and cross-domains conditions. The model also favored the posterior probability of 'cattails' over 'garden'. It was slightly less successful at capturing the degree to which children would choose 'feeling scared' as the cause; the model predicted that the posterior probability of 'feeling scared' as the candidate cause should have been significantly greater than 'sandwich'. Children showed slightly greater resistance to parting with their initial inductive biases. Importantly however, the model captured the overall pattern of children's learning; children were significantly more willing to select 'feeling scared' after seeing the evidence then at baseline.

Ambiguity in Children's Causal Inferences

The model proposed above has offered a formal account of children's theory-based learning in terms of Bayesian inference. By providing a formal account, we hope to make clear the interaction between domain-specific prior knowledge and domain-general learning mechanisms. Although the content of children's framework theories and the priors over those theories may differ from adult

theories, Bayesian inference suggests a universal system for integrating theories and evidence. Most importantly, this computational account captures a hallmark of children's causal theories: conservativism with respect to prior knowledge and yet flexibility in the face of new evidence.

The results of the developmental experiments also reveal two conditions under which ambiguity may arise as a result of the interaction of prior beliefs and novel evidence. In both cases, ambiguity arises because the posterior probability of the two candidate causal explanations is equal. The first case is seen in the baseline condition of the within domain book. In this case, the prior probability of both candidate causes is equal, and the likelihoods fail to further disambiguate the two potential causes. The second case is seen in the evidence condition of the cross domains book. In this second case, there is a high prior probability of one explanation, and a low prior probability of the second; however, the evidence strongly favors the a priori unlikely candidate and disfavors the a priori likely candidate. This interaction leads to equally plausible posteriors.

In the following, we suggest that children are sensitive to the ambiguity that may arise in competing causal explanations whether it is due to A: to evidence failing to discriminate among multiple equally plausible hypotheses or B: to evidence favoring an a priori unlikely hypotheses. We suggest that when children are faced with such ambiguities, they are more likely to engage in exploratory play (thus potentially generating new evidence that could support learning).

Learning from Play

Since Piaget (1930), and even earlier, people have suggested that children learn through play and through actively exploring their environment, (e.g., Bruner, Jolly, & Sylva, 1976; Singer, Golinkoff, & Hirsh-Pasek, 2006). However, little is actually known about what children do in the course of exploratory play or how children's exploratory play might connect to formal accounts of causal learning. Indeed, the overwhelming finding has been that when children are left to figure things out on their own, they are very unsystematic: children do not isolate variables; their play does not resemble the way we learn about causal relations through experimentation in science (e.g. Chen & Klahr, 1999; Inhelder & Piaget, 1958; Kuhn, 1989). Furthermore, the number of events children might explore in principle is vastly more than they could ever explore in practice. If children's own exploration is hopelessly unsystematic, how might they get the type of evidence that could support causal learning?

We suggest that children's exploratory play reflects the same sensitivity to prior knowledge and evidence that we find in causal inference. Here we will discuss how prior knowledge and evidence interact to affect children's exploratory play, both in contexts where children have no strong differential prior beliefs and in contexts where they do.

Causal Ambiguity 1 & Children's Play

The first question we asked is whether children play differently when evidence disambiguates or fails to disambiguate a priori equally plausible causal hypotheses. To test this, we created a new toy box with two levers. The two levers can be depressed simultaneously such that both a toy duck and straw puppet pop-up at the same time and the location of the duck and puppet are ambiguous with respect to the levers. A number of possible causal hypotheses may explain the pattern of results, (e.g. either lever might make the duck go, might make the puppet go, one lever might make both toys go, or levers might interact, etc.).

In this study, (Schulz & Bonawitz, in press), we introduced children to a toy and showed them either confounded or unconfounded evidence about the causal structure of the toy. We removed the toy and then returned it along with a novel toy and then allowed the children to play freely for sixty seconds.

Because the two most likely hypotheses (e.g. see Figure 2), are a priori equally plausible and the evidence in the Confounded condition fails to provide support for one hypothesis over the other, there is causal ambiguity. In contrast, the evidence in the Unconfounded condition strongly supports a single hypothesis. We predicted that children who observed confounded evidence, (that is evidence that is equally likely to be observed by either of the two possible causal hypotheses), would preferentially play with the familiar toy, but that children who observed unconfounded evidence (evidence that strongly favored a causal hypotheses), would show the standard novelty preference and play primarily with the novel toy.

