Don’t throw the associative baby out with the Bayesian bathwater: Children’s retrospective reasoning about multiple causes suggests multiple systems for causal inference

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Data availability statement: The code and network-modeling scripts are available upon reasonable request.

Conflicts of interests: none

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Submitted to *Developmental Science* on DATE

Abstract

Causal reasoning is a fundamental cognitive ability that enables human beings to learn about the complex interactions in the world. The mechanisms that underpin causal reasoning, however, are not well understood. An open question is the extent to which children retrospectively reevaluate causal efficacy given ambiguous information, based on observing novel patterns of data. Here, we report two experiments that test children’s capacity to engage in such inferences. We also fit those data to different computational frameworks – one more associative and one more Bayesian – to consider the strengths and weaknesses of each approach, and the possibility that these approaches together better explain children’s causal reasoning than either approach individually.

Keywords: causal reasoning; causal mechanisms; computational models; analytical models; associative learning; Bayesian inference

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Few capacities are more important than the ability to reason and make inferences about cause-and-effect relations. Causal reasoning enables human learners to make predictions and inferences (e.g., Bullock, et al., 1982; Leslie & Keeble, 1987; Oakes & Cohen, 1990; Shultz, 1982), to intervene on those relations to generate new effects (e.g., Butler et al., 2020; Gopnik et al., 2001; Schulz et al., 2007), and to reason about counterfactual claims – both about what might have been and how events could have turned out differently (e.g., Harris et al, 1996; Sobel, 2004; Walker & Nyhout, 2020). These and many other studies (e.g., Bonawitz & Lombrozo, 2012; Gopnik et al., 2001; Legare et al., 2010; Meltzoff et al., 2014; Walker & Gopnik, 2014) posit that young children have sophisticated causal reasoning capacities.

A fundamental question that underlies this research is *how*—that is, by what cognitive mechanism or mechanisms—children make such inferences. One answer to this question is that children’s causal inferences are underpinned by a Bayesian-inference mechanism that is in place early in development. The crux of this idea is that learners use a simple form of Bayes’ rule to reason about causal events and to choose the causal hypothesis—among potentially infinitely many causal hypotheses—that is most consistent with the observed data (e.g., Bonawitz et al., 2014; Gopnik & Wellman, 2012; Griffiths & Tenenbaum, 2005, 2007; Xu, 2019). Crucially, causal reasoning starts with statistical learning capacities that are present in infancy (e.g., Gomez, 2002; Johnson et al., 2006; Kirkham et al., 2002; Marcus et al., 1999; Saffran et al., 1996) but that develop into a system that infers abstract patterns of coherent causal structure from probabilistic data.

An alternative perspective is that associative learning alone sufficiently explains children’s causal inferences. On this view, children build up a representation of causal structure from connecting and processing multiple associative relations and statistical regularities. Connectionist accounts of causal reasoning (e.g., Rogers & McClelland, 2004), comparative investigation between non-human animals and adults (e.g., Heyes, 2012), and studies of instrumental action and conditioning on human infants (e.g., Greco et al., 1990; Rovee-Collier, 1999) suggest that associative processing is a candidate mechanism for how children reason in the world.

One way to illustrate the tension between these hypotheses in development is through investigations of *backwards blocking* (Shanks, 1985). This is a retrospective inference in which learners reevaluate the causal status of an ambiguous event based on learning more about the status of other unambiguous events (see also De Houwer et al, 2002; Larkin et al, 1998; Kruschke & Blair, 2000; Lovibond et al., 2003; Van Hamme & Wasserman, 1994, for other work on adults). For example, Sobel et al. (2004) introduced 3- and 4-year-olds to a machine called a “blicket detector” that lit up and played music when certain objects were placed on it (Gopnik & Sobel, 2000). Children were then shown that two novel objects, A and B, together caused the detector to activate when they were placed on the machine. Children were then shown that object A alone activated the machine. Children in both conditions were then asked which of the two objects were blickets and to make the machine go by placing the blicket on the detector. Sobel et al. (2004) found that the 4-year-olds (and to a lesser extent, 3-year-olds) were less likely to place B on the machine than on trials in which object A did not make the machine go by itself (a condition referred to as *indirect screening off*). Using an anticipatory eye-tracking procedure, Sobel and Kirkham (2006) found that 8-month-olds showed this same response pattern.

