Choosing to Learn:

Evidence evaluation for active learning and teaching in early childhood

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Abstract

Choosing to take certain actions has direct consequences for learning. Do children tend to choose actions that support learning? We present research suggesting that before reaching kindergarten, children demonstrate proficiency in active learning that cannot be accounted for by simple heuristics for decision-making. Instead, children's choices reveal a sophisticated ability to evaluate evidence (computing information gained by particular actions); potential evidence is compared to other possible rewards and costs associated with actions. This early emerging ability to select evidence underpins informal teaching of, and reasoning about, others. Specifically, we discuss recent empirical work demonstrating that preschool-aged children are able to evaluate potential evidence to support their own learning, another's learning, and that they can even evaluate a teacher's evidential selection for a third party's learning.

Socrates gives us a fairly disturbing hypothetical to describe the problem of induction: Consider the underground den described in Plato's Republic (Jowett, 1941), in which humans are chained from childhood, seeing "*only their own shadows, which the fire throws on the opposite wall of the cave... To them truth would be literally nothing but the shadows of the images.*" Socrates is explaining that we can never be sure about the truth of the world. It

is an important problem to be sure, but lucky for us, we have tools to lessen (albeit not eliminate) our uncertainties. We are not restrained, passive observers from birth. Unlike Socrates' prisoners, we are equipped with the ability to choose. We can select what we want to attend to, we can pick our favorite people to emulate, we can decide to play with one toy or another; we can look, we can ask, and we can act. Most importantly, in action we reap the benefits of effects. We see events, we are told truths, and we observe outcomes. This gathering of evidence – that we ourselves cause – connects us to the world behind the shadows. It enriches our knowledge in ways beyond Socrates's passive learners. It is thus an important factor to insert into the Piagetian constructivist circle (1954): we see and are curious, *we choose to act*, we observe evidence, we revise beliefs, we see anew.

Why one initially chooses to act to learn is an important question for us constructivists. This choice, curiosity, is perhaps one of the longest studied and yet least well understood aspects of psychology. Part of the problem in studying curiosity is that, as Berlyne suggested (1978) it defines both the need to satiate specific knowledge ("where did my daughter hide my shoes this morning?") and diversive knowledge ("reading further will keep me from feeling bored"); it includes both perceptual stimuli ("what was that sudden flash I noticed out of the corner of my eye?") and the epistemic ("how can I learn more about black holes?"). Researchers appear to contradict each other attempting to specify the drives to resolve curiosity: on the one hand we are curious because we want to resolve the unpleasurable, aversive state caused by lack of coherence (as with the Information Gap Model, Loewenstein, 1994); on the other hand, curiosity is driven by the pleasurable, satisfying experience of learning (Spielberger & Starr, 1994; or, as with

“Explanation as Orgasm”; Gopnik, 2000). Its role in cognition has been argued to be fundamental to numerous factors including creativity (Csikszentmihalyi, 1996; Day & Langevin, 1969), emotional intelligence (Leonard & Harvey, 2007; Penney, 1965), and learning (Stahl & Feigenson 2015; 2017; Jirout & Klahr, 2012). It seems a hopeless endeavor to characterize the trait, and certainly beyond what any reasonable person would undertake pre-tenure. It would be hubristic at best, and likely plain foolish to attempt to tackle such a large topic.

With this in mind, perhaps you will forgive us for instead focusing on *how* one chooses to act. The “why” and “how” of choosing to act may seem entangled, but here we will attempt to disentangle, by focusing on how children decide what, among many options, they should attend to, ask about, or intervene on. This choice is itself a multifaceted decision. It requires considering what options exist, what evidence is possible, and which, among these possibilities will be most rewarding.

Are children “active learners” in the sense that they tend to make good choices when considering the options, evidence, and rewards? Consider the complexity of the world. There are potentially infinite options to consider, each with many possible outcomes, and a plethora of costs and rewards that may play into each action. In such a world, even random actions may lead to learning, but an active learner – one who wishes to exhibit some meaningful control over her environment – *evaluates* these options. She must predict the possible outcomes of actions and consider the consequent pros and cons of each.

A learner who can perform these evaluations can choose between evidential options for themselves, whether in choosing to explore particular events over other events or in

choosing to approach particular informants over other informants. But, she may also be able to choose between evidential options to teach others. Teaching requires recognizing the evidential needs of others, to get a learner from one stage of knowledge to another. Thus, the ability to select evidence to teach others may emerge as a result of the ability to select evidence to explore for one's self.