We tested 48 preschoolers (mean age: 56 months; range: 48 – 67 months), 16 in each of three conditions: a Confounded evidence condition (where evidence remained ambiguous) and three Unconfounded conditions, described below. Children were tested individually. In all conditions, children were introduced to a box with two levers. In the Confounded condition, the experimenter said, "You push down your lever and I'll push down my lever at the same time. Ready: one, two, three, down!" When both levers were depressed, a duck and a straw puppet popped out of the middle of the box. The spatial locations of the duck and the puppet were uninformative about their causal relationships with the lever; that is, the objects appeared in the middle of the box so it was not possible, just by looking, to determine which lever controlled which objects. After approximately two seconds, the experimenter said, "One, two, three, up!" The experimenter and the child simultaneously released the levers and the duck and puppet disappeared from view. The procedure was repeated twice more, so that in total, both levers were pushed three times and both effects (the duck and the puppet) occurred three times. Because the

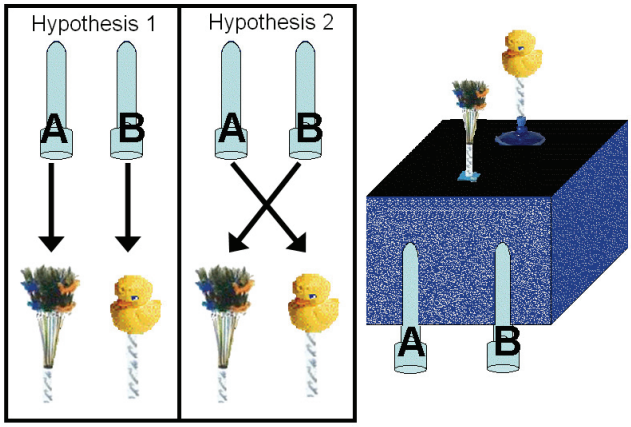

Figure 2: Two a priori equally likely hypotheses to describe the causes of the toy duck and straw puppet. (other hypotheses are also plausible -- for instance, that both levers generate both effects or that the levers interact)

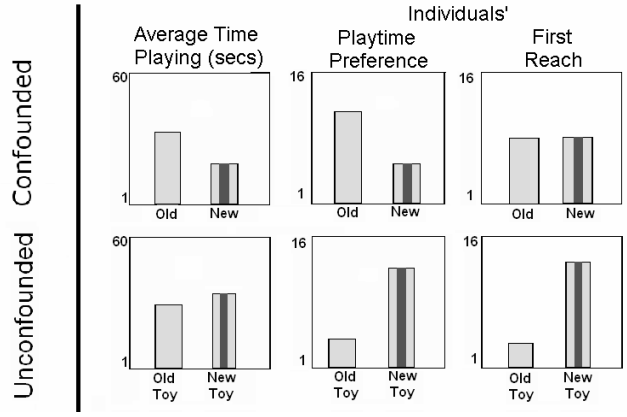

Figure 3: Results of children's play in causal ambiguity case 1 experiment.

two candidate causes were always manipulated simultaneously, the evidence failed to disambiguate the many possible causal structures that might underlie the event (either lever might activate the duck or the puppet, one or both levers might activate both, or the levers might interact).

Children might play more with the familiar toy in the Confounded condition simply because it was perceptually more interesting than the novel toy. Thus, we also ran an Unconfounded condition. In this condition, the experimenter and the child pressed and released their levers simultaneously once. Then the experimenter pushed one lever and just the duck popped up. She released that lever and pushed the other lever and just the puppet popped up. The experimenter and the child then pressed and released their levers simultaneously a second time. As in the Confounded condition, the child never had a chance to manipulate the toy without the experimenter, however, this evidence fully disambiguated the causal structure of the toy. Thus, though either hypothesis (see Figure 4) was equally likely a priori, the pattern of evidence in only the Unconfounded condition strongly supported just one hypothesis, (namely that lever A caused the duck and lever B caused the straw puppet.) There was no significant difference in the length of time children were exposed to the effects of the familiar toy in the Confounded condition and the Unconfounded conditions (Confounded: mean = 12.1 seconds; Unconfounded/No Independent Play: mean = 13 seconds; t(30), p = ns).

The experimenter said, "I'll be back in a minute. Go ahead and play." She stood up and walked out of the child's line of sight. The children were left to play freely for 60 seconds and their free play was videotaped.

