Do I know that you know what you know? Modeling testimony in causal inference

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Abstract

We rely on both our own observations and on others' testimony when making causal inferences. To integrate these sources of information we must consider an informant's statements about the world, their expressed level of certainty, their previous accuracy, and perhaps their apparent self-knowledge – how accurately they convey their own certainty. It can be difficult to tease apart the contributions of all these variables simply by observing people's causal judgments. We present a computational account of how these different cues contribute to a rational causal inference, and two experiments looking at adults' inferences from causal demonstrations and informant testimony, focusing on cases where these sources conflict. We find that adults are able to combine social information with their own observations, and are sensitive to the reliability of each. Adults are also sensitive to the accuracy, certainty and self-knowledge of the informant, a result confirmed by comparing predictions from models with and without these variables.

Introduction

People face challenging causal learning problems on a daily basis. They have a variety of information they can use to help solve these problems, including directly observed patterns of cause and effect, and social data such as the statements of others about existing causal relationships. Informant testimony is a key type of social information that guides learning across domains, but the role of testimony in causal learning has not been extensively explored. We attempt to better understand how people combine different sources of information when making causal inferences, and in particular how they integrate their own observations with testimony and how this affects their future evaluation of the social informant.

Both children and adults are skilled causal learners, and can use information from social demonstration to inform their causal inferences (e.g. Kushnir, Wellman, & Gelman, 2008; Sobel & Sommerville, 2009; McGuigan, Makinson, & Whiten, 2011). Research on how we incorporate information from the social context into our causal judgments has investigated how we learn by observing other people (e.g. Goodman, Baker, & Tenenbaum, 2009; Buchsbaum, Gopnik, Griffiths, & Shafto, 2011), and by observing different types of people (e.g. Kushnir et al., 2008), but has not examined in detail how we make inferences about their credibility based on their causal statements.

Recently, there has been a growing literature on how people, especially children, evaluate informants (e.g. Borckardt, Sprohge, & Nash, 2003; Corriveau, Meints, & Harris, 2009; Koenig & Harris, 2005), including work on how children integrate their prior knowledge with informant testimony (e.g. Jaswal, 2010; Jaswal & Markman, 2007). Here, we explore how people combine information from causal observations and testimony, both to make causal judgments and to evaluate the informants themselves, especially in cases where these sources of data contradict each other.

Integrating testimony with other sources of evidence is particularly interesting and challenging because the quality of the informant and of the information they communicate can vary. Multiple aspects of informants and their testimony contribute to the value of the information they provide, and to how much they should be trusted in the future. These include the level of certainty informants express, their past accuracy, and their self-knowledge – how well their certainty reflects their true knowledge level (for an exploration of a similar idea in the context of eye-witness testimony see Tenney, Small, Kondrad, Jaswal, & Spellman, 2011).

All of these factors might impact people's evaluation of how knowledgeable an informant is, and how useful the information they offer will be. We aim to tease apart these variables to better characterize their influence. Bayesian modeling provides a mechanism to help us explicitly represent the contributions of different sources of information to judgments about causal structure and informant credibility. Previous work has used such models to explore the role of social observations in causal learning (e.g. Goodman et al., 2009), and to evaluate the role of informant knowledgeability and helpfulness (Shafto, Eaves, Navarro, & Perfors, in press). Here we present a model that helps us evaluate the roles of observed cause and effect patterns, as well as an informant's expressed certainty, current and past accuracy, and awareness of their own knowledge level, when making a causal inference.

In this paper, we first review a study exploring how preschoolers combine information from informant testimony with conflicting information from observed causal data. Next, we introduce a computational model of causal inference from testimony that explicitly represents the roles of informant certainty, accuracy and self-knowledge, as well as direct causal observations, allowing us to assess the contributions of each to a rational causal inference. We then present a series of adult experiments motivated by both the model and the child experiments. Finally, we conclude by discussing how predictions by models including some or all of these variables provide us with further insight into our ability to learn from multiple sources, and the information we use to determine when to trust what other people say.

Children's Causal Inferences from Testimony

Bridgers, Buchsbaum, Seiver, Gopnik, and Griffiths (2011) presented preschoolers with either an informant who claimed to know which of two blocks was better at activating a machine or an informant who claimed to be guessing, and with observed statistical data that contradicted the informant's claim. The study investigated which source of information (the person or the data) children would rely on to resolve the conflict as well as how likely children would be to trust the informant in a new situation. Though both informants made incorrect predictions, the naïve informant actually demonstrated more self-knowledge because she knew she did not know, while the knowledgeable informant was unaware she was mistaken.

