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In Pursuit of Knowledge: Preschoolers Expect Agents to Weigh Information Gain and Information Cost When Deciding Whether to Explore

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When deciding whether to explore, agents must consider both their need for information and its cost. Do children recognize that exploration reflects a trade-off between action costs and expected information gain, inferring epistemic states accordingly? In two experiments, 4- and 5-year-olds ($N = 144$; of diverse race and ethnicity) judge that an agent who refuses to obtain low-cost information must have already known it, and an agent who incurs a greater cost to gain information must have a greater epistemic desire. Two control studies suggest that these findings cannot be explained by low-level associations between competence and knowledge. Our results suggest that preschoolers' theory of mind includes expectations about how costs interact with epistemic desires and states to produce exploratory action.

Humans are intrinsically motivated to learn about the world (Kidd & Hayden, 2015). From early childhood, we discover causal relations through everyday play (Cook, Goodman, & Schulz, 2011; Schulz & Bonawitz, 2007), we explore based on how much we expect to learn (Bonawitz, van Schijndel, Friel, & Schulz, 2012; Bonawitz et al., 2011; Stahl & Feigenson, 2015), and we draw rational generalizations from limited observations (Gweon & Schulz, 2011; Xu & Garcia, 2008). As social creatures, however, we also rely on others to help us learn more than we could on our own (Bridgers, Gweon, Bretzke, & Ruggeri, 2018; Ruggeri & Lombrozo, 2015), seeking informants who are confident (Birch, Akmal, & Frampton, 2010; Brosseau-Liard & Poulin-Dubois, 2014), reliable (Poulin-Dubois, Brooker, & Polonia, 2011; Zmyj, Buttelmann, Carpenter, & Daum, 2010), and with a track record of being right (Koenig, Clément, & Harris, 2004; Pasquini, Corriveau, Koenig, & Harris, 2007).

Despite the usefulness of social learning, identifying knowledgeable agents is a challenge in and of itself, requiring us to infer what others know based on how they behave. Nonetheless, adults routinely make quick and accurate guesses about others' knowledge from limited interactions. Imagine, for instance, asking a stranger on the street for directions to a nearby shop. If the stranger immediately told you where to go, you could reasonably assume that they know the place you are looking for, even if you could not immediately verify their answer. If instead, the stranger spent a painstaking amount of time consulting a map on their phone before telling you where to go, you could infer that the stranger had not heard about the shop you are looking for or did not know its location.

Although these examples show that others' decisions to seek information can reveal what they know, many situations offer an even more nuanced glimpse into other people's minds. When the stranger consulted their map, the effort they invested in looking for information also reveals how much they cared about finding out the directions so that they could be helpful. Conversely, if the stranger gave you directions without consulting their phone, you might be more confident that their answer was accurate if they were leisurely sitting at a bench, phone in hand (and could have easily confirmed

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their directions before giving them), than if they were running late to a meeting, tried to check their phone but had poor reception, and pointed you in some direction before leaving abruptly (where their cost for confirming the directions would have been high).

These examples suggest that to infer knowledge, we consider not only whether others seek information, but also the costs associated with obtaining it, adjusting our inferences accordingly. Recent research suggests that even young children can make epistemic inferences from information-seeking behavior. Four- and five-year-olds judge that agents who can name animals without help are more likely to be knowledgeable relative to agents who accept help (Einav & Robinson, 2011), and they believe that agents who can state what's inside a container without checking are more likely to be knowledgeable, relative to agents that check before answering (Aboody, Huey, & Jara-Ettinger, 2018). While these studies show that children recognize the connection between information seeking and knowledge, it remains unknown whether children also understand that agents' decisions about when to seek information are modulated by costs.

While epistemic inferences that incorporate costs might appear simple and intuitive to adults, they may not be obvious to children. On the one hand, even infants can integrate cost information to infer other people's mental states (Gergely & Csibra, 2003; Jara-Ettinger, Gweon, Schulz, & Tenenbaum, 2016; Liu, Ullman, Tenenbaum, & Spelke, 2017). However, prior work has restricted its focus to inferences about goals and desires: two mental-state representations that emerge very early in development (Gergely & Csibra, 2003; Woodward, 1998), where the logic of children's inferences is already structurally similar to that of adults (Baker, Saxe, & Tenenbaum, 2009; Jara-Ettinger, Schulz, & Tenenbaum, 2020; Jern, Lucas, & Kemp, 2017; Lucas et al., 2014).

In contrast, representations of knowledge and belief develop later in childhood (Wellman, 2014; Wellman, Cross, & Watson, 2001) and inferences about these mental states appear to be brittle and guided by simple heuristics. For instance, preschoolers do not recognize that ignorant agents will search randomly between two boxes (Chen, Su, & Wang, 2015; Friedman & Petrashek, 2009; Saxe, 2005), they preferentially learn from familiar agents over accurate ones (Corriveau & Harris, 2009), they over-generalize knowledge onto a "halo effect" (Brosseau-Liard & Birch, 2010), they fail to distinguish epistemic competence from nonepistemic competence (Fusaro, Corriveau, & Harris, 2011), they struggle to infer partial knowledge from partial goal-completion (Ronfard & Corriveau, 2016), and they incorrectly attribute expertise to agents who confidently answer questions that are impossible to answer correctly (Kominsky, Langthorne, & Keil, 2016). These heuristic-based inferences contrast with goal and desire inferences which, from infancy, are structured around an expectation of rational action that is sensitive to costs (Gergely & Csibra, 2003; Jara-Ettinger et al., 2016; Liu & Spelke, 2017; Liu et al., 2017).