Finally, a learner who can perform these kinds of evaluations may even be able to use this evidential reasoning ability to evaluate the teaching of another. That is, she may be able to recognize the knowledge lacking in others. She might then understand what evidence is needed to support learning as well as what evidence is available to the teacher. Finally, she may reconcile all of this information to evaluate whether the teacher has performed well – given the needs of the learner and the resources of the teacher.

Here we will describe some recent studies in developmental psychology that investigate evidential reasoning abilities. These studies will support the claim that children are thoughtful, active learners and teachers. Before reaching school, young learners consider possible opportunities for evidence, and choose options that are likely to lead to learning. Preschoolers can also choose between evidential options when teaching others. And, they can even apply this ability in their evaluations of others' teaching. That these skills are so early emerging supports a story in which we are built for learning. Our evidential reasoning abilities may emerge because we are optimally designed to make informative exploratory choices to support learning and teaching.

Evidence selection in choosing to explore

A simple view of choosing to learn suggests that pursuing novel or surprising events

is sufficient for a theory of learning in early childhood. But, what remains lacking in this simplified view is that in any environment, myriad actions are possible for the learner. Novel and surprising events are only a draw with respect to some other alternative. Given this, any agent who acts on the world to learn must be able to weigh these many actions and evaluate their potential. There is something to be learned by almost any action, so to understand *how* one chooses to learn, we must consider that the child performs a kind of utility calculus over possible choices. Schulz and Bonawitz (2007) have shown that children will overcome a novelty preference to play more with the familiar toy if information about the family toy is confounded. Bonawitz, van Schijndel, Friel, & Schulz (2012) have found that children also forgo novelty when there are opportunities for learning from events that are surprising with respect to beliefs. Under a naïve theory of curiosity-driven learning, we would have no way to predict how children would trade-off the choice of a novel toy with a familiar but confounded or surprising one. To predict these results, a complete theory of active learning must include expectations about the learning opportunities that could arise with either choice (discovering a new toy verses the possibility that new actions with the familiar toy will generate meaningful evidence), as well as other learning utilities (such as whether one toy will need to be mastered later for some reason), and other rewards (such as whether one toy is “simply” more appealing, flashy, exciting).

A further consideration for active learning is that not all opportunities for learning are ideal. It might not be surprising to imagine a learner who shows little interest in simple events that have been mastered. But this does not mean a learner should always favor the

“richer” events. Information can quickly become overwhelming; events can become too complicated to be useful to support learning. Indeed, work by Kidd and others (2012) has found that, beyond factors of novelty or familiarity, children’s visual attention behavior is sensitive to differences in information content. Infants preferentially look away from very simple, high probability events. However, infants also look away from very complex, low probability events that offer little or hard-to-obtain information. Instead, infants prefer events that are neither too simple nor too complex; they go for a Goldilocks sweet-spot for information gathering (Kidd et al., 2012). This finding suggests that direction of visual attention (and auditory, see Kidd et al., 2014) is not just an indiscriminate response to stimuli salience or novelty, but is dependent on the probability of being able to learn from the complexity of information.

Another point to be clarified in a theory of children’s active learning is how a learner decides between whether to learn (e.g., explore something new) or whether to exploit a known reward. A curiosity driven model of choice might be predicted to always favor the novel options over known rewards, but surprisingly this does not seem to be the case for children in early childhood. For example, in one set of studies in our lab (Lapidow & Bonawitz, in review) we suggest that, despite the preference for novel and uncertain outcomes, children as young as four choose *not* to explore in contexts where there is not good reason to do so. Our task took the form of a game, in which preschoolers (age range: 48 to 68 months) tried to collect marbles by selecting and revealing boxes from different ‘sets’; (See Figure 1a). All the boxes in a set were identical in appearance, and every set had a different appearance and distribution of average amounts of marbles that were in each

box. (Rather than actually containing different amounts of marbles, boxes had arrangements of black dots drawn inside them, which children understood corresponded to the amounts of marbles they would be given by the experimenter.) On each trial, the experimenter brought up one set of boxes and selected one box from it at random. Children were then given a choice between selecting (and thereby revealing) the contents of this unknown box or a known box, which had a different appearance from the set and was presented open to show the number of marbles inside. Thus, children were repeatedly given a choice between exploring to reveal new information, or avoiding uncertainty by selecting an already known outcome.

Figure 1. Task designs for Studies 1, 2, and 3 in Lapidow & Bonawitz (in review). In Study 1 (A.), on each trial, a closed box is drawn at random from one of five sets of six identical boxes. In Study 2 (B.), the contents of all eight boxes in one of the ten sets of identical boxes are shown to participants, then the boxes are closed, mixed, and one is drawn at random from the set. In Study 3 (C.), one set of boxes is known to contain exactly two dots in each and the other set's contents are unknown. On each trial, one box is drawn from the 'known' set and opened, and one box is drawn from the 'unknown' set and remains closed.