By all measures, children were more likely to explore the familiar toy in the Confounded condition than in the Unconfounded condition, (see Figure 3). We compared how long children played with each toy in each condition by doing a 2 x 2 mixed ANOVA with play time on each toy as the within-subjects variable and condition as the between-subjects variable. Comparisons between the Confounded condition and the Unconfounded condition revealed no main effect of play time (averaging across the two conditions, children did not prefer one toy to the other) and no main effect of condition (overall, children played for the same amount of time in each condition), but did reveal a significant interaction: children spent more time playing with the familiar toy in the Confounded condition than in the Unconfounded condition ($F(1, 32) = 10.83$, $p < .01$).

Additionally, more children spent the majority of their time playing with the familiar toy in the Confounded condition than in the Unconfounded condition (2 (1, N = 32) = 4.5, $p < .05$). Finally, children were more marginally likely to reach first for the familiar toy in the Confounded condition than in the Unconfounded condition (2 (1, N = 32) = 3.46, $p = .06$).

Within the Confounded condition, children played significantly longer with the familiar toy than the novel toy ($t(15) = 2.79$, $p < .01$). These results did not hold for children in the Unconfounded condition, ($t(15) = 1.06$, p = ns). In the Confounded condition, a non-significant majority of children played most with the familiar toy (p = ns by binomial test; one-tailed throughout) but children were marginally more likely to play with the novel toy in the Unconfounded condition ($p = .07$ by binomial test). Finally, in the Confounded condition, children's first reach was just as likely to be for the familiar toy as the novel toy (p = ns by binomial test), whereas children were significantly more likely to reach first for the novel toy than the familiar toy in the Unconfounded condition ($p < .01$ by binomial test).

Note that in both conditions, children were familiarized with the same toy and children's exposure to the toy's effects and affordances was closely matched across conditions. A single manipulation seemed to drive the

effect: if the two levers moved separately, on just a single trial, (thus providing strong evidence for only a single hypothesis and disambiguating the posteriors), the children spent most of their time playing with the novel toy; if the two levers always moved simultaneously, children spent most of their time playing with the familiar toy. These results suggest that preschoolers' spontaneous exploratory play is sensitive, not just to stimulus features such as novelty and perceptual salience, but also to formal properties of evidence, like confounding.

In the course of their free play with the red box, 12 of the 16 children (75%) manipulated each lever separately, fully disambiguating the evidence. This suggests that children's free exploratory play could, in principle, generate the type of evidence that would support causal learning.

The results from this experiment suggest that children's normative understanding of evidence and their curiosity about the causal structure underlying observed evidence play a significant role in their decision to explore. At least in simple cases, preschool children distinguish confounded and unconfounded evidence and selectively engage in more exploration when the causal structure of events is ambiguous because hypothesis are a priori equally likely and because evidence fails to strongly support only one hypothesis.

Causal Ambiguity 2 and Children's Play

Our third set of studies, (see Bonawitz, Lim, & Schulz, 2007) was designed to test the second case of causal ambiguity. In this case, one potential candidate cause is a priori much more likely then the second. However, ambiguity arises in situations where evidence strongly supports the a priori unlikely cause. To test whether such causal ambiguity affects children's play, we needed to find a domain where children already have strong prior beliefs and where they can, in principle, play to explore surprising evidence.

Because children's knowledge has been well characterized in the domain of balance and support relations, this domain is particularly conducive for investigating the relationship between children's strong prior beliefs and their exploratory play. In a seminal study, Karmiloff-Smith & Inhelder (1974) looked at children's understanding of balance between 4 and 9 years of age. The authors demonstrated that between 6 and 8 years, children entertain a "Center Theory", believing that regardless of the center of mass, an object should be balanced at its geometric center. Center Theorists repeatedly attempt to balance unevenly weighted blocks at their geometric center. Gradually, children develop the correct, adult theory of balance: "Mass Theory". Mass Theorists understand that in order for a block to be stable, it must be balanced over its center of mass. Children's understanding of balance has subsequently been investigated by many researchers (e.g. Halford et al., 2002; Siegler, 1976). However, much of this literature focuses on the transition between incorrect and correct rules and strategies and not on the processes, like exploratory play, that might generate the evidence that could support such discoveries.