These findings were interpreted as support for Bayesian inference rather than associative learning. This is because some associative models (e.g., Rescorla & Wagner, 1972) predict that the strength between object B and the machine’s activation is equivalent between the backwards blocking (where A is effective) and indirect screening-off (where A is not effective) trials. However, some caution should be exercised before accepting the conclusion that Bayesian inference rather than associative learning underpins how children process backwards blocking events. One reason is that it is unclear whether the difference in how children treated object B was due to backwards blocking, indirect screening-off, or some combination of both (Beckers et al., 2005; McCormack et al., 2009). In particular, McCormack et al. (2009) showed children a standard backwards blocking sequence (AB+, A+), and compared their judgments of the efficacy of object B with a sequence in which a third object, unrelated to the compound set, had efficacy (i.e., AB+, C+). The 4-year-olds they investigated did not differ in their judgments (although 5-year-olds did). While these studies used different control trials, the critical point of agreement between these investigations is that at some point in development, children have the capacity to make retrospective inferences. But the fundamental question remains as to how children engage in such reasoning.

In light of these unresolved issues, the present investigation had two goals. The first goal was to examine backwards blocking in the presence of multiple potential causes and using a logic like that of McCormack et al. (2009). Five- and 6-year-old children were introduced to a computer-animated “blicket detector” machine and were told that their task was to determine which objects activated the machine. We chose to test 5- and 6-year-olds as opposed to 4-year-olds because the latter group likely has more robust information-processing capacities than the former group and thus a greater chance of engaging in Bayesian inference. Research by Sobel et al. (2017; see also Erb & Sobel, 2014) is consistent with this contention. Participants then received either two backwards blocking and two backwards blocking control trials or two indirect screening-off and two indirect screening-off control trials. Participants in both conditions were then asked to indicate whether the objects in each trial were blickets. The second goal was to determine whether children’s causal inferences were best explained by an associative-learning mechanism or a simple Bayesian mechanism. We did this by fitting a connectionist (associative learning) model and a Bayesian model to participants’ data. The Experiment below addresses the first goal. The “Computational Models” section addresses the second goal.

**Experiment 1**

**Method**

**Participants.** Participants were 32 5-year-olds (16 boys and 16 girls; *M* = 64.81 months, range = 60-71 months, SD = 3.48) and 31 6-year-olds (17 boys and 15 girls; *M* = 77.81 months, range = 72-83 months, SD = 3.78). Sample size was determined based on previous studies on backwards blocking reasoning in human children (e.g., Gopnik & Sobel, 2000; Griffiths et al., 2011; Sobel et al., 2004). Two children were excluded from analysis for failing to participate (*N* = 1) or missing video (which made coding their responses impossible) (*N* = 1). Although most children were from white, middle-class backgrounds, a range of ethnicities that resembled the diversity in the population were represented. All children were tested in a quiet room at a local children’s museum.

**Materials.** The “device” used in the current study was a computer-animated version of the canonical blicket detector (e.g., Gopnik & Sobel, 2000). The device was a white rectangle with a black border that measured 5.99 cm × 23.47 cm. If the device was “on”, the white region of the rectangle turned blue. No music was played when the machine activated. If the device was “off”, the white region remained white. A maximum of 4 differently colored circles were used, and each circle measured 2.67 cm × 2.67 cm (see Figure 1 below). The machine was designed such that it activated immediately when the bottommost edge of a circle predetermined to be a blicket contacted it. At the start of any given trial, three (for the backwards blocking or indirect screening-off trials) or four (for the backwards blocking or indirect screening-off control trials) equally spaced circles appeared above the machine. Finally, the videos contained a built-in script, which experimenters read. All video events were created in Microsoft PowerPoint.