If children simply always favor novel over known options, then we would expect to see them choose the unknown box on the majority of task trials because it offers the opportunity for novel information. However, this choice was presented in a context where children could form no expectations about the possible outcomes of the unknown box (as they had no prior information about the contents of any of the sets). Furthermore, children had no way of applying their learning about the task to future choices so there was no utility in the information gained (the contents of selected, unknown boxes, were only revealed after the end of the game). Under these conditions, children showed an “ambiguity aversion” and *avoided* the novel box, preferring instead to stick with the known reward (64% of the trials; $p = 0.04$).

We conducted a second study to investigate whether children can compute expected values of rewards and use this information in their exploratory decisions. The procedure of the task was identical to the one described above, except that participants were first shown the contents of the sets of boxes. Then, a box was randomly sampled from this set; (See Figure 1b). Although children could not see the value of the particular box that was chosen, because they were provided with information about the overall distribution of possible outcomes, a savvy chooser could compute an expected value to this unknown box. Thus, if children’s exploratory choices incorporate probabilistic expectations of this sort, we might expect children to choose the definitively known box when the expected value of the sampled box is lower, but for this pattern to flip as the expected value of the unknown box becomes larger.

To test whether children considered the expected value, we varied the distributions

of rewards in each set, such that the ratio of the reward in the known box to the expected value of the reward in the unknown box included a range, 1:4, 1:2, 1:1, 2:1, and 4:1. Each ratio was tested twice, with a different set with different exact amounts inside the boxes used each time. There was a significant overall correlation between the ratio of known to unknown reward and choices to explore ($r = .88$, $t = 3.21$, $p < .05$), as well as significantly different choice behavior at the lowest and highest ratios ($p = 0.008$). Children chose to explore least often (42% of choices) when the expected value of the unknown was smaller than the value of the known amount (1:4), and they explored most often (69% of choices) when the expected value of the unknown box was higher than the value of the known amount (4:1). Thus, children appear able to compute and consider expected rewards when choosing whether to explore.

Our final question in this line of studies was whether children were more likely to explore unknown rewards, when learning about these rewards could be useful for later decision-making. That is, we provided children with a positive utility for learning about the boxes. In this study, we again presented children with the choice of revealing new information or selecting a known amount. However, in this version of the task we used two sets of boxes on each trial: a known set, for which participants are told and shown that all boxes contain the same amount; and an unknown set, for which the amounts are unknown (See Figure 1c). Then, on each trial, the known and unknown options were drawn, apparently at random, from these sets. Our question pertained to understanding the conditions that might encourage children to overcome an ambiguity aversion (as demonstrated in the first study) to explore the unknown boxes.

Children were tested in one of three conditions that differed in whether the sets remained consistent across the task and in when unknown boxes would be revealed if selected. The No-Feedback condition used the same two sets of known and unknown boxes on each trial of the task, but if an unknown box was selected, it was not revealed until after the game was over. Thus, learners would not gain any information about the contents of unknown boxes until after such knowledge would be useful. In the Feedback-Switch condition, the contents of the selected unknown box would be revealed immediately (so children would receive the immediate satisfaction of learning about the contents of the selected box); however, we changed the sets of boxes (each with different possible distributions) after every trial of the task. Thus, learning the contents of a particular box (and thus something about the set from which it was drawn) would not provide any utility for future decisions because it would not provide information about the new set used in the next trial. Finally, in the Feedback-Stay condition, the rewards in selected boxes were revealed immediately and the same set of boxes was drawn from repeatedly. Thus, in this condition, children would have the opportunity to learn about the competing distribution if they selected it, which would have the benefit of future decision-making about the two sets. Therefore, children in all three conditions were given a choice between exploring by revealing an unknown outcome or obtaining a reward of a known amount, but whether exploration could lead to meaningful information gain was varied.

Results revealed sophisticated reasoning in preschoolers' explore-exploit decisions. Most children did not explore in the No-Feedback condition (40.7%) replicating the ambiguity aversion results found in Study 1. Exploratory choices were slightly higher for

children in the Feedback-Switch condition (53.7%), presumably because receiving a little bit of feedback about past decisions is intrinsically rewarding. Critically, however, children in the Feedback-Stay condition choose to explore a whopping 76.8% of the time, significantly more than children in the No-Feedback ($p < 0.001$) and Feedback-Switch ($p < 0.001$) conditions. Children chose to explore significantly more when there was a potential to gain useful information that would increase their knowledge and allow them to make more informed decisions for future exploratory choices.