To a Center Theorist, a block with a conspicuously heavy side balancing on its geometric center may not be surprising; however, this evidence should surprise a Mass Theorist. Conversely, to a Center Theorist, a block with one heavy side balancing under its center of mass might be surprising, but that evidence should not surprise a Mass Theorist. If a child sees surprising evidence of this sort, then ambiguity arises. Either the a priori likely hypothesis is correct and the data observed is very unlikely to have been generated, (the likelihood is very small), or an a priori unlikely hypothesis that strongly supports the data is true.

To investigate how children's theories affect their exploratory play, we used a method similar to the free play paradigm used in study two of this paper. We presented children with evidence about the balancing blocks and then let them choose to play freely with either the balancing blocks (the familiar toy) or a peg and ring toy (the novel toy). If children are unsurprised by the evidence about the balancing blocks, they should spend most of their time playing with the novel toy; if they are surprised by the evidence, they might overcome the novelty preference and preferentially explore the familiar toy. We predict that children who observe identical evidence but have different theories will show different patterns of exploratory play.

Fifty-seven six and seven-year-olds (range = 72 to 96mths, M = 85mths) participated. Children were then given a theory-classification task. In this task, children were presented with the three classification blocks in random order and were asked to try to balance each block on the post. We coded whether the child attempted to balance the block at its geometric center or towards the center of mass. The experimenter took hold of the block before the child actually set it on the post so children never observed the outcome of their balancing attempts. The child was then shown the 3 familiarization blue blocks, given a chance to explore the blocks for a few seconds, and was then asked to point to the heavier side of each block. Throughout the classification and familiarization trials, the novel toy was on the table, covered so as to be out of the child's view, and off to the right or left side (counterbalanced). Children were classified as Center or Mass Theorists based on where they attempted to balance the classification block on at least two of the three trials. Center balances included a 10% margin of error around the center of the block (~1 inch radius from center.) All balances towards the heavy side of the block that fell outside of this margin of error were coded as mass balances. The experimenter then randomly assigned children to either a Balance at Geometric Center condition or Balance at Center of Mass condition, (see Figure 4).

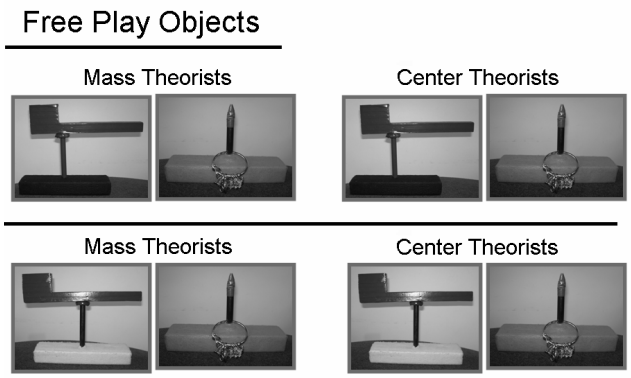

Figure 4: Method and Design of causal ambiguity case 2 experiment.

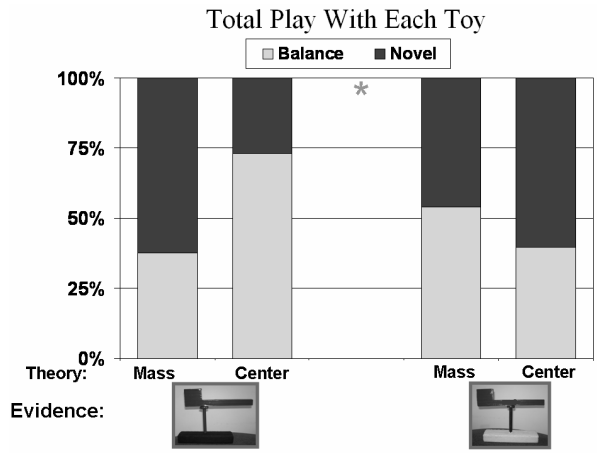

Figure 5: Results of children's play in causal ambiguity case 2 experiment.

The experimenter said, "I'm going to try to balance my block here very carefully," and 'balanced' the test block either in the geometric center of the block or over the center of mass. Then the experimenter uncovered the novel toy and told the child, "Go ahead and play with which ever toy you want until I come back." After 60 seconds of free-play, the experimenter returned to the table and covered up the novel toy. She returned the test block to its original balanced position and asked, "Why is this block staying up? How come it's not falling over?"