**Procedure.** Participants were tested in a quiet room in local children’s science museum. At the beginning of the experiment, all participants were shown a pretraining video. The video consisted of a rectangular base (i.e., the previously mentioned “blicket detector”) and two shapes (i.e., a gray triangle and a gray pentagon). Crucially, these shapes were unrelated to the circles used during the main portion of the experiment. The pretraining phase began with the triangle (object A) and pentagon (object B) above the machine and next to one another. Object A then descended until it contacted and immediately activated the machine (i.e., the white region changed from white to blue). Object A then returned to its starting position above the machine. Object B then descended until it contacted and failed to activate the machine. Object B then returned to its starting position. Finally, both objects descended until they contacted and activated the machine. Participants were then asked whether each object was a blicket. This event was and was included to ensure that participants understood the task and recognized that individual objects could activate the machine and that the machine activated if at least one effective object was placed on it.

Following the pretraining phase, participants were given four trials. Half the participants received two backwards blocking trials and two backwards blocking control trials. The other half received two indirect screening off trials and two indirect screening off control trials. The order of these trials within each condition was counterbalanced using a Latin square design. Different colored objects were used across all trials to prevent carryover effects. A schematic of this procedure is shown in Table 1.

Diagram

Description automatically generated

Figure 1. Schematic of a Backwards Blocking experimental trial. The upper-right portion of the figure shows the backwards blocking event as it unfolded across time. The lower-left portion of the figure shows the three objects and the text, “Is this one a blicket?” above each object across time.

**Backwards Blocking Main and Control Trials.** The two backwards blocking main trials began with three differently colored objects, which were located above the machine. The text, “Look, I have these three toys. Let’s find the blickets. Watch what happens” appeared above the objects. All three objects (i.e., objects A, B, and C) then descended until they contacted and activated the machine. At this point, the text, “Look, these also make the machine go!” appeared above the objects. The objects then returned to their starting positions.

The left- or right-most (counterbalanced) object (which we will refer to here as object A) then descended until it contacted and immediately activated the machine. The text, “Look, this one makes the machine go!” then appeared above the objects. This object then returned to its starting position. Children were then asked whether each object was a blicket. Specifically, the text, “Is this one a blicket?” with a downward-facing arrow then appeared above each object, and participants were asked to indicate whether each object was a blicket. Children received two of these trials, which were identical except for the color of the objects.

The two backwards blocking control trials began with four differently colored objects (i.e., objects A, B, C, and D), which were located above the machine. Objects A, B, and C then descended until they contacted and activated the machine; object D remained in place while objects A-C descended onto the machine. Object D then descended by itself until it contacted and activated the machine. The left-right position of object D was counterbalanced. Children were then asked whether each object was a blicket. Children once again received two trials, which were identical except for the color of the objects.

**Indirect Screening-Off Main and Control Trials.** The procedures for the indirect screening-off main and control conditions were identical to the backwards blocking trials except that object A (main trials) and D (control trials) failed to activate the machine.

**Results**

Figure 2 shows the number of times children responded “yes” to the question “Is this a blicket” for each object. Using this dependent measure, the data were entered into a five-way linear mixed-effects model with Age as a continuous fixed effect, Condition (Backwards blocking vs. Indirect screening-off) as the between-subjects fixed effect, Trial Type (Experimental vs. Control), Objects (A vs. B vs. C vs. D), and Trial Number (Trial 1 vs. Trial 2) as the within-subjects fixed effects, and participant as the random effect. This analysis yielded several main-effects and two-way interactions, which were qualified by 3 three-way interactions. These included a three-way interaction among Age, Condition, and Object, χ*2*(3) = 7.90, *p* = .05, a three-way interaction among Condition, Trial Number and Object, χ*2*(3) = 13.31, *p* = .006, and a three-way interaction among Condition, Trial Type, and Object, χ*2*(2) = 64.85, *p <* .001.