Children's exploratory choices thus depend on more than simple novelty or familiarity biases. Instead, children weigh multiple factors. Their choices depend on the degree to which there is uncertainty (such as that caused by confounding or by events that are belief violating), the degree of complexity in the stimulus, whether there are known rewards and unknown risks, the expected reward value of an action, and whether the information to be gained by exploring will be useful for later decision making.

Evidence selection in choosing informants

So far we have suggested that we must extend beyond a simplified account of active learning that only considers novelty or familiarity. Instead, children appear to come equipped to evaluate myriad factors when considering what to learn about. Of course, children are not left alone to explore the world without feedback from parents and peers. They are surrounded by other people who themselves may be sources of information. Thus, a child who weighs opportunities for information must also be able to consider informants; she must be able to reason about the pedagogical goals, intentions, and knowledge state of others to effectively extract information from her interactions with others.

Indeed, children are well equipped to reason about others' mental states in guiding their learning. For example, Bonawitz, Shafto et al. (2011) showed children a novel toy with many interesting pieces (knobs, tubes, buttons) that might afford an interesting event (perhaps squeaking, lighting up, or making music). In one condition children were given strong pedagogical cues and told, "this is how my toy works" as the demonstrator pulled a tube out and caused the toy to squeak. In another condition children were shown the same outcome (the tube causing the toy to squeak) but the event happened accidentally. What should children infer about the number of possible additional causes in the toy? Although one event has been demonstrated, there is uncertainty pertaining to whether (and how many) remaining causal properties the toy has. In the accidental condition, children explored the toy broadly suggesting that they believed the toy was likely to have additional properties. In contrast, children in the pedagogical condition constrained their exploration to the pedagogically demonstrated function; this less variable play suggests that children believed that there was likely only one causal property (the demonstrated squeaking event). Thus, children were sensitive to whether information was presented by a knowledgeable, helpful other, with the intention to teach (as in the pedagogical condition) and used this information to shape their exploration.

Children can also use another's mental states and goals to discern whether questions are being asked for the purposes of teaching (as in "pedagogical questions"; Yu, Bonawitz, & Shafto, 2017) or merely whether questions are being posed for the purposes of seeking information. For example, in a study much like the novel toy study described above, Yu et al. (in review) asked children about the to be discovered toy with the question

“What does this button do?” Importantly, in one condition, the person asking was known to be knowledgeable about how the toy worked, but in another condition, the person asking was ignorant about the toy’s functions. In both conditions, children explored the toy more variably than when the same information was presented as a direct instruction. However, children were significantly more likely to discover and correctly repeat the target, queried function in the knowledgeable condition, than in the ignorant condition. These results suggest that even when evaluating the questions of another person, children can consider the knowledge state of the questioner and use this information to guide their exploratory choices.

This social savvy reasoning also helps to explain why children sometimes change their minds when faced with repeated questioning (e.g. Krahenbuhl, Blades, & Eiser, 2009). Bonawitz et al. (in revision; see also Gonzalez, Shafto, Bonawitz, & Gopnik 2012) have suggested that this switching behavior can be a rational inference, if the repeated questioning is taken as a cue to the correct answer. Critically, this inference depends on the knowledge of the questioner. Across several studies, Bonawitz et al. (in revision) found that when the questioner was shown to be knowledgeable about the answer on a task where children had uncertainty about the correct answer, children were likely to switch responses following a neutral prompt (“are you sure?”). However, when the questioner was known to be ignorant of the correct answer, this switching pattern was significantly reduced. These results further demonstrate the power of children’s reasoning about others’ intentions in guiding their decision-making. Indeed, a growing body of research has demonstrated that the inferences of even very young children depend on their assumptions

about another's intentions while generating evidence (Gweon, Tenenbaum, & Schulz, 2010; Wellman et al., 2016).

Taken together, these studies demonstrate that children are sensitive to the knowledge state of others in guiding their inferences, but they do not speak to whether children *choose among informants as possible sources of information*. That is, being guided in your exploratory choices because a knowledgeable other shapes your goals is certainly a prevalent part of childhood learning. However, it does not speak to whether children are active choosers in these processes. One possibility is that children *seek out* information differentially, depending on the assumptions about another's knowledge.

Do children create opportunities for learning by seeking out these knowledgeable and helpful informants? Conversation with knowledgeable and fully fluent adults may provide opportunities to gain information, both by directly asking questions and by eliciting feedback or correction. Ongoing research in our lab is looking at spontaneous speech in preschool children, aged three- to five-years-old, to see whether there are systematic differences in their speech, depending on the target of the conversation. Specifically, our hypothesis is that children may be more likely to seek out information and produce opportunities for feedback when speaking with knowledgeable adults than when speaking to other (less knowledgeable) children or when speaking aloud to themselves.