Based on the balancing attempts in the classification trials, 32 children were classified as Center Theorists and 22 were classified as Mass Theorists. Twelve Mass Theorists were assigned to the Center of Mass condition; 10 were assigned to the Geometric Center condition; the 32 Center theorists were evenly divided between the two conditions, (16 children in each).

Children were counted as playing with the toys as long as they were touching the toys and we coded the total amount of time each child played with each toy. We analyzed children's play by looking at how long, on average, children played with the balance block.

Children were more likely to explore the familiar toy (the block) when the evidence conflicted with their theories than when it confirmed their theories (See Figure 5). To compare the amount of time playing with the blocks, we ran a two-way-between subjects ANOVA with theory and type of evidence as the between subjects variables and time spent playing with the blocks as the dependent measure. Comparisons between conditions revealed no main effect of theory (averaging across the two conditions, Center theorists and Mass theorists played for equal amounts of time) and no main effect of evidence type (averaging across the two conditions by theory, children who saw the block balancing at the geometric center played as long as children who saw the block balancing at the center of mass). However, comparisons revealed a significant interaction: children spent more time playing with the block when the evidence conflicted with their theories than when the evidence confirmed their theories ($F(1, 53) = 5.38$, $p = .024$).

The results support the claim that in cases of causal ambiguity, children's prior beliefs and the evidence they observe shape their choices in play, suggesting that young children's spontaneous exploratory play is sensitive not just to the perceptual novelty of an object, but also to whether or not observed evidence is consistent with the child's theoretical predictions. Thus, given identical evidence, children with different theories engage in different patterns of exploration. This suggests that children's spontaneous play is not entirely unsystematic but rather, it is guided by their prior causal knowledge about the world.

Discussion

We have highlighted two conditions under which ambiguity arises: in the first case, the prior probability of multiple candidate causes is equivalent, and the likelihoods fail to further disambiguate the potential causes; in the second case, the evidence strongly favors an a priori unlikely candidate cause and disfavors an a priori likely candidate cause. If children are more motivated to explore in these cases, then they may be more likely to spontaneously generate the kinds of interventions that can help them both a) acquire more evidence to disambiguate a priori equally likely hypotheses, or even b) discover that an a priori likely causal hypothesis was in fact incorrect. This discovery lies at the heart of the claim that children's play may provide the kinds of evidence that can support conceptual change.

However, we do not want to suggest that in all cases children's free play reliably leads to accurate causal inferences. There is every reason to believe that in many contexts children's spontaneous exploratory play might not

suffice for accurate causal learning. Children might be inaccurate for many reasons: because they are unable to disambiguate the relevant variables, because they fail to disambiguate the relevant variables, or because they fail to attend sufficiently to the evidence they generate in exploratory play. Nonetheless, we do want to suggest that children's tendency, reported here, to selectively explore causally ambiguous events would be advantageous for causal learning; whether or not children learn from their explorations in any particular instance, overall, they would be more likely to investigate where there is indeed something to be learned.

What we've demonstrated supports an account of causal learning where a common rational inference process, consistent with Bayesian inference models, underlies both children's causal judgment and their exploratory play. Children's prior knowledge shapes their actions, which in turn shapes the evidence they get, which can lead to updated beliefs about the world. These feedback loops begin to give us an account of how children can learn so much about the world so quickly. Causal theories help shape the way we perceive, interpret, and act on the world; however, our actions help us gain new evidence which in turn can influence our causal theories. The exploratory play of even very young children thus appears to reflect some of the logic of scientific inquiry.

References

Ahn, W., Kalish, C.W., Medin, D.L., Gelman, S.A., 1995. The role of covariation versus mechanism information in causal attribution. Cognition 54, 299–352.

Bonawitz, E.B., Griffiths, T.L., & Schulz, L. (2006) Modeling Cross-Domain Caussal Learning in Preschoolers as Bayesian Inference. *Proceedings of the 28th Annual conference of the Cognitive Science Society.* Vancouver, Canada.

Bonawitz, E.B., Lim, S., & Schulz, L. (2007) Weighing the Evidence: Children's theories of Balance affect play. Proceedings of the Twenty-Ninth Annual Conference of the Cognitive Science Society. Nashville, Tennessee.

Bruner, J., Jolly, A., & Sylva, K. (1976). *Play-Its Role in Development and Evolution.* New York: Basic Books, Inc.

Bullock, M., Gelman, R., & Baillargeon, R. (1982) The development of causal reasoning. In W.J. Freidman (Ed.), *The developmental psychology of time* (pp.209-254). New York: Academic Press.