Results from this study imply that preschoolers are sensitive to the certainty and accuracy of an informant – they were more likely to trust the informant's endorsement over the data when the informant was knowledgeable than when she was naïve, and were more likely to trust the knowledgeable informant before her inaccurate statements than afterwards. However, these results also suggest that children may not be as sensitive to an informant's level of self-knowledge, since children were as likely to trust the knowledgeable informant (who was mistaken in her certainty) as they were to trust the naïve informant (who was correctly uncertain) in a new situation.

Intuitively, an informant's certainty, past accuracy, *and* self-knowledge should all be useful indicators of an informant's credibility, and other research has suggested that adults may be sensitive to all three (Tenney et al., 2011). A computational model of how people combine information from both observed data and an informant to determine the likelihood of a causal relationship could help clarify the factors impacting people's resolution of the conflict, and their decision of whether or not to trust the informant in the future.

Modeling Causal Inference From Testimony

When people make causal inferences that rely on another person's testimony, these inferences may take into account social information besides the informant's statements about the world. As noted earlier, there is evidence that both children and adults are sensitive to an informant's expressed certainty as well as their previous accuracy. People may also have preexisting assumptions about how knowledgeable others tend to be in general, and how often others make mistakes in their assertions. Finally, there is some evidence that at least adults are sensitive to others' self-knowledge (Tenney et al., 2011).

These different pieces of social information also interact with the individual's own causal observations. It can therefore be difficult to disambiguate the contributions of all these variables when observing people's resulting causal inferences. The purpose of this model is to help evaluate the roles of these different variables by making explicit our assumptions about how they should contribute to a normative causal inference. The model makes causal inferences using both direct observation of potential causes and their outcomes, and information provided by an informant's statements. This includes both statements about the causal system, and the informant's level of confidence in their knowledge of the system. We can then examine the model parameters that best fit human performance on an inference task, contrasting them with simpler models leaving out some of the contributing variables, to evaluate which sources of information people in fact rely on.

The model is defined in terms of observed variables representing causal outcomes, statements by an informant about the causal strengths of potential causes, and about their level of certainty about their causal knowledge. The model also has hidden variables representing the actual causal strengths of the potential causes, the informant's general level of knowledgeability, their specific knowledge of the individual causes, and their level of self-knowledge – how well they know what they know. We capture the complex relationships among these variables in a graphical model (see Figure 1).

In this model, we assume that all of the variables are binary valued, as they were presented to children in the Bridgers et al. (2011) experiments. Each cause c has a causal strength w_c where $p(w_c = \rho) = \gamma$ and $p(w_c = 1-\rho) = 1-\gamma$. Here, ρ is some relatively high probability of effect, corresponding to the causal strength "almost always makes it go" in Bridgers et al. (2011), and $1-\rho$ is some relatively low probability of effect, corresponding to "almost never makes it go".

The informant's prediction r_c about the causal strengths of each cause depends on the true causal strength w_c, and on their knowledge of the cause k_c. Here, we assume that $k_c \in \{0,1\}$, corresponding to two possible states of knowledge of a cause: guessing and knowing. If $k_c = 1$ (the informant knows about the causal strength of c) then $p(r_c = w_c \mid k_c = 1, w_c) = 1-\varepsilon$ — an informant with knowledge of cause c will predict the true value of w_c with probability $1-\varepsilon$, but with small error probability ε will report the incorrect value. On the other hand, if $k_c = 0$ and the informant is guessing about cause c, then $p(r_c = w_c \mid k_c = 0, w_c) = p(r_c = w_c \mid k_c = 0) = 0.5$ – the informant will choose uniformly at random between the two possible causal strengths.

We assume that the probability of the informant knowing about a particular cause depends on the informant's global knowledgeability $g \in \{0,1\}$, with the informant having probability κ of being globally knowledgeable. If $g = 1$ then the informant is globally knowledgeable and $p(k_c = 0 \mid g = 0) = 1-\tau$ and $p(k_c = 0 \mid g = 0) = \tau$, that is, the informant is knowledgeable about cause c with some relatively high probability τ. Conversely, if $g = 0$ and the informant is globally ignorant then $p(k_c = 0 \mid g = 0) = \tau$ and $p(k_c = 0 \mid g = 0) = 1-\tau$.