Using a clip-on microphone recorder, individual preschooler's spontaneous speech productions were recorded in 40-minute sessions during the school day. During the recording, an experimenter observed the child and recorded their visible behaviors and interactions with other individuals in the classroom. Recordings were then transcribed,

pairing speech productions (including grammatical errors) of the participant with their actions and, critically, their speech partners – whether the child was speaking to an adult, another child, or themselves. This allowed us to explore whether particular kinds of speech acts by children are more likely depending on the target of their conversation.

Our preliminary analysis has thus looked at whether there are differences in both direct and indirect information seeking behaviors, depending upon speech-partner type (self, other children, adults). So far, our results show that although children spend roughly equal amounts of time speaking to each of the three groups, questions take up a greater proportion of children's adult-directed speech than it does for other groups. Question-asking made up 21.7% of adult-directed speech, compared to only 10.1% for other children ($p < 0.004$) and 4.5% for self ($p < 0.001$). This initial result supports the idea that children might be more likely to seek out information from individuals that are more likely to be knowledgeable. Thus, although past work has demonstrated that children ask abundant questions in early childhood (Callanan & Oakes, 1992; Chouinard, 2007), and that older children can use principles such as information gain to effectively choose which questions to ask (Ruggeri et al., 2016), this preliminary data provides tentative support for the claim that children also consider *who to ask* discriminately.

In our transcribing analysis, we also looked for a second, and more subtle effect of speaker directed language. In early childhood, as grammatical rules are learned, children enter a period where regular grammatical patterns are incorrectly extended to irregular verbs (e.g. Marcus et al., 1992). An active learner might attempt to produce these constructions more often around speech partners that are likely to be able to provide

feedback for uncertain irregulars. Furthermore, if errors in irregular verb construction reflect failed memory traces (e.g., Pinker & Ullman, 2002), then we might observe more errors on irregular constructions around adults because children may not “work as hard” in selecting correct conjugations in conversation with speakers who could provide feedback if errors are made. Thus, we predicted that children would produce more irregular-conjugation errors around adults, rather than around other children. Indeed, in our initial analysis, children produce more of these errors in speech to adults than to other children ($p = 0.007$). Thus, while children directed the same amount of speech to each of the three speech partners, adult-directed speech contained the majority of their conjugation errors and questions, suggesting both direct and indirect efforts of information seeking in the verbal behavior of young children.

Past research has provided evidence for the claim that children are able to reason about the knowledge state and intentions of others in guiding exploration (e.g. Bonawitz, Shafto et al., 2011). However, this recent preliminary research suggests that children are not only being guided by these inferences about others, but also that they use this knowledge to decide from whom to choose to learn. Children can evaluate the potential information sources of both objects and people in their decision-making. When exploring events, they consider the information and reward from possible choices; when querying others, they consider the information another person may provide by considering their expertise.

Evidence selection in teaching

We have suggested that children are active learners in the sense that they evaluate possible opportunities for acquiring evidence and then make choices that support learning. This ability to evaluate evidence and distinguish helpful from unhelpful information may be critical for young children's learning. Indeed, evidential reasoning skills emerge early in development (Bonawitz, Fischer, & Schulz, 2012; Koerber et al., 2005), and even infants understand that certain evidence may be more useful to different people (Knudsen & Liskowski, 2012; Liskowski, Carpenter, & Tomasello, 2008).

However, just because children appear to effectively evaluate evidence in the service of their own learning, does not mean they apply this evidential reasoning in the service of teaching another. Nonetheless, children appear to be highly sensitive to the special role of evidence selection in pedagogy. For example, six-year-olds select diverse samples to teach a novel concept to a peer, but not to learn that concept for themselves (Rhodes, Gelman, & Brickman, 2010). Further, Rhodes, Bonawitz, Shafto, Chen, & Caglar (2015) found that even preschoolers are capable of selecting evidence to communicate different pedagogical goals, even when the goal is to lead a learner to a *false* conclusion. Rhodes et al. (2015) showed three- to six-year-olds a novel toy that activated when any block was placed on it. They then asked children to pick two blocks to either 1) teach a naïve puppet how the toy really worked, or 2) trick her into thinking that only red blocks made it go. Children reliably selected blocks that would best communicate the pedagogical goal, regardless of whether the goal was to teach or to deceive. Even young children thus appear to be acutely aware how pedagogical sampling can constrain learners' inferences, and tailor their evidence selection to specific pedagogical goals.