Carey, S. (1985). *Conceptual change in childhood.* Cambridge, MA: MIT Press/Bradford Books.

Carey, S., & Spelke, E. (1994). Domain-speciªc knowledge and conceptual change. In L. A. Hirschfeld & S. A. Gelman (Eds.), *Mapping the mind: Domain speciªcity in cognition and culture* (pp. 169–200). New York: Cambridge University Press.

Chen, Z. & Klahr, D. (1999). All other things being equal: Acquisition and transfer of the control of variables strategy. *Child Development, 70*(5), 1098-1120.

Estes, D., Wellman, H.M., & Woolley, J.D. (1989) Children's understanding of mental phenomena. In H. Reese (Ed.), *Advances in child development and behavior*. New York: Academic Press.

Gelman, S.A., & Wellman, H.M. (1991) Insides and Essence: Early Understandings of the Nonobvious. *Cognition, 38*(3), 213-244.

Gopnik, A., & Meltzoff, A. (1997). *Words, thoughts and theories*. Cambridge, MA: MIT Press.

Halford, G.S., Andrews, G., Dalton, C., Boag, C., & Zielinski, T. (2002) Young children's performance on the balance scale: The influence of relational complexity. *Journal of Experimental Child Pscychology, 81,* 417-445.

Hatano, G., & Inagaki, K. (1994) Young children's naïve theory of biology. *Cognition*, *50*, 171-188.

Inhelder, B. & Piaget, J. (1958). *The growth of logical thinking from childhood to adolescence.* New York: Basic Books.

Kalish, C. (1996) Causes and symptoms in preschoolers' conceptions of illness. *Child Development*, *67*(4), 1647-1670.

Karmiloff-Smith, A., & Inhelder, B. 1974, If you want to get ahead, get a theory. *Cognition, 3*(3), p. 195-212.

Keil, F.C. (1989) *Concepts, kinds, and cognitive development.* Cambridge, MA: MIT Press.

Keil, F.C. (1995). The growth of causal understandings of natural kinds. In D. Sperber & D. Premack (Eds.), *Causal cognition: A multidisciplinary debate. Symposia of the Fyssen Foundation.*. New York: Clarendon Press/Oxford University Press.

Kuhn, D. (1989). Children and adults as intuitive scientists. *Psychological Review, 96*(4), 674-689.

Notaro, P.C., Gelman, S., & Zimmerman, M.A. (2001) Children's Understanding of Psychgenic Bodily Reactions, *Child Development 72(2),* 444-459.

Pearl, J. (2000). *Causality: models, reasoning, and inference*. Cambridge University Press.

Piaget, J. (1930). *The child's conception of physical causality*. New York: Harcourt, Brace & Company.

Schulz, L., & Bonawitz, E.B. (in press), Serious fun: Preschoolers play more when evidence is confounded. *Developmental Psychology.*

Schulz, L., Bonawitz, E.B., & Griffiths, T. (in press) Can being scared give you a tummy ache? Naive theories, ambiguous evidence and preschoolers' causal inferences. *Developmental Psychology.*

Schulz, L. E. & Gopnik, A. (2004). Causal learning across domains, *Developmental Psychology, 40*(2), 162-176.

Shultz, T.R. (1982). Rules of causal attribution. *Monographs of the Society for Research in Child Development, 47*(1), 1-51.

Siegler, R.S. (1976) Three aspects of cognitive development. *Cognitive Psychology, 8,* 481-520.

Singer, D. G. , Golinkoff, M. R., & Hirsh-Pasek, K. (2006). *Play = Learning: How play motivates and enhances children's cognitive and social-emotional growth.* New York: Oxford University Press.

Spirtes, P., Glymour, C., and Scheines, R. (1993) *Causation, Prediction, and Search*, Springer-Verlag, New York.

Tenenbaum, J.B., Griffiths, T. L., and Niyogi, S. (2007). Intuitive theories as grammars for causal inferences. Gopnik, A., & Schulz, L. (Eds.), *Causal learning: Psychology, philosophy, and computation.* Oxford University Press.

Tenenbaum, J.B. and Niyogi, S. (2003). Learning Causal Laws. *Proceedings of the Twenty-Fifth Annual Conference of the Cognitive Science Society.*

Wellman, H. (1990). *The Child's theory of mind.* Cambridge, MA: MIT Press.