Epistemic inferences that integrate others' information-seeking behavior with their costs would not only require children to break away from their typical use of heuristics in knowledge inferences, but also impose two difficult demands. First, such inferences require reasoning about how agents compare and balance quantities that are in fundamentally different metric spaces—information and cost. Second, they require children to represent how the cost of actions and the value of information vary across agents, depending both on agent-variable traits like physical competence or curiosity, and agent-variable mental states like goals or desires.

Here we test if children can infer others' epistemic states and desires by reasoning about rational trade-offs between agent-variable energy expenditure and information value. While substantial research has looked at children's own information-seeking behavior (Bonawitz et al., 2011, 2012; Cook et al., 2011; Ruggeri, Lombrozo, Griffiths, & Xu, 2016; Schulz & Bonawitz, 2007; Schulz, Wu, Ruggeri, & Meder, 2019; Stahl & Feigenson, 2015), less is known about children's epistemic inferences from others' information-seeking behavior. Instead, the vast majority of research on children's action understanding has focused on reasoning about goals and preferences (e.g., Csibra, Bíró, Koós, & Gergely, 2003; Jara-Ettinger, Gweon, Tenenbaum, & Schulz, 2015; Lucas et al., 2014; Pesowski, Denison, & Friedman, 2016).

We present four experiments testing whether children make epistemic inferences through an expectation that agents rationally trade-off agent-variable costs and information value. We focus on a cost that even young children understand: physical effort (Jara-Ettinger, Floyd, Huey, Tenenbaum, & Schulz, 2019; Leonard, Lee, & Schulz, 2017; Liu et al., 2017). In Experiment 1, we test if preschoolers believe that agents who refuse to seek (agent-variable) low-cost information are more likely to have already known it. In Experiment 2, we test if preschoolers believe that agents who seek (agent variable) high-cost information are more likely to have a strong desire for it. We focus on 4- and 5-year-olds because, although inferences based on action cost emerge early in infancy (Csibra et al., 2003; Liu et al., 2017), reasoning about agent-variable traits develops between ages five and eight (Liu, Gelman, & Wellman, 2007; Ruble & Dweck, 1995; Seiver, Gopnik, & Goodman, 2013). Moreover, our tasks require children to distinguish physical competence from epistemic competence, an ability which develops between ages three and five (Brosseau-Liard & Birch, 2010; Fusaro et al., 2011). We consequently also include two control experiments ruling out the possibility that children simply assume that stronger agents are more knowledgeable. Together, our experiments show that children expect agents to rationally trade-off information gain with costs, and that they use this expectation to infer others' knowledge based on agent-variable properties.

Approach to Analyses

In line with current recommendations for statistical best practices, we take an estimation approach to data analysis rather than relying on null-hypothesis significance testing (Cohen, 1994; Cumming, 2014). We estimate effect sizes by bootstrapping our data and obtaining 95% confidence intervals; we take confidence intervals that do not cross chance as evidence of a reliable effect. Additionally, we use Bayesian data analyses to test whether our theoretical account can explain the full pattern of data obtained across all four experiments better than a simpler rule-based alternative.

Experiment 1

In Experiment 1, children watched a strong and a weak agent decline to lift a box to find out what was underneath. Participants were asked which of the two puppets already knew what was under the box. If children consider agent-variable tradeoffs between cost and information, they should infer that the stronger agent already knew what was inside. If, instead, children attend to information-seeking actions alone, they should perform at chance.

Method

The procedure, predictions, and analysis plan were all preregistered and are available at: https://osf.io/27dkb/?view_only=fbe4da575b3c44b3a641da351d5e4b07.

Participants

Forty-eight 4- and 5-year-olds (M_{age} = 4.99 years, range = 4.20–5.88 years; n = 24 participants per age group) participated. Five additional participants were recruited but not included in the study (see Results). Participants were recruited and tested at preschools in Los Angeles County. Schools that agreed to participate in research distributed consent forms to families; children whose parents returned a completed consent form were given the option to participate if they wished. We did not collect demographic information from participants, but report summary statistics based on their location of participation. In 2018, on average the median income for these areas was $69,042. As of the 2010 Census, on average 15% of adults in these areas were Asian, 5.7% were Black, 23.5% were Hispanic or Latino, 0.5% were Native American, 0.2% were Native Hawaiian or Pacific Islander, 52.2% were White, and 15.5% were two or more races, or marked "Other." All data were collected in May 2018.

The preregistered sample size for this and all following experiments was determined through a Monte Carlo power analysis (see Supporting Information).

Stimuli

Stimuli consisted of two female puppets, two 5.75 × 5.75 × 5.25-in. gray boxes, and a small rubber duck. The boxes were closed at the top and open at the bottom, so items could be hidden underneath, and boxes could be lifted to reveal their contents. The first ("warm-up") box was empty and the second ("test") box had a rubber duck hidden underneath.