Are a learner's knowledge and beliefs also used to guide young children's evidential demonstrations? In one set of studies (Bass et al., in review), we investigated this question within a group of three- and four-year-olds. Children were first shown a novel toy, and learned that it activated any time a red block was placed on top of it. Then, children showed two confederates (one at a time) how to use the toy. Each confederate saw just one of two red blocks (square or circle) activate the toy, after which they voiced either a false belief about the toy's causal mechanism ("I see, square/circle blocks make the toy go!"), or a true belief ("Red blocks make the toy go!"); see Figure 2. After ensuring that children understood the confederates' beliefs, one of the two confederates returned to the room; both red blocks (square and circle) were placed on the toy simultaneously, the toy activated, and the confederate asked, "Huh, why did that happen?", ambiguously referencing one of the two blocks (see also Legare, Gelman, & Wellman, 2010 for a similar method). Children were asked to point to just one of the two blocks and explain why the toy activated. If children are using the confederate's false belief to guide their evidence selection, they should point to the shape that the confederate did not see, because that evidence contradicts (and may thus rectify) the confederate's false belief. In contrast, if the confederate has a true belief, children should point at either block at chance rates, since there is no false belief to rectify.

We found that 75% of four-year-olds in the False-Belief condition ($N = 20$) pointed to the block that the confederate had not seen (which differed significantly from chance, $p = .041$), while only 50% of three-year-olds in the False-Belief condition did so ($N = 20$; $p = 1.0$). Further, only 45% of four-year-olds in the True-Belief condition ($N = 20$) provided

contradictory evidence ($p = .824$), significantly fewer than four-year-olds in the False-Belief condition ($\chi^2, p = .027$), suggesting that older preschoolers were not simply pointing to the block that the confederate did not see, but rather tailoring their evidence selection to their learner's beliefs. (See Figure 3 for summary of results.) Therefore, while all children successfully *tracked* the confederate's beliefs, only the older preschoolers used the confederate's incorrect beliefs to guide their subsequent evidential demonstrations.

Figure 2. Children first learned the true causal rule of the toy (red blocks make it go). Then, children showed two confederates that red blocks of different shapes activated the toy; confederates formed either false or true beliefs based on this evidence. In the test trial, children showed one of the confederates that both red blocks made the toy go, and then pointed to one block and explained why the toy activated.

These results suggest that the development of Theory of Mind (ToM) is closely related to pedagogical evidence selection. To examine this relationship, we (Bass et al., in review) ran a second experiment asking whether preschoolers with more proficient false-belief understanding would be better at pedagogical evidence selection, and also whether

training pedagogical skill might improve ToM abilities. We assessed children's ToM understanding (Wellman & Liu, 2004) on a preliminary testing day, and compared their performance on two teaching tasks. Children who failed the false-belief battery (i.e., scored 0 or 1 out of 3 points) were either trained on the two pedagogical tasks for 6 weeks beginning on the preliminary testing day (training condition; $N = 22$) or given a 6-week delay (control condition; $N = 18$), after which their false-belief understanding was reassessed. Children who passed the false-belief battery ($N = 21$) completed each pedagogical task just once on the preliminary testing day. We also assessed children's performance on a numerical conservation task as a control measure of more general cognitive development.

Figure 3. From Bass et al. (in review). The proportion of three-year-olds and four-year-olds in the False-Belief and True-Belief conditions who pointed to the block that the confederate had not seen. Only four-year-olds in the False-Belief condition pointed to the block that the confederate had not seen more often than would be expected by chance (50%). Asterisks denote significant group differences at the $p < .05$ level, one-tailed; tildes represent significance at the $p < .10$ level, one-tailed.

Both pedagogical tasks required children to select evidence to lead a naïve learner to a correct target hypothesis. In the novel word task, a novel word represented a target concept (e.g., “Dax means fork.”), which children had to teach to a confederate by presenting pictures that did and did not represent the novel word, without explicitly saying what the word meant. In the causal toy task, a causal toy activated when some combination of its two mechanisms were operated, and children demonstrated to a confederate which combinations of mechanisms did and did need to be operated to make the toy go. The number of prompts children required before providing necessary and sufficient evidence was the primary measure for both tasks, with fewer prompts representing more advanced pedagogical skill.

We first asked whether false-belief understanding at pre-test predicted children’s performance on the pedagogical tasks on the preliminary testing day (i.e., prior to any training). As we predicted, children who passed the false-belief battery at pre-test provided necessary and sufficient evidence with significantly fewer prompts than those who had failed the battery, $t(41)=2.38, p = .022$. This effect was driven by differences in performance on the causal toy task ($t(41)=3.17, p = .003$), which persisted when controlling for age ($p = .018$) and numerical conservation scores ($p = .004$), suggesting that ToM is directly related to the ability to select evidence in the service of teaching.