Finally, we need to represent the informant's statement about their knowledge of cause c. The informant's statement q_c depends on their knowledge k_c, and their level of self-knowledge s. We assume that $s \in \{0,1\}$, corresponding to two possible states of self-knowledge: accurate and inaccurate. If $s = 1$ (the informant has accurate self-knowledge) then $p(q_c = k_c \mid s = 1, k_c) = 1-\delta$ — the informant will accurately report their level of knowledge k_c with probability $1-\delta$, but with small error probability δ will report their level of knowledge inaccurately.

If $s = 0$ and the informant has inaccurate self-knowledge then $p(q_c = k_c \mid s = 0, k_c) = p(q_c = k_c \mid s = 0) = 0.5$ — the informant will choose uniformly at random when stating their knowledge of the causal system. We assume that any given informant has probability η of having accurate self-

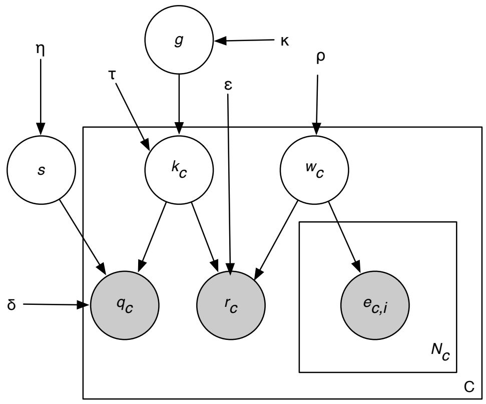

Figure 1: Causal testimony graphical model

knowledge, and $1-\eta$ of having inaccurate self-knowledge.

We assume $p(\text{choose } c) \propto p(\text{effect} \mid c, \text{obs})$ — people choose causes in proportion to how likely they think they are to produce the effect, given their observations (including the informant's statements). This is computable from the model and the dependencies defined in our graphical model, Figure 1. To evaluate our model, we conducted a series of experiments with adults, exploring whether they can successfully use an informant's certainty, accuracy and self-knowledge when making causal inferences.

Experiment 1: Adult Inferences from Testimony

We investigate how adults resolve a conflict between an informant's explanation of how a causal system works and actual demonstrations of that system, closely following the procedure of Bridgers et al. (2011). We hypothesized that like preschoolers, adults would be sensitive to the certainty of the informant and more likely to trust an informant who claimed to be knowledgeable over one who claimed to be naïve. However, unlike children, we predicted that adults would be sensitive to an informant's level of self-knowledge, and would be more likely to extend their trust to a previously incorrect informant who had claimed ignorance than a previously incorrect informant who had claimed knowledgeability.

Methods

Participants A total of 204 participants were recruited: 100 were UC Berkeley undergraduates who received course credit and 104 were Mechanical Turk workers who were compensated $0.50. Participants were randomly assigned to one of two experimental groups: the Knowledgeable condition (n = 103) or the Naïve condition (n = 101).

Stimuli The experiment was a web-administered survey involving text and pictures. An image of a brown-haired woman was the informant, and an image of a blonde woman was her assistant. The machine was an image of a green box with a black top. The activated machine had a yellow top and musical notes were placed around it. The blocks were a green rectangle, a pink disk, an orange cube, and a blue cylinder.

Procedure First, a woman named Ann (the *informant*) introduced a machine that could light up and play music

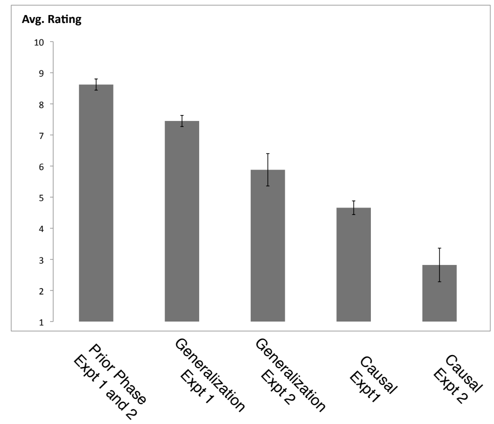

Figure 2: Adult ratings in the Knowledgeable condition vary continuously with the strength of the data

when certain blocks were placed on top. She then introduced two different blocks and explained that one block almost always activated the machine (the *endorsed* block), while the other block almost never did (the *unendorsed* block). In the Knowledgeable condition, the informant claimed that she really knew which block was better at activating the machine, while in the Naïve condition, the informant claimed that she was just guessing. Besides this difference, the procedure was identical across conditions. Ann then said she needed to leave, and her assistant Jane continued the experiment.