To explore the first three-way interaction between Age, Condition, and Object, we conducted separate two-way linear mixed-effects models between Age and Object for each condition. Age was included as a continuous fixed effect, Condition as a between-subjects fixed effect, Object as a within-subjects fixed effect, and subjects as a random effect. Both linear models only yielded main effects of Objects, both χ2’s > 31.88, both *p*-values < .001, which indicated that participated treated the objects differently. To explore the second three-way interaction between Trial Number and Object for each condition. Trial Number and Object were included as within-subjects fixed effects and subjects were included as a random effect. Although both linear models yielded main effects of Object, both χ2’s > 31.86, both *p*-values < .001, only the two-way linear mixed-effects model for the Indirect Screening Off condition yielded an additional interaction between Trial Number and Object, χ*2*(3) = 9.57. This interaction reflected the fact that participants treated the objects differently across the two phases.

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Figure 2. Participants’ mean responses to whether each object was a blicket across the conditions and trial types. Bars show standard error.

To examine the final interaction between Condition, Trial Type, and Object, we constructed a set of one-way linear mixed-effects models for the experimental and control trials within the backwards blocking and indirect screening-off conditions. The Objects factor was treated as the sole within-subjects fixed effect in these follow-up analyses. Participants were once again treated as a random effect to control for the within-subject variance from multiple responses. The first one-way linear model for the control trials within the backwards blocking condition did not reveal a significant effect of Objects,χ2(3) = 1.34, *p* = .72. This means that participants treated the objects similarly in the control trials of the backwards blocking condition. In contrast, the second one-way linear model for the main trials within the backwards blocking condition revealed a significant main effect of Objects, χ2(2) = 55.20, *p* < .001. This main effect reflected the fact that participants considered object A to be more of a blicket (*M* = .98, *SD* = 0.13) than object B (*M* = .55, *SD* = 0.50), *t*(30) = 6.45, *p<* .001, or object C (*M* = .61, *SD* = 0.49), *t*(30) = 5.62, *p* < .001. Participants treated objects B and C equivalently, *t*(30) = -1.07, *p* = .29.

The third and fourth one-way linear models for the main and control trials within the indirect screening-off condition both revealed a significant main effect of Objects, both χ*2*-values > 76.81, both *p*-values < .001. This reflected the fact that participants considered object A (*M* = 0.26, *SD* = 0.44) in the ISO experimental trials and object D (*M* = 0.36, *SD* = 0.48) in the ISO control trials to be less likely to be blickets than any of the other objects, all *t*-values > -7.45, all *p*-values < .001. Participants treated object B and C equivalently in the experimental trials, *t*(30) = -0.77, *p* = .29, and objects A-C equivalently in the control trials, all *t*-values < -1.07, all *p*-values > .29.

Finally, to examine whether there was any evidence specifically of backwards blocking—that is, whether participants provided higher combined ratings of objects A, B and C in the control trials their combined ratings of objects B and C in the experimental trials—data were entered into a two-way linear mixed-effects model with Trial Type and Object as the within-subjects fixed effects and participants as the random effect. This analysis revealed only a main effect of Trial Type, *χ2*(1) = 21.97, *p* < .001. This result indicated that participants did engage in backwards blocking reasoning: they provided higher ratings of objects A, B, and C in the control trials than objects B and C in the experimental trials.

**Discussion**

The results of Experiment 1 indicated that participants engaged in backwards blocking reasoning. Specifically, participants were more likely to treat the redundant objects as blickets during the backwards blocking control trials than during the backwards blocking experimental trials. These results indicate that participants show some evidence of backwards blocking reasoning when asked to make inferences about multiple potential causes. However, an open question concerns whether participants will continue to engage in backwards blocking reasoning when two rather than one object participants on the machine during the second (i.e., the A+) phase of the backwards blocking condition.