To evaluate the effect of training pedagogical skill on ToM understanding, we compared false-belief failers in the training condition to those in the control condition on false-belief improvement from pre- to post-test. Looking only at failers who had the most room for improvement (i.e., those who answered zero false-belief questions correctly at

pre-test), we observed improved false-belief understanding for children in the training condition ($M_{\text{improve}}=.19$, $SD=.26$; $t(11)=2.55$, $p = .027$), but not for children in the control condition ($M_{\text{improve}}=.08$; $p = .170$). Importantly, conservation scores did not differ for either group between pre- and post-test ($p's \geq .197$), suggesting that the pedagogical training targeted ToM without necessarily leading to general improvement in cognitive reasoning.

Overall, we found evidence for a meaningful relationship between children's capacity to reason about others' minds and the ability to select optimal evidence to teach others. Young children are thus not only able to evaluate evidence to decide when to explore and learn for themselves (e.g., Lapidow & Bonawitz, in review); they also reason about what kinds of evidence would be useful in teaching another. Our findings also tie into prior work that has observed children's sensitivity to others' knowledge states when using their questions to guide exploratory choices (Yu et al., 2017), suggesting that reasoning about others' minds may be manifest in many distinct aspects of evidential reasoning. Children thus draw from many sources in their environments, including the minds of others, to form rich representations of the utility of evidence for learning.

Evaluating other's evidence selection

Children are sensitive to the quality of evidence when learning from events and consider evidence when helping others learn. Do they also make inferences about the quality of information when reasoning about the effectiveness of potential informants? As discussed above, children implicitly use another's knowledge state to guide their actions (Bonawitz, Shafto, et al., 2011), and may even use this knowledge to guide the kinds of information they seek from and present to differently skilled others. Furthermore, children

are sensitive to how evidence is presented by others. For example, children avoid learning from informants who provide inaccurate information (Jaswal & Neely, 2006; Koenig, Clément, & Harris, 2004; Pasquini et al., 2007); and, children prefer to learn from informants who have provided fully informative evidence, instead of those who have omitted relevant information (Gweon et al., 2014; Gweon & Asaba, in press).

However, it remains an open question as to whether children can explicitly evaluate another teacher, based on the constraints the teacher faces and how they select evidence for another given these constraints. This kind of reasoning may be more complicated than reasoning about evidence for one's own exploration or even than reasoning about evidence to help teach another. To reason about a teacher's ability to select evidence for another, one must be able to suppress one's own knowledge while reasoning about the ideal evidence given the teacher and learner's beliefs. Furthermore, rather than potentially implicit responses to evidence and stimuli, evaluating another's actions requires at least some explicit representations of these factors. Nonetheless, given the importance of evidential reasoning and natural pedagogy in early childhood, it may be the case that even young children can make informed decisions about both the resources available to the teacher and the effectiveness of selected evidence for teaching another.

Recent work from our lab (Bass, Bonawitz, & Gweon, 2017) explored the nuance of children's evaluations of under-informative teachers. We familiarized preschool-aged children with a novel toy with four functions. Then, children watched videos of different teachers first exploring the toy, and then teaching some subset of what they had discovered to a naïve learner. The number of functions the teacher discovered and taught in these

videos was systematically varied. After watching each video, children rated the teacher on a 20-point scale.

We found that children rated a teacher higher if they had demonstrated two of the toy's functions instead of just one ($p=.019$). Children were thus sensitive to the *degree* of a teacher's omission, suggesting that children have a nuanced understanding of precisely how helpful different sets of evidence are. Surprisingly, we also found that children were sensitive to the informant's epistemic state: Relative to an informant who had discovered all four functions and taught just one (thereby omitting three of the four functions she knew), children exonerated an informant who had discovered just one function and taught it, thus teaching everything she knew ($p= .017$). Although both of these teachers taught identical information, children were willing to pardon under-informative pedagogy when it could be explained by a teacher's limited knowledge. Therefore, while preschoolers are only just beginning to reason explicitly about others' minds (e.g., Wellman, Cross, & Watson; Wellman & Liu, 2004), they are able to integrate a teacher's mental state into their evaluation of her quality. These findings suggest that children use the quality of evidence to make highly nuanced inferences about others' efficacy as teachers, and that the ability to reason about others' knowledge may play an important role in children's evidential reasoning.

Together, the work discussed here suggests that young children are able to reason fluidly and comprehensively about the quality of evidence, both as learners evaluating the source of that evidence, and as teachers sampling evidence for others. This finding is particularly striking when considering that children must be able to withhold their own

beliefs to evaluate the best evidence provided by another for a third party. However, this ability may derive from a core drive to understand the world by evaluating evidence to support exploratory decision making and learning from others.