Procedure

Figure 1 shows the experimental procedure. The experimenter began by introducing the two boxes and the puppets, Adrienne and Sophie. The experimenter then explained that "Adrienne is really strong, so it's easy for Adrienne to lift boxes." Adrienne then lifted the warm-up box swiftly on her first try, with no signs of exertion. The experimenter next explained that "Sophie is not strong, so it's very hard for Sophie to lift boxes." Sophie then struggled to lift the warm-up box, huffing with exertion and succeeding on the third try.

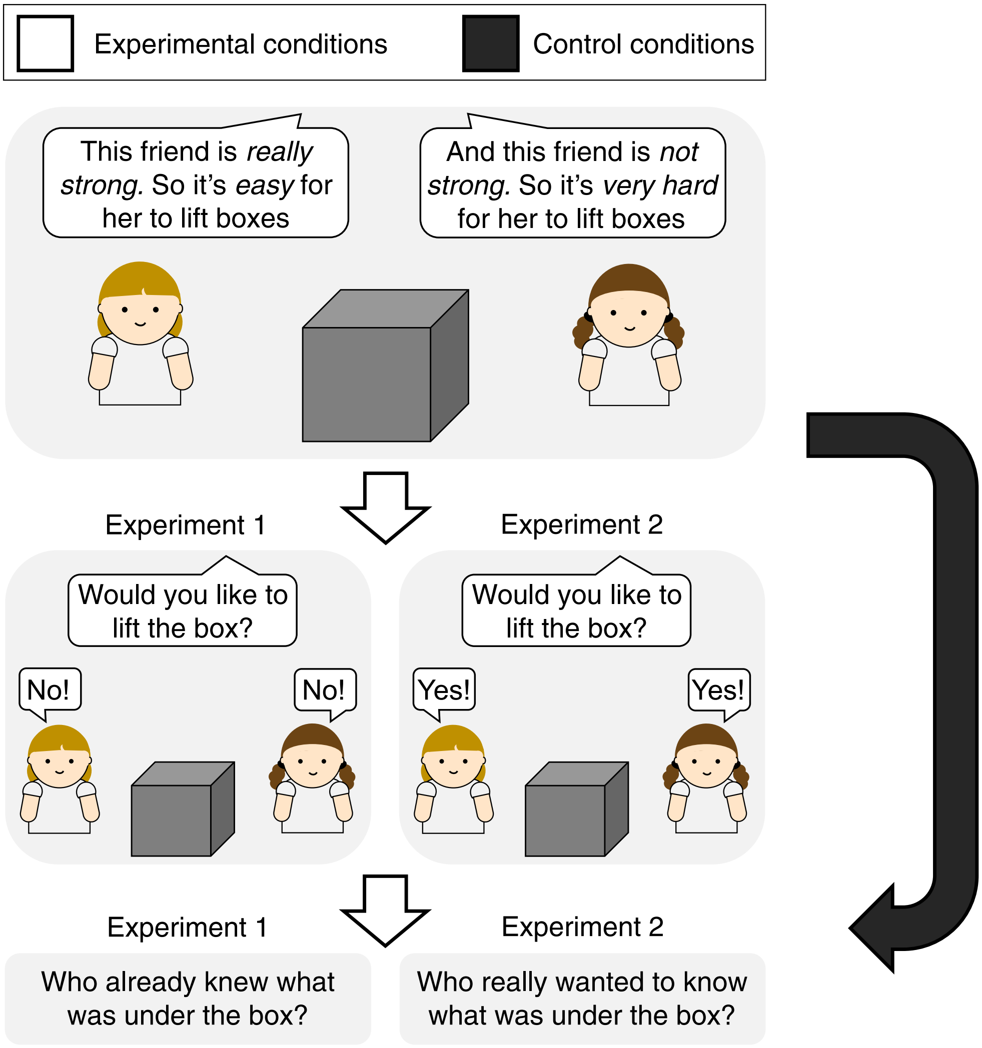

Figure 1. Schematic of Experiments 1–2 and their control conditions. After demonstrating their strength by lifting a first box, puppets were given the chance to lift a second box to find out what was underneath. Both agents refused to lift the box in Experiment 1, and they agreed to lift it in Experiment 2. The control experiments were identical to the main experiments, except that puppets were never given the chance to lift the second box. Instead, the experimenter proceeded directly to the test question. [Color figure can be viewed at wileyonlinelibrary.com]

Presentation order, and association between puppet (Adrienne or Sophie) and strength (weak or strong) were counterbalanced across participants.

The empty warm-up box was then removed and both puppets left the scene. The experimenter drew children's attention to the test box, saying, "And here we have a special box. This box is special because underneath, there's a rubber ducky!" She lifted the box to show participants the duck underneath, and then covered the duck again with the box. The experimenter then brought back the first puppet she had introduced, saying, "Let's give Adrienne a turn. Adrienne, there's something special under this box! Would you like to lift up the box, to find out what's underneath?" The puppet thought and said, "Hmm, no thanks!" The experimenter replied, "Ok!" and the puppet left the scene. Next, the experimenter brought back the second puppet and said "Let's give Sophie a turn. Sophie, there's something special under this box! Would you like to lift up the box, to find out what's underneath?" This puppet also thought and said, "Hmm, no thanks!" The experimenter replied "Ok!" and the puppet also left the scene.