Jane first asked participants to rate how likely each block would be to activate the machine on a scale from 0 (definitely will not make it go) to 10 (definitely will make it go) (the *prior* rating). Jane demonstrated each block on the machine, providing probabilistic evidence that contradicted Ann's claim: the endorsed block only activated the machine 2/6 times, while the unendorsed block activated it 2/3 times[1]. Participants were then asked to again rate how likely each block would be to activate the machine (the *causal* rating).

Finally, Ann returned with two new blocks, and in both conditions, claimed that she *knew* which block was better at activating the machine. Jane asked the participants to rate how likely they thought these new blocks were to activate the machine (the *generalization* rating).

Results and Discussion

We analyzed causal efficacy ratings with a $2 \times 3 \times 2$ repeated measures ANOVA, with endorsement (endorsed or unendorsed), and rating phase (prior, causal, generalization) as the within subject variables, and knowledge condition (Knowledgeable or Naïve) as the between subjects variable. There was a main effect of endorsement – adults rated the endorsed block more highly across phases and conditions ($F(1, 1206) = 77.69$, MSE = 372.1, $p < 0.001$). There was also an effect of endorsement $\times$ condition ($F(1, 1206) = 73.19$, MSE = 350.5, $p < 0.001$), with the endorsed block rated higher in the Knowledgeable condition across phases, and of endorsement $\times$ phase ($F(2, 1206) = 62.18$, MSE = 297.8, $p < 0.001$),

[1]This pattern of probabilistic data is the same as was used in Experiment 3 of Kushnir and Gopnik (2007).

with the rating of the endorsed block decreasing and of the unendorsed block increasing in the causal phase. Finally, there was a significant three-way interaction of endorsement $\times$ phase $\times$ condition ($F(2,\ 1206) = 13.89$, MSE = 66.5, $p < 0.001$), indicating that the degree to which the ratings change between phases varied by the claimed knowledge level of the informant and whether the block was endorsed.

We explored the particulars of these findings via within phase ANOVAs and t-tests. In the prior phase, a 2×2 ANOVA revealed significant effects of endorsement ($F(1, 148)=75.30$, MSE = 371.8 $p < 0.001$) and of knowledge $\times$ endorsement ($F(1, 148) = 80.47$, MSE = 397.4 $p < 0.001$) on adults' ratings. In both conditions, adults were significantly more likely to give the endorsed block a higher rating (paired t-tests. Knowledgeable: $t(102) = 17.76$, $p < 0.001$, Naïve: $t(100) = 5.02$, $p < 0.001$) though participants in the Knowledgeable condition gave the endorsed block a significantly higher rating than those in the Naïve condition (two sample t-test, $t(202) = 5.72$,$p < 0.001$). These results suggest that before seeing any data, adults in both conditions were likely to trust the informant's testimony. However, adults were also sensitive to the certainty expressed by the informant, trusting the endorsement of the informant to a greater extent in the Knowledgeable than in the Naïve condition.

In the causal phase, a 2×2 ANOVA again revealed significant effects of endorsement ($F(1,148) = 16.89$, MSE = 75.42 $p < 0.001$) and of condition $\times$ endorsement ($F(1, 148) = 15.27$, MSE = 68.17 $p < 0.001$). There was no difference in adults' ratings of the endorsed and unendorsed blocks in the Knowledgeable condition (paired t-test, $t(102) = 1.39$, $p = 0.17$), while adults in the Naïve condition gave the unendorsed block a higher rating (paired t-test, $t(102) = 7.18$, $p < 0.001$). Adults in the Knowledgeable condition gave the endorsed block a higher rating than adults in the Naïve condition (two sample t-test, $t(202) = 2.00$, $p < 0.05$) and vice versa for the unendorsed block (two sample t-test, $t(202) = 3.62$, $p < 0.001$). The fact that in the causal phase adults thought the two blocks had approximately equal causal efficacy in the Knowledgeable condition but rated the unendorsed block more highly in the Naïve condition suggests that participants were responding to both the observed statistical data and the claimed knowledge level of the informant.