Final remarks

Perhaps it is shocking that after a mere 1000 days or so on the planet children are not only able to evaluate and choose between exploratory learning opportunities but also reason about the evidence required to help another learn and to apply this reasoning to evaluate the likely effectiveness of teachers. Yet, it is also difficult to see how else a learning agent that meets the high bar of human intelligence could be designed. Given the complexity of our environment and the nearly infinite opportunities for exploration, an intelligent being must have some ability to evaluate options and choose the paths with greatest opportunities. Exploratory diligence provides well-timed evidence to support learning. Whether it be an optimal intervention or an ideal inquiry, children who control their actions appear to be well served by their choices. Furthermore, we are all served by the cognitive ratcheting effect that comes from our ability to apply evidential reasoning when teaching.

The results of particularly precocious evidential reasoning described here, seem to stand in conflict with another line of research: In scientific reasoning tasks children often have great difficulty designing informative interventions to learn about variables and their causes (e.g., Kuhn & Phelps, 1982; Kuhn, Amsel, & O'Loughlin, 1988; Dunbar & Klahr, 1989; Kuhn, 1989). How might we reconcile the idea that children are sophisticated drivers of their own discovery with the fact that scientific inquiry skills are so elusive? One answer is

that whether children are metacognitively able to plan careful experiments does not preclude happenstance learning from your own interventions. Children indeed perform informative, deconfounding interventions during their spontaneous exploratory play after seeing both confounded (Cook, Goodman, & Schulz, 2011) and contradicting (van Schijndel, Visser, van Bers, & Raijmakers, 2015) evidence. Nonetheless, that children can apply these abilities in evidential selection for teaching, yet not necessarily apply these abilities to formal scientific practice, remains a puzzle. A valuable enterprise might utilize the implicit proclivities described here to support other skills such as explicit scientific reasoning.

Another important open question involves the role of emotion in learning. Indeed, while we have focused on the role of evidence in exploratory decision-making, the choice of when and what to explore is also driven by emotional evaluations (e.g. Valdesolo, Shtulman, & Baron, 2017). It is a great mystery why some people seem to have insatiable curiosity while others are content to remain comfortable in the known. Children, in particular, may have more conducive dispositions for constant curiosity (Gopnik, 2009), but it is not clear how these drives intersect with emotional development. Although it is likely that emotions play an important role in learning, (and anyone with a toddler can tell you that children are extremely emotional beings), there are surprisingly few studies that explore how emotion in early development plays into a drive to explore and learn. If we are to fully understand the utilities driving children's exploration, emotion must be a factor to be studied.

Finally, the account of children's active learning and teaching presented here suggests that at some level children are maintaining a set of beliefs about the world,

considering multiple opportunities for evidence to discern between these beliefs, and then selecting the best action based on these utilities. However, such an account may put an unrealistic demand on our young learners. Given the vast (and potentially infinite) space of possible options in the world, how could a learner consider so many possibilities? In other research, we have taken inspiration from machine learning accounts that use sampling algorithms to help solve this computational problem – only requiring the learner to entertain one or a few options at a time, but still producing behavior that on aggregate appears to match optimal predictions from probabilistic models (Denison, Bonawitz, Gopnik, & Griffiths, 2013; Bonawitz, Denison, Gopnik, & Griffiths, 2014; Bonawitz, Denison, Griffiths, & Gopnik 2014; Bonawitz, Ullman, Gopnik, & Tenenbaum, 2012, *in review*). These models are an important step to describing how learners move from one belief to the next, while addressing the problem of computational intractability given by uncertainty in the world. These same approaches may help elucidate how multiple options for learning are evaluated in the mind.

Our ability to choose to act plays an important role in learning. The act of acting provides a clearer causal story of the world (Woodward, 2005), which partly solves the problem of Plato’s cave. Active learning also likely supports cognitive functions, such as enhancing memory for evidence that was generated from self-directed interventions (Markant et al., 2016). We have suggested that core abilities are required to support this decision making, and these same abilities also underlie our early emerging natural pedagogical skills. To choose effectively, agents must use more than simple heuristics; they must be able to evaluate the possible rewards and costs of different actions and their

outcomes. These rewards may entail information gain, so learning agents must be able to evaluate and select evidence effectively.

We have provided some support for the claim that children are learning agents. Evidential selection emerges very early in development and may even be a core component of the constructivist cycle. Children evaluate potential evidence to support their own learning; they evaluate potential evidence to support another's learning; and, perhaps most impressively, they evaluate a teacher's evidential selection for a third party's learning. While there is still much we do not understand about the roots of curiosity and action in cognitive development, the ability to choose and evaluate evidence seems a critical component. It is in choosing that we become active learners, controllers of our epistemic destinies.

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