**Experiment 2**

**Method**

**Participants.** ADD RELEVANT INFO WHEN WE GET IT.

**Stimuli, Design, and Procedure.**  All aspects of Experiment 2 were identical to Experiment 1 with one exception: Two objects participated on the machine during the elemental phases of the backwards blocking and indirect screening-off events. Thus, participants in the backwards blocking condition saw an ABC+ AB+ series of events during the experimental trials and an ABC+ DE+ series of events during the control trials. In contrast, participants in the indirect screening-off condition saw an ABC+ AB- series of events during the experimental trials and an ABC+ DE- series of events during the control trials. Similar to Experiment 1, to prevent potential carryover effects differently colored objects were used across all trials to prevent carryover effects and the left-right positions of objects A and B during the experimental trials and D and E during the control trials in both conditions were counterbalanced.

**Results**

**Computational Models**

We fit two competing computational models to these data. The first was a model based on Bayesian inference, described initially by Sobel et al. (2004) and in more detail in Griffiths et al. (2011). The second was a simple connectionist model. The computational details of both models are described in the Supplemental Materials. Below, we briefly describe each model.

**Bayesian Model.** The Bayesian model starts with a set of hypotheses *H*. Each hypothesis *h* ∈ *H* is assigned a *prior probability*, *p*(*h*), which indicates the initial belief in that a learner has in a particular hypothesis prior to seeing data. After the learner observes data, *d*, the learner computes a posterior probability, *p*(*h* | *d*), given an updated belief about each hypothesis given the data. This is done using Bayes’ rule, shown in Equation 1:

(1)

In this formula, *p*(*d | h*) is the probability of the data *d* given each a particular hypothesis *h* (also known as the *likelihood*).

Forming the initial hypothesis space relies on assuming that there is a set of objects *O* and a set of detectors *D*, such that any object *o* ∈ *O* can potentially cause any detector *d* ∈ *D* to activate. Given that participants are told that the machine in front of them activates when blicket objects are placed on its surface, a hypothesis *h* corresponds to a structure that posits whether individual objects have the causal efficacy to activate the detector (see Griffiths & Tenenbaum, 2005, for more computational details). Griffiths et al. (2011) describe the formal parameterization of this hypothesis space and model that results in the hypothesis space shown in Figure 8A-E1. This figure shows the model’s predictions for Experiments 1 and 2.

To instantiate the model, each hypothesis is given a prior probability *p*(*h*), which is a function of the child’s belief about the base rate of blickets **. This prior corresponds to the number of blickets posited by the hypothesis. For example, in the figure, Hypothesis 0 posits 3 blickets, so its *p*(*h*) = ** Hypotheses 1, 2, and 4 posit exactly 2 blickets, so their *p*(*h*) = ****Hypotheses 3, 5, and 6 each posit 1, making their *p*(*h*) = ****Finally, Hypothesis 7 posits no blickets, making its *p*(*h*) = (1-**

**Timeline

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Figure 3. The eight different causal hypotheses indicating the possible causal relations for a causal event that involves three objects and one blicket detector. *A*, *B*, and *C* correspond to the three objects that were used on the machine and *E* indicates the activation of the machine.

Because the model assumes that objects with causal efficacy will act deterministically on detectors, the likelihood of each hypothesis is equal to 1 if that hypothesis could produce the data and 0 if not. This allows each model to be updated based on Bayes’ rule given the data. The way the model determines the probability that an object is a blicket is based on the posterior probability of the models in the hypothesis space; that is, the probability that any object *o* is a blicket given the data *d* can be calculated by the equation in (2)

where *p*(*o*→*E* | *h*) is 1 if there is an edge between that object and the detector in h, and 0 otherwise.

Crucially, because the predictions of this (or any) Bayesian model will depend on the prior probability that any given object is a blicket, below we show the predictions of the model when the probability of a blicket is .5, .65, .8, .95, and 1. Figure 8A-E1 shows the model’s predictions for Experiments 1 and 2 for the various probabilities. Our rationale for plotting the model’s predictions for various prior probabilities was that it was unclear what participants’ baseline assumptions would be about the prior probability of blickets in the absence of explicit manipulations to those probabilities. Thus, by deriving the model’s predictions for various prior probabilities, it was possible to compare (qualitatively and quantitatively) the model’s predictions for the different probabilities to children’s actual treatment of the objects. Figure 8A-E1 shows these predictions.