Finally, a 2×2 ANOVA in the generalization phase showed an effect of endorsement ($F(1, 402) = 104.82$, MSE = 520.4, $p < 0.001$) and a marginal effect of condition $\times$ endorsement ($F(1, 402) = 3.61$, MSE = 17.9, $p = 0.058$). Adults in both conditions gave the endorsed block higher ratings (paired t-tests. Knowledgeable: $t(102) = 13.21$, $p < 0.001$. Naïve: $t(102) = 8.23$, $p < 0.001$). Unlike the previous phases, there was no difference between conditions in ratings of the endorsed block (two sample t-test, $t(202) = 0.82$, $p = 0.41$),

We also looked at differences between the prior, causal, and generalization phases in both conditions. Adults' ratings of the endorsed and unendorsed block differed in each phase-to-phase comparison in both conditions. Overall, adults' ratings of the endorsed block in the Knowledgeable condition decrease from prior to generalization (paired t-test, $t(102) = 3.30$, $p < 0.01$) to causal (paired t-test, $t(102) = 10.93$, $p < 0.001$). Adults' ratings of the endorsed block in the Naïve condition decrease from generalization to prior (paired t-test, $t(100) = 2.12$, $p < 0.05$) to causal (paired t-test, $t(100) = 8.31$, $p < 0.001$). If we compare ratings in the two no-data phases – prior and generalization – we can capture how participants' evaluation of the informant might have changed after receiving evidence about their accuracy. Adults' ratings decrease between prior and generalization in the Knowledgeable condition, while they increase in the naïve condition. This difference suggests that adults may actually be sensitive to an informant's self-knowledge, increasing their trust in an informant who was incorrect but uncertain in the past over an informant was incorrect but certain.

We did not find significant differences in participants' generalization ratings, implying that adults were willing to trust both informants more or less equally regardless of their level of self-knowledge. However, due to the stochastic nature of the data, participants may have made excuses for the discrepancy between the data and the knowledgeable informant's endorsement, possibly appealing to hidden causes that would explain away the conflict. In Experiment 2, we contrasted an informant's testimony with deterministic data to see if increasing the apparent inaccuracy of the informant would reveal a use of informant self-knowledge.

Experiment 2: Deterministic Data

We replicated Experiment 1 but with deterministic data, to explore how changing the strength of the data might impact adults' inferences. We predicted that adults would weight conflicting deterministic data more heavily than conflicting probabilistic data, and would therefore prefer the unendorsed block more often in the causal phase. We also predicted that the stronger data would exaggerate the knowledgeable informant's lack of self-knowledge leading adults to consider the naïve informant's testimony as more reliable than the knowledgeable informant's in the generalization phase.

Method

Participants A total of 74 participants recruited from Mechanical Turk were compensated \$0.50 and randomly assigned to the Knowledgeable condition ($n = 34$) or the Naïve condition ($n = 40$).

Stimuli Stimuli were identical to those in Experiment 1.

Procedure The procedure was the same as in Experiment 1 except that the endorsed block activated the machine 0/6 times, while the unendorsed block activated it 6/6 times.

Results and Discussion

We analyzed causal efficacy ratings with a $2 \times 3 \times 2$ repeated measures ANOVA on endorsement, ratings phase, and knowledge condition, and found no main effects, but significant effects of knowledge $\times$ endorsement ($F(1, 426) = 16.99$, MSE = 95.40, $p < 0.001$), endorsement × phase ($F(2, 426)$ = 54.67, MSE = 306.93, $p < 0.001$) and knowledge × endorsement × phase ($F(2, 426)$ = 16.87, MSE = 94.72, $p < 0.001$).

Replicating the prior phase results of Experiment 1, a 2 × 2 ANOVA revealed significant effects of endorsement ($F(1, 142)$ = 60.59, MSE = 159.49, $p < 0.001$) and of endorsement × knowledge ($F(1, 142)$ = 62.97, MSE = 165.74, $p < 0.001$). Adults again rated the endorsed block as more likely to make the machine go (paired t-test. Knowledgeable: $t(33)$ = 20.66, $p < 0.001$. Naïve: $t(39)$ = 4.69, $p < 0.001$) and were even more likely to do so if they were in the Knowledgeable condition (two sample t-test, $t(72)$ = 5.45, $p < 0.001$).