Finally, the experimenter brought both puppets out and asked, "[Participant name], right before you came here today, one of my friends saw me put the rubber ducky under the box. So one of my friends already knew what was underneath the box. Can you tell me, which friend already knew what was underneath?"

The experimenter then asked participants to explain their choice (pre-registered as a variable not to be analyzed, but included for completeness), and then asked two inclusion questions: "Which one of my friends is really strong? And which one of my friends is not strong?"

Results

For the 88.7% of participants whose sessions were video or audio taped (*n* = 47/53), two coders who were not involved in data collection determined exclusions according to preregistered criteria. The first coder, blind to participant answers, determined whether the experiment was run correctly. The second coder, blind to condition, coded participant answers. The experimenter took notes on any deviations from the procedure, and for participants who were not video or audio-taped the first author determined exclusions by comparing these notes to the pre-registered inclusion criteria. Five participants were recruited but not included in the final sample because they incorrectly answered one or both of the inclusion questions (*n* = 2), because of experimenter error (*n* = 2), or because the participant took longer than 30 s to answer the test question (*n* = 1).

Of the final 48 participants included in the study, 75% judged that the strong agent already knew what was under the box (*n* = 36; 95% CI [62.5, 87.5]; Figure 2). A logistic regression predicting performance as a function of age did not reveal any significant age difference ($\beta = -0.65$, $p = .40$), and performance within each age group was qualitatively similar: 79.2% of 4-year-olds (*n* = 19 of 24) and 70.8% of 5-year-olds (*n* = 17 of 24) judged that the strong agent already knew what was under the box. While young children often fail to produce relevant explanations in experimental contexts (Legare & Lombrozo, 2014; Walker, Bonawitz, & Lombrozo, 2017; Walker, Lombrozo, Legare, & Gopnik, 2014), many participants explained their answers by appealing to puppets' strength (see Supporting Information for explanations).

Experiment 2

Experiment 1 shows that when inferring knowledge from agents' exploratory choices, children consider the cost of seeking information. In Experiment 2, we test whether children believe that agents who incur a higher cost to gain information must have a stronger epistemic desire. Children watched a strong and a weak puppet lift a box to find out what was underneath. Participants were asked which agent really wanted to know what was underneath. If children consider agents' costs when inferring their epistemic desires, they should infer that the weaker agent had a stronger desire to know. If, instead, they focus on the outcome alone, they should perform at chance.

Method

Participants

Forty-eight 4- and 5-year-olds (M_{age} = 5.04 years, range = 4.19–5.95 years; *n* = 24 participants per age group) were recruited. Eight additional participants were recruited but not included in the study (see Results).

71.4% of participants (*n* = 40) were recruited and tested at preschools in Los Angeles County; recruitment proceeded as in Experiment 1. As before, we did not collect demographic information from participants, but report summary statistics based on their location of participation. In 2018, on average the median income for these areas was $90,133. As of the 2010 Census, on average 7.7% of adults in these areas were Asian, 4.6% were Black, 24.7% were Hispanic or Latino, 0.5% were Native American, 0.2% were Native Hawaiian or Pacific Islander, 59.9% were White, and 15.4% were two or more races, or marked "Other". 28.6% of participants (*n* = 16) were recruited and tested at a museum in New Haven; attendees passing by were given the opportunity to participate. On average, 3% of visitors are Asian, 19% are Black, 13% are Hispanic or Latino, 1% are Native American, 58% are White, and 6% are two or more races (Peabody Museum of Natural History, Yale University, 2005). In 2018, the median household income in New Haven was $41,142. All data were collected between May and August 2018.

Stimuli

Materials were the same as in Experiment 1.

Procedure

The procedure was nearly identical to Experiment 1, except that when given the opportunity to lift the test box, both puppets agreed, saying,

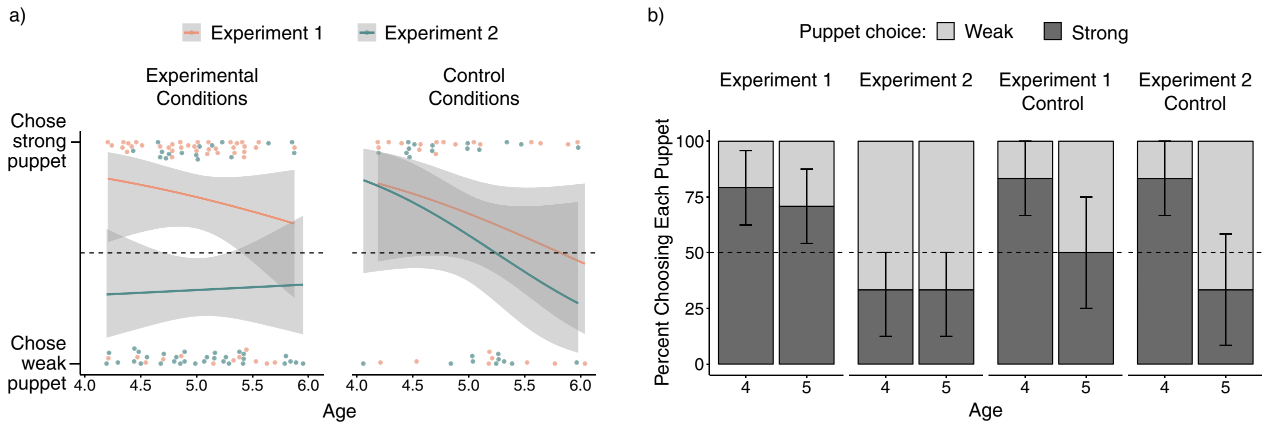

Figure 2. Results from all experiments. (a) Participant choices (strong puppet vs. weak puppet) as a function of age, along with logistic regressions fit to each data set. Points are jittered along the *Y* axis. The dotted line indicates chance performance. Gray bands show 95% CIs in the regression. (b) Participant choices were visualized by age group. Vertical bars show 95% bootstrapped confidence intervals. [Color figure can be viewed at wileyonlinelibrary.com]