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| Chart, bar chart  Description automatically generated  B1 | Chart, bar chart  Description automatically generated  C1 |
| Chart, bar chart  Description automatically generated  D1 | Chart, bar chart  Description automatically generated  E1 |

Figure 8A-E1. A-E displays the Bayesian model’s predictions for the backwards blocking and indirect screening-off conditions in Experiment 1 when *P*(Blickets) = .5 (3A), *P*(Blickets) = .65 (3B), *P*(Blickets) = .8 (3C), *P*(Blickets) = .95 (3D), *P*(Blickets) = 1 (3E). A1-E1 displays the Bayesian model’s predictions for the backwards blocking and indirect screening-off conditions in Experiment 2 for the same probabilities.

With the exception of Figure 8E and 8E1 in which the baseline probability that an object is a blicket is 100% (and thus children should treat all objects as blickets except those that are shown explicitly not to activate the machine), the model makes several notable predictions. First, participants in the backwards blocking condition in Experiment 1 should be most confident that objects A (during the main trials) and D (during the control trials) are blickets for all prior probabilities. In contrast, participants in the indirect screening-off condition should be maximally confident that objects A (during the main trials) and D (during the control trials) are not blickets. Second, participants in the backwards blocking condition in Experiment 2 should be more (but not maximally) confident that objects A and B (during the main trials) and D and E (during the control trials) are blickets than the causally redundant objects (i.e., objects C in the main condition, and objects A-C in the control condition). In contrast, participants in the indirect screening-off condition in the same experiment should be maximally confident that objects A and B (during the main trials) and D and E (during the control trials) are not blickets in the indirect screening-off condition. Third, within the backwards blocking condition in both experiments, the model predicts that participants should engage in backwards blocking reasoning: Participants should be more confident that objects in the control trials are blickets than objects in the main trials.

**Connectionist model**. We built a two-layer connectionist model. The network architecture is shown in Figure 9. The model used to simulate the experiment reported here consisted of an input layer and an output layer—there were no hidden layers in these models. The input layer for the model consisted of four units, and the output layer consisted of a single unit. Each input unit corresponded to each of the four possible objects used in the experiment. Whenever an object was present, the activation value of its corresponding input unit was set to a value of “1”; the activation of these units was set to a value of “0” if the corresponding objects were not present. If a predetermined blicket was presented at the input layer, then the model was trained to turn on the single output unit (i.e., to produce an activation of 1). This process corresponded to an object activating the blicket machine. All simulations used a learning rate of .05 but no momentum. Model weights were initialized to 0, and the output units used sum-squared activation functions (which enabled the weights to be modified with training).

Diagram

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Figure 9. The neural network model used to simulate Experiment 1. The architecture used to simulate Experiment 2 was identical to that used to simulate Experiment 1 except that an additional input unit was included to simulate object E.

The procedure for training the models was the same as that for children. For example, networks were assigned randomly to the indirect screening-off condition or to the backwards blocking condition. To match the behavioral experiment, networks experienced two of each kind of event within a given condition. For example, during the two “experimental trials” for networks in the backwards blocking condition in Experiment 1, the first three input units were turned on (i.e., the activation of each input node was set to a value of 1), and the network’s task was to learn to activate the single output unit (i.e., to set the activation of the single output unit to 1). Turning on the first three input units simulated placing objects A, B, and C on the blicket machine, and training the model to turn on the single output unit corresponded to networks learning that A-C activated the machine. This segment of training corresponded to the ABC+ events. During the subsequent A+ trials, only the first input unit was turned on, but again the network’s task was to activate the single output unit. The backwards blocking control trials were identical to the backwards blocking experimental trials except that the fourth input unit (corresponding to object D in experiment 1) or the fourth and fifth input units (corresponding to objects D and E in Experiment 2) rather than first input unit was turned on. The indirect screening off experimental and control trials were identical to the backwards blocking experimental and control trials except that the network was trained to turn off the single output unit (i.e., set its value to 0) during the A- and D- phases of the indirect screening-off experimental and control trials in Experiments 1 and during the AB- and DE+ phases of the same trials in Experiment 2, respectively. The compound (e.g., ABC+) and elemental (e.g., A+/D+; A-/D- in Experiment 1; AB+/DE+; AB-/DE- in Experiment 2) phases—which were shown twice to be consistent with the behavioral study—lasted anywhere between 200 and 375 epochs each. This meant that one complete simulation lasted anywhere between 800 (i.e., 400 × 2) and 1500 (i.e., 375 × 4) epochs. The model’s predictions for the different numbers of training epochs is shown below in Figure 10A-D1. **We trained the model for different numbers of epochs** to ensure that the model-fit results were not idiosyncratic to the precise number of training epochs.

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| Chart, bar chart  Description automatically generated  A1 | Chart, bar chart  Description automatically generated  B1 |
| Chart, bar chart  Description automatically generated  C1 | Chart, bar chart  Description automatically generated  D1 |
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Figure 10A-D1. A-D shows the connectionist model’s predictions for how participants should treat the objects between the main and control trials of the backwards blocking and indirect screening-off conditions in Experiment 1 after 800 (A), 1,600 (B), 2,000 (C), and (3) 3,000 epochs of training. A1-D1 shows the connectionist model’s predictions for how participants should treat the objects between the main and control trials of the backwards blocking and indirect screening-off conditions in Experiment 2 after the same amount of training.

As can be seen, the connectionist model predicts that participants should treat the redundant objects equivalently across the different trials, conditions, and training epochs. However, the model predicts that participants should be more (though not maximally) confident that object A (in the backwards blocking main trials) and objects A and B (in the backwards blocking control trials than the causally redundant objects. Finally, for the indirect screening-off experimental trials, the model predicts that participants should be less (though not maximally) confident that objects A and D (in main and control trials in Experiment 1, respectively) and objects A and B and D and E (in the main and control trials in Experiment 2, respectively) are blickets compared to the causally redundant objects across the same trials.

It is clear that the Bayesian model and the connectionist model make distinct predictions for how participants should respond to the objects across the various conditions, trials, and two experiments. Where these models especially diverge is in their predictions for the backwards blocking control condition: the connectionist model predicts that participants should treat objects A-D equivalently during regardless of the number of training epochs; the Bayesian model predicts that participants should only treat the objects differently. The models also differ in terms of whether they predict backwards blocking reasoning; the Bayesian model, but not the associative model, predict backwards blocking reasoning. Thus, it should be possible to determine which model participants relied on based on their performance during the backwards blocking control condition by determining which model best fits participants’ data.

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| **Qualitative and Quantitative Model fits: Experiment 1**  **Chart, bar chart  Description automatically generated**  A | |
| Chart, bar chart  Description automatically generated  B | Chart, bar chart  Description automatically generated  C |

Figure 7A-C. Participants data (6A) compared to the predictions of the best-fitting connectionist model trained for 800 epochs (6B) and the best fitting Bayesian model, where the *P*(Blicket) = .80 (6C).

To assess the quantitative fit of the predictions of the connectionist and Bayesian models to the data, we computed the root mean square (RMSE) and mean absolute error (MAE) between each model’s predictions and participants’ mean responses to objects A-C during the backwards blocking and indirect screening-off main trials and objects A-D during the backwards blocking and indirect screening-off control trials. These two metrics have been used in previous simulation studies to assess model’s quantitative fit to behavioral data (e.g., Bhat et al., 2022; Buss & Spencer, 2014). Lower values on each metric indicate better model fit. Table 2 below shows the fits for the different model instantiations applied to Experiment 1.