A 2 × 2 ANOVA in the causal phase showed effects of endorsement ($F(1, 142)$ = 74.34, MSE = 402.2, $p < 0.001$) and of endorsement × knowledge ($F(1, 142)$ = 16.57, MSE = 89.7, $p < 0.001$). As predicted, adults were more likely to give the unendorsed block a higher causal rating than the endorsed block in both conditions (paired t-test. Knowledgeable: $t(33)$ = 5.76, $p < 0.001$. Naïve: $t(39)$ = 20.72, $p < 0.001$) . Even so, participants in the Knowledgeable condition were more likely to give the endorsed block a higher rating and the unendorsed block a lower rating than participants in the Naïve condition (two sample t-test. Endorsed: $t(72)$ = 2.63, $p < 0.05$. Unendorsed: $t(72)$ = 3.39, $p < 0.01$), showing they still took the informant's certainty into account..

Adults in both conditions gave lower ratings to the endorsed block as compared to the causal phase of Experiment 1 (two sample t-tests. Knowledgeable: $t(135)$ = 3.77, $p < 0.001$. Naïve: $t(139)$ = 7.90, $p < 0.001$). Adults thus were sensitive to the deterministic data, and recognized that the unendorsed block was more causally efficacious.

In the generalization phase, a 2 × 2 ANOVA revealed an effect of endorsement ($F(1, 142)$ = 5.92, MSE = 52.14, $p < 0.05$) and a marginally significant effect of endorsement × condition ($F(1, 142)$ = 3.34, MSE = 29.44, $p = 0.07$). There was no significant difference in ratings of the endorsed and unendorsed blocks in the Knowledgeable condition (paired t-test, $t(33)$ = 1.69, $p = 0.10$), but adults in the Naïve condition rated the endorsed block as more effective that the unendorsed block (paired t-test, $t(39)$ = 4.02, $p < 0.001$).

Comparing across experiments, we found that adults in the Knowledgeable condition of Experiment 1 gave the endorsed block a higher generalization rating than those in Experiment 2 (two sample t-test. $t(135)$ = 3.77, $p < 0.001$). On the other hand, there was no difference in adults' generalization ratings of the endorsed block in the Naïve condition (two sample t-test. $t(135)$ = 0.41, $p = 0.68$). As predicted, increasing the strength of the conflicting data magnified the knowledgeable informant's inaccuracy. However, since the naïve informant claimed ignorance, this change did not affect how adults evaluated future information from this informant. In general, trust in the knowledgeable informant varied continuously with the increasingly conflicting data, Figure 2.

Finally, comparing between phases of Experiment 2, in the Knowledgeable condition, adults' ratings of the endorsed

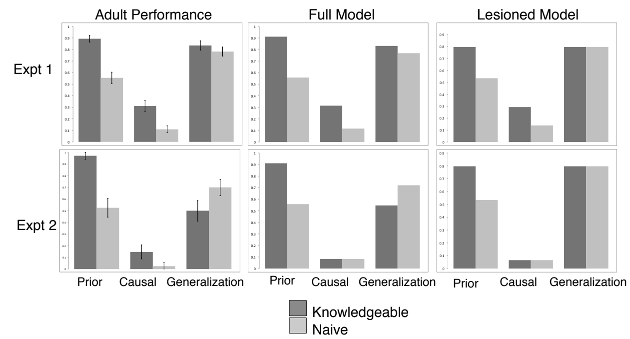

Figure 3: Probability of choosing the endorsed block, experimental results vs model

block in the Knowledgeable condition decrease between prior and generalization phases (paired t-test, $t(33)$ = 4.99, $p < 0.001$). Thus, adults are likely to intially trust the endorsement of an informant, whereas they are less likely to extend that trust to a new situation (the generalization phase) after observing evidence that contradicts the informant's prior claim. Conversely, in the Naïve condition there was no difference between adults' prior and generalization phase ratings (paired t-test, $t(39)$ = 0.79, $p < 0.43$). Thus, adults' evaluation of the credibility of the naïve informant does not appear to have changed after observing the conflicting data. This further suggests adults' sensitivity to self-knowledge when determining the usefulness of an informant's statement.