"Hmm, okay!" The strong puppet lifted the test box with ease, and the weak puppet struggled but ultimately succeeded, as they had with the warm-up box (see Figure 1; presentation order, and association between puppet and strength was counterbalanced across participants).

After both puppets lifted the test box, the experimenter brought out the two puppets and asked "[Participant name], one of our friends really wanted to know what was under the box. Can you tell me, which friend really wanted to know?" Participants were then asked to explain their choice, followed by the same two inclusion questions from Experiment 1.

Results

Results were coded as in Experiment 1. 85.7% of participants were video or audio taped ($n = 48/56$). Eight participants were excluded from the final sample, because of interruptions or participant distraction ($n = 3$), experimenter error ($n = 2$), because the participant incorrectly answered one or both of the inclusion questions ($n = 2$), or because the participant took longer than 30 s to answer the test question ($n = 1$).

As predicted, children's pattern of responses flipped in Experiment 2. Of the final 48 participants included in the study, 66.6% judged that the weak agent had the stronger epistemic desire ($n = 32$; 95% CI [54.2, 81.3]). A logistic regression predicting performance as a function of age did not reveal any significant age difference ($\beta = -0.11$, $p = .86$), and performance within each age group was identical: 66.6% of 4-year-olds ($n = 16$ of 24) and 66.6% of 5-year-olds ($n = 16$ of 24) judged that the weak agent really wanted to know what was under the box. As in Experiment 1, participants who produced explanations often referred to puppets' strength (see Supporting Information for all explanations).

Experiments 1 and 2 Discussion

Experiments 1 and 2 suggest that children considered the cost associated with information gain when interpreting information-seeking behavior. By expecting agents to rationally trade-off agent-variable costs with agent-variable desires for information, children successfully inferred which of two agents was already knowledgeable when they both refused to obtain information (Experiment 1), and which of two agents most wanted knowledge when both agents chose to obtain information (Experiment 2).

Related research, however, has argued that children have a general representation of competence that combines strength, niceness, and knowledge (Brosseau-Liard & Birch, 2010; Fusaro et al., 2011). It is thus possible that children succeeded in Experiment 1 simply by assuming that stronger agents are more knowledgeable, and in Experiment 2 by assuming that weaker agents lack knowledge (and must therefore have stronger epistemic desires). Experiment 1 and 2 controls test for this possibility.

Experiment 1 and 2 Controls

The control conditions for Experiments 1 and 2 had identical procedures to the main experiments, with the difference that puppets were not given the opportunity to lift the test box (Figure 1). Instead, the experimenter asked the (respective) test question immediately after the puppets had lifted the warm-up box (see Figure 1). If children's inferences in Experiments 1 and 2 were driven by a superficial assumption that stronger agents are more knowledgeable and that weaker agents are more curious, then the same pattern of results from Experiments 1 and 2 should appear in the control conditions.

Method

Participants

Because we did not find any age difference in Experiment 1 and 2, we collapsed the two age groups and collected a single pre-registered sample of twenty-four 4- to 5-year-olds for each control experiment (Control Experiment 1: M_{age} = 5.01 years, range = 4.19–6.04 years; Control Experiment 2: M_{age} = 4.97 years, range = 4.06–5.98 years; n = 12 participants per age group per experiment). Eight additional participants were recruited but not included in the study (six in Control Experiment 1, and two in Control Experiment 2; see Results). All participants were recruited and tested at a museum in Boston. Recruitment of museum attendees proceeded as in Experiment 2. On average, 9% of attendees are Asian, 24% are Black, 17% are Hispanic or Latino, 47% are White, and 4% are two or more races. 29% of museum attendees visit on days when there is free or discounted admission. Data were collected between November 2018 and January 2019.

Stimuli

Materials were the same as in Experiments 1 and 2.

Procedure

The procedure for Experiment 1 control began in an identical way to Experiment 1. After the two puppets demonstrated their strength by lifting the warm-up box, the experimenter showed the participant (but not the puppets) that there was a rubber duck underneath the test box. However, instead of asking each puppet if they wanted to lift the box to find out what was underneath, the experimenter skipped straight to the test question ("which friend already knew what was underneath"), explanation prompt, and inclusion questions. Experiment 2 control was identical to Experiment 1 control with the difference that we matched the test question to the one from Experiment 2 ("which friend really wants to know?"). Note, however, that we switched the past-tense term "wanted" to present tense "wants", as puppets in this condition did not lift the test box (the action the past-tense "wanted" originally referred to).

Results

Results were coded in the same way as Experiments 1–2 (as pre-registered). In Control Experiment 1, 90% of participants were video or audio taped (n = 27/30), and in Control Experiment 2, 88.5% of participants were video or audio taped (n = 23/26). Eight additional participants were excluded and replaced, because they incorrectly answered inclusion questions (Control Experiment 1, n = 2; Control Experiment 2, n = 2), or because they did not answer the test question within 30s (Control Experiment 1, n = 4).

In Control Experiment 1, 66.6% of participants judged that the strong agent already knew what was under the box, a proportion reliably higher than chance (n = 16 of 24, 95% CI [50, 87.5]). A logistic regression predicting performance based on condition (control vs. experimental) revealed no significant effect of condition between Experiment 1 control and Experiment 1 ($\beta = 0.41$, $p = .46$).

In Control Experiment 2, only 41.7% of participants judged that the weak agent had the stronger epistemic desire, a proportion not reliably different from chance (n = 10 of 24; 95% CI [20.8, 62.5]). A logistic regression predicting performance based on condition (control vs. experimental) revealed a significant effect of condition between Experiment 2 control and Experiment 2 ($\beta = 1.03$, $p = .046$). Participant explanations from both experiments are available in Supporting Information.

Combined, the results from the two control experiments suggest that a simple association between competence and knowledge cannot explain our full pattern of data. The strength-competence account predicts that children's performance in both control conditions should mirror performance in the experimental conditions, but children's responses significantly differed between Experiment 2 and its control.

The results above suggest that children in our main experiments flexibly adjusted their response based on the costs involved, whereas children in the control conditions did not. Consistent with this, a logistic regression predicting participant choice as a function of experimental condition (Experiment 1 vs. Experiment 2; not pre-registered) revealed a significant difference across conditions: participants were significantly less likely to select the strong agent in Experiment 2 ($\beta = -1.79$, $p < .001$). In contrast, an equivalent (not pre-registered) regression predicting participant choice as a function of control condition found no significant difference across control conditions ($\beta = -0.36$, $p = .55$).

Control Experiments 1 and 2 Discussion

The results from our control conditions suggest that children's responses in our main studies were not driven by a simple strength-competence heuristic: If children assumed that strong agents are knowledgeable and weak agents desire knowledge (ignoring the costs that agents choose or refuse to incur), the pattern of results in the control conditions should have been identical to the pattern from the experimental conditions. Instead, children's responses in Experiment 2 significantly differed from their responses in the corresponding control condition.

Combined Bayesian Data Analysis

Our results suggest that children's epistemic inferences rely on their theory of mind (ToM), sensitive both to others' exploratory choices and their costs. However, these conclusions are based on analyses examining each experiment separately. To further evaluate both our theory and competing explanations, we tested how well each account could explain the entire pattern of data observed across all experiments (not preregistered).

Formally, we considered three hypotheses: children select agents randomly (*baseline* model), children make epistemic inferences through a strength-competence heuristic (*heuristic* model), and children make epistemic inferences through their TOM (*ToM* model). Throughout, we use Bayes factors to compare theories, using standard terminology of Bayesian data analysis (Jeffreys, 1998).

To calculate the likelihood of the data given each theory, we took the product of four binomial distributions (one per data set), varying the probability of selecting each puppet according to each theory's predictions. The baseline model used a parameter of 0.5, expressing the prediction that participants had a 50% chance of selecting either puppet. The heuristic model used a parameter that tracked the chance a participant would use the strength-competence heuristic. For instance, a parameter of 0.75 would mean that each child had a 75% chance of selecting the strong agent in Experiment 1 and its control condition (judging that this agent was more knowledgeable) and a 75% chance of selecting the weak agent in Experiment 2 and its control condition (judging that this agent most desired knowledge). Finally, the ToM model used a parameter that indicated how children ought to perform when mental-state inference was possible, and predicted chance performance when cost information was absent. For instance, a parameter of 0.75 would mean that participants had a 75% chance of selecting the strong agent in Experiment 1 and the weak agent in Experiment 2, and a 50% chance of selecting either agent in the controls (as the ToM account makes no predictions in this case).

What factors might determine a participant's probability of success? In our preregistered power analysis, we expected participants to succeed or fail based on a theory-independent feature: their attention. If this is the case, then the same proportion of participants should answer correctly no matter which theory they relied on (heuristic vs. ToM). Thus, in line with the preregistered effect size that we expected, we began by setting the success probability to 75% in both the heuristic and ToM models. Using a uniform prior over hypotheses, we found decisive evidence for the ToM model (Bayes Factor = 3,510.5 comparing ToM vs. baseline; Bayes Factor = 110.7 comparing ToM vs. heuristic).

To test the robustness of our results, we also reproduced our analyses varying the expected probability of success of both models from 51% to 99% (in increments of 1%), and now additionally included the possibility that participants' probability of success differs based on the theory they relied on (e.g., it could be easier for participants to answer correctly if they relied on a simple heuristic rather than on their ToM). The ToM model outperformed the heuristic model in 67% of cases ($n = 1{,}612$ of 2,401), with a mean Bayes Factor of 2.99×10^{58}, and a median Bayes Factor of 17.2 (see Figure 3 and Supporting Information for details).

Finally, we also conducted a full Bayesian model comparison that integrated uncertainty over the effect size. To achieve this, we placed a prior distribution over effect sizes centered at 75% success, and with a symmetrical shape (formally achieved by projecting a Beta distribution with parameters $\alpha = 15$ and $\beta = 15$ onto the .51–.99 range; see Supporting Information for details). Given this prior over effect sizes, and a uniform prior over theories (i.e., $p(\text{ToM}) = p(\text{heuristic}) = .5$) we found strong evidence in favor of the ToM account

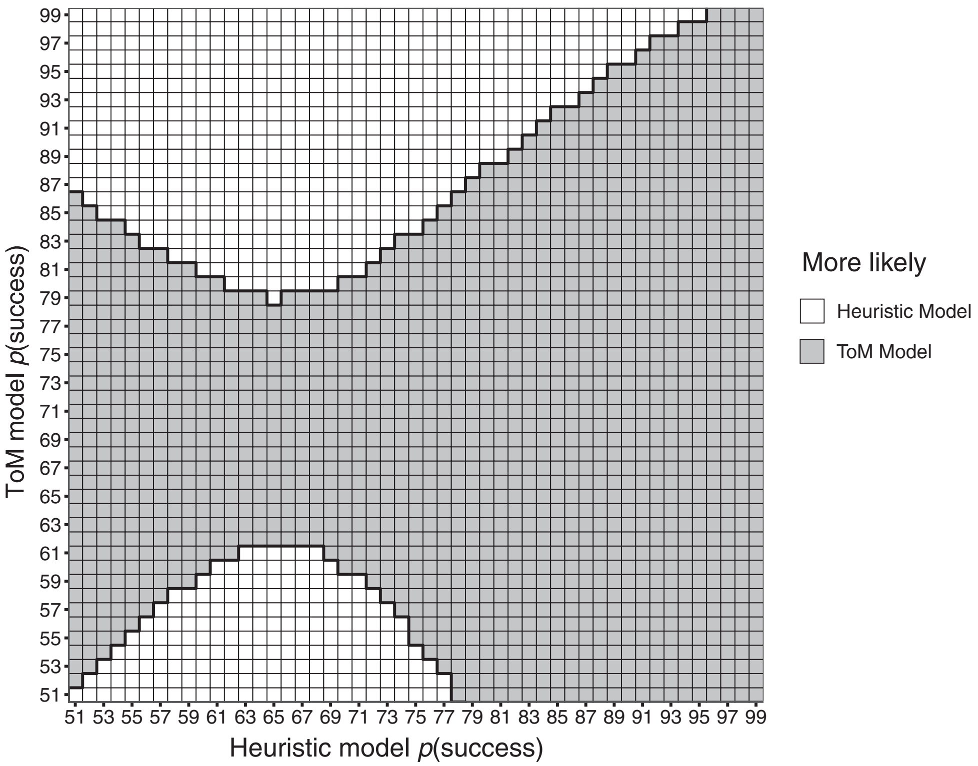

Figure 3. Each tile represents a comparison of the heuristic and theory of mind (ToM) models, given different parameter values for the expected probability of success. Dark gray tiles indicate cases where the ToM model is better able to explain the pattern of data (Bayes Factor > 1). White tiles indicate cases where the heuristic model is better able to explain the pattern of data (Bayes Factor < 1). For more information about the magnitude of the Bayes Factors, (see Supporting Information).

(Bayes Factor = 19.5). Additional robustness analyses showed that the qualitative conclusions are the same when the prior over effect sizes is relaxed (see Supporting Information).

Together, these results show that the ToM account was better at explaining our data than the strength-competence heuristic. This held true no matter how we varied our parameters, whether we assumed that performance was theory-independent (i.e., the same across theories) or theory-dependent (i.e., different theories predicting different probabilities of success), and even when we integrated over these parameters using a prior over effect sizes.

General Discussion

As we navigate the social world, we must frequently infer what others believe and know from their actions. Such inferences can be far from straightforward: agents can produce the same action for different reasons, or pursue the same goal driven by different desires. Across four experiments, we showed that preschoolers infer agents' epistemic states and desires by considering how agents trade-off the agent-variable value of information with the agent-variable cost of obtaining it. In Experiment 1, 4- and 5-year-olds judged that an agent who declined to pursue low-cost information was more likely to be knowledgeable than an agent who declined to pursue the same information at a higher cost. In Experiment 2, children judged that an agent who incurred a higher cost to gain information must have wanted it more than an agent who incurred a low cost to obtain it. Two control experiments revealed that a superficial connection between strength and knowledge could not explain our results.

In all experiments, both agents always made identical decisions in identical situations. Thus, if children attempted to infer epistemic states on the basis of superficial observable cues, they should have performed at chance. Instead, our findings suggest that children attended to the psychological causes behind each agent's actions, taking into account their competence. Our findings add to a broader literature showing that, while children often make epistemic judgments on the basis of simple cues like accuracy or error (e.g., Koenig et al., 2004; Pasquini et al., 2007; Ruffman, 1996), they can nonetheless reason about the causes behind these cues when necessary (Aboody et al., 2018; Einav & Robinson, 2011; Nurmsoo & Robinson, 2009a, 2009b).

Our work also sheds light on children's ability to represent compositional mental states. Research in ToM has typically focused on beliefs and desires as representations about the world (see Wellman, 2014, for a review). However, agents can also have beliefs about their desires (e.g., believing that they will like a new food) and desires about their beliefs (e.g., wanting to find out if their beliefs are true). To our knowledge, our work is the first to provide evidence that preschoolers can represent and infer desires about beliefs: In Experiment 2, children successfully identified the puppet that wanted to know. Along with research showing that preschoolers can also infer beliefs about desires (Jara-Ettinger, Floyd, Tenenbaum, & Schulz, 2017), our results suggest that the ability to combine mental-state representations in a compositional manner emerges early in development.

Finally, our results converge with related work showing that inferences about desires are structured around an expectation that agents maximize utilities—the difference between costs agents incur and rewards they obtain (Gergely & Csibra, 2003; Jara-Ettinger et al., 2016; Liu et al., 2017). Our work extends these findings, showing that similar utility-based computations also enable children to infer others' epistemic desires and states. Together, this suggests that by age four, mental-state inference is grounded in a unified expectation that agents quantify, compare, and maximize their physical and epistemic utilities.

Our work opens several questions. First, our study focused on children's ability to infer epistemic states from information-seeking actions and their costs. If participants' judgments were guided by a causal understanding of how agents' competence and knowledge combine to produce action, children should be able to use information about any two of these factors to infer the third. That is, children should also be able to infer an agent's costs from their epistemic state and information-seeking actions; and predict whether an agent is likely to seek knowledge based on their costs and epistemic states. In contrast to a heuristics-based perspective, our account predicts that children should be able to derive all of these inferences given their causal utility-based naïve theory, and future work will test this possibility.

A related open question is whether children make such inferences spontaneously. In our experiments, we explicitly highlighted agents' actions and their costs, and prompted children to make epistemic inferences. But when children are not explicitly prompted to consider costs, they might be more likely to rely on quick and simple heuristics, or may not derive any epistemic inferences at all. Similarly, our tasks used constrained situations where only a few mental-state explanations were available; it is possible that children might appeal to other nonepistemic explanations in more naturalistic situations (e.g., assuming that an agent was doing something for fun rather than to gain information). As such, our work shows that children understand the role of costs in information seeking, but leaves open the question of whether they make such epistemic inferences spontaneously.

Furthermore, our studies manipulated the cost of action by varying agents' strength. If children's judgments were guided by an abstract representation of costs, then children should be able to solve equivalent tasks involving different sources of cost, such as dexterity, time, and mental effort. For instance, a willingness to incur a high cost to solve a puzzle box intuitively reveals a strong desire to know what's inside. However, these inferences should emerge only when children understand a domain well enough to grasp its cost structure (for instance, understanding how difficult it is to solve different kinds of puzzle boxes), which may take time to develop (e.g., Liu, Cushman, Gershman, Kool, & Spelke, 2019; Richardson & Keil, 2020, for children's understanding of mental effort).

More broadly, agents' decisions to seek or confirm information also depend on agent-variable traits. For instance, while an anxious person might continuously check for their wallet despite knowing it's there, a careless one might leave the house without even thinking to do so. Effective epistemic inferences must therefore integrate richer agent-variable traits. Our work leaves open the question of whether children can infer these agent-variable traits and adjust their epistemic inferences accordingly.

In addition, our work did not explore the distinction between information that is intrinsically rewarding and information that serves as a means to an end. An ability to distinguish between the two is critical for inferring agents' desires (do they care about what they are learning?) and deciding how to react accordingly (should we tell them more, or focus on helping them achieve their ultimate goal?). Future work will explore whether children are sensitive not only to trade-offs between agents' costs and rewards, but also to trade-offs between the different kinds of rewards that can motivate agents to seek information.

Finally, our work leaves open questions about the developmental trajectory of the inferences we report here. In particular, we did not anticipate any age effects in our control conditions, and thus preregistered a single sample of twenty-four 4- and 5-year-olds in each experiment. However, post hoc analyses suggested that children's responses in the control conditions may differ by age (Figure 2b): 4-year-olds appeared to prefer the strong agent in both control conditions (10 of 12 selecting this agent in each control, 95% CI [66.6, 100]), whereas 5-year-olds showed no reliable preference for either agent (6 of 12 children selecting the strong agent in Control Experiment 1, 95% CI [25, 75]; and 4 of 12 in Control Experiment 2; 95% CI [8.3, 58.3]). While exploratory, these results are consistent with prior research suggesting that younger preschoolers associate strength and competence (e.g., Fusaro et al., 2011), but suggest that this association can be easily overridden when more information about agents' costs is available. Note, however, that our control experiments were not powered to detect age effects and it is possible that these qualitative differences could have arisen due to chance. Future work will investigate this possibility.

Conclusion

During our preschool years, we invest so much time and effort into learning about the world. To learn most efficiently, we often rely on others to teach us what they know. Across four experiments, we find that preschoolers already appreciate the heterogeneity in what others know or want to know, engaging in nuanced mental-state reasoning to determine others' epistemic desires and states. This capacity may be at the heart of epistemic social behavior, not only guiding our decisions about whom to ask or trust, but also allowing us to determine who to help, how to teach, and even who should have known better.

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Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Appendix S1. Sample size and power analysis; Combined Bayesian data analysis; Participant explanations