|  |  |  |
| --- | --- | --- |
| Computational Models | root mean square (RMSE) | mean absolute error (MAE) |
| Connectionist Model (800 epochs)++ | .10 | .07 |
| Connectionist Model (1600 epochs) | .13 | .09 |
| Connectionist Model (2000 epochs) | .15 | .11 |
| Connectionist Model (3000 epochs) | .17 | .14 |
| Bayesian model (.5) | .21 | .19 |
| Bayesian model (.65) | .16 | .13 |
| Bayesian model (.80)++ | .15 | .10 |
| Bayesian model (.95) | .22 | .19 |
| Bayesian model (1) | .25 | .22 |

Table 2. Overall Model fit indices for the various models and instantiations. The shaded rows correspond to the best fitting connectionist and Bayesian models.

|  |  |  |
| --- | --- | --- |
| Computational Models | root mean square (RMSE) | mean absolute error (MAE) |
| Connectionist Model (800 epochs)++ | .14 | .09 |
| Connectionist Model (1600 epochs) | .18 | .15 |
| Connectionist Model (2000 epochs) | .19 | .16 |
| Connectionist Model (3000 epochs) | .22 | .19 |
| Bayesian model (.5) | .19 | .17 |
| Bayesian model (.65) | .10 | .10 |
| Bayesian model (.80)++ | .14 | .09 |
| Bayesian model (.95) | .26 | .24 |
| Bayesian model (1) | .31 | .29 |

Table 2. Model fit indices for the various models and instantiations for the BB experimental and control conditions. The shaded rows correspond to the best fitting connectionist and Bayesian models.

|  |  |  |
| --- | --- | --- |
| Computational Models | root mean square (RMSE) | mean absolute error (MAE) |
| Connectionist Model (800 epochs)++ | .04 | .04 |
| Connectionist Model (1600 epochs) | .06 | .05 |
| Connectionist Model (2000 epochs) | .08 | .06 |
| Connectionist Model (3000 epochs) | .09 | .09 |
| Bayesian model (.5) | .22 | .21 |
| Bayesian model (.65) | .13 | .11 |
| Bayesian model (.80)++ | .14 | .13 |
| Bayesian model (.95) | .22 | .19 |
| Bayesian model (1) | .19 | .18 |

Table 2. Model fit indices for the various models and instantiations for the ISO experimental and control conditions. The shaded rows correspond to the best fitting connectionist and Bayesian models.

|  |  |  |
| --- | --- | --- |
| Computational Models | root mean square (RMSE) | mean absolute error (MAE) |
| Connectionist Model (800 epochs)++ | .13 | .11 |
| Connectionist Model (1600 epochs) | .18 | .15 |
| Connectionist Model (2000 epochs) | .19 | .16 |
| Connectionist Model (3000 epochs) | .21 | .18 |
| Bayesian model (.5) | .13 | .11 |
| Bayesian model (.65) | .12 | .08 |
| Bayesian model (.80)++ | .17 | .14 |
| Bayesian model (.95) | .26 | .23 |
| Bayesian model (1) | .29 | .26 |

Table 2. Model fit indices for the various models and instantiations for the BB and ISO experimental conditions. The shaded rows correspond to the best fitting connectionist and Bayesian models.

|  |  |  |
| --- | --- | --- |
| Computational Models | root mean square (RMSE) | mean absolute error (MAE) |
| Connectionist Model (800 epochs)++ | .07 | .05 |
| Connectionist Model (1600 epochs) | .08 | .06 |
| Connectionist Model (2000 epochs) | .10 | .07 |
| Connectionist Model (3000 epochs) | .12 | .09 |
| Bayesian model (.5) | .26 | .25 |
| Bayesian model (.65) | .19 | .17 |
| Bayesian model (.80)++ | .14 | .08 |
| Bayesian model (.95) | .18 | .16 |
| Bayesian model (1) | .21 | .19 |

Table 2. Model fit indices for the various models and instantiations for the BB and ISO control conditions. The shaded rows correspond to the best fitting connectionist and Bayesian models.

It should be clear from the table above that the connectionist model provided a better quantitative fit to the behavioral data than any of the Bayesian models. It should also be clear that the connectionist model provides a better *qualitative* fit to the data than the Bayesian model. This is most evident when one considers the model’s predictions for participants’ judgements during