Modeling People's Inferences

We can use our model to further test whether an informant's expressed certainty, accuracy and apparent self-knowledge inform adults' causal judgments. We first evaluate the model by fitting it to data from Experiment 1. In order to be consistent with Bridgers et al. (2011), where children were asked to choose the better block, we assumed that for each set of ratings adults would choose the block they had rated as most likely to be effective. We then optimized the log likelihood of these choices under the model. The best fitting model corresponded to model parameters of $\rho = 0.91$, $\gamma = 0.40$, $\varepsilon = 0.01$, $\delta = 0.1$, $\tau = 0.91$, $\kappa = 0.74$ and $\eta = 0.93$, (Pearson's $\rho = 0.999$, $p < 0.001$). However, a reasonable range of values around these settings also fit the data well. Of particular note are the values of κ and η, corresponding to a belief that most people have good general knowledge, but a substantial minority are relatively clueless, and that almost everyone is aware of their own knowledge level, but a small number of people tend to inaccurately assess what they know.

We tested the generalization of these model parameters by looking at how well they predict adult performance in Experiment 2. The parameters fit to the Experiment 1 data also provide a good fit to the results of Experiment 2 (Pearson's $\rho = 0.9664$, $p < 0.001$). This suggests that our model is accurately capturing human performance, so we can use it to tease apart the contributing variables to adult causal inferences.

We then conducted a nested model comparison, examining whether representing the informant's global knowledgeability and their self-knowledge add explanatory value to the model, by creating a series of "lesioned" models, lacking global knowledge g and self knowledge s. Removing global knowledge corresponds to a model that assumes that all informants have the same probability of knowing about all causes, and that an informant knowing about one cause does not make them any more likely to know about others. Removing self-knowledge corresponds to a model where informants' statements of certainty always reflect their true knowledge – if they say they know something, then they must really know it.

Compared to a model lacking both global knowledge and self-knowledge variables, adding global knowledge to the model resulted in a marginally significant ($\chi^2(1) = 3.29, p = .07$) improvement in model fit, Figure 3. Adding self-knowledge on its own did not improve model performance ($\chi^2(1) = 0.392, p = 0.53$), however adding both self-knowledge and global knowledge variables significantly improved model fit over having only global knowledge ($\chi^2(1) = 22.04, p < 0.001$), or having neither ($\chi^2(1) = 25.30, p < 0.001$), Figure 3.

Qualitatively, while the addition of global knowledge and self-knowledge modestly improves the model fit to Experiment 1, their biggest effect is on the fit to Experiment 2, where the deterministic data made it clear that the informants' endorsements were incorrect. This supports the interpretation that in the first experiment participants continued to extend trust to the knowledgeable informant by explaining away their apparent incorrectness, inferring that the ambiguous data could have been "unlucky". However, in Experiment 2, where the data strongly support the inference that the informant was incorrect, it requires both a concept of general knowledge ("if this person was wrong before, they're more likely to be wrong again"), and self-knowledge ("they said they 'knew' before and they didn't, why should I think they know now?" vs. "they said they didn't know, so it's okay that they were wrong"), in order to correctly infer that the naïve informant is more deserving of trust in the generalization phase.

Overall, the close fit of the model to adult performance, and its ability to generalize from Experiment 1 to Experiment 2, confirms that adults are rationally integrating information from their direct observations with testimony from a social informant when making causal inferences. Our nested model comparison demonstrates that adults take into account the informant's past performance when deciding how much to weight their current testimony, and in particular that adults are sensitive to both the apparent knowledgeability of the informant and their level of self-knowledge, when assessing the informant's past performance.

Conclusion

We examined how people combine an informant's statements about a causal system with direct observations of that system, and how this influences their evaluation of the informant's knowledgeability and credibility. Together, Experiments 1 and 2 suggest that adults are weighting and integrating evidence from both observed data and the informant in their causal inferences, and that their trust in the informant is moderated by the degree to which the informant's testimony conflicts with the data. Adults were sensitive to both the informant's certainty and accuracy, and to how well the informant's certainty reflected their accuracy. These findings support our intuition that self-knowledge is a valuable cue adults can use to determine the trustworthiness of an informant's testimony. The close fit of our model to adult performance further confirms these results. It also allows us to make specific predictions for how people might perform in future experiments, such as how people should optimally combine information from multiple informants, especially when they make contradictory claims, an experiment we are currently running. Overall, these results provide us with further insight into how we learn from and evaluate the sources of information available to us and in particular, revealing that knowing that you do not know can be just as important as knowing that you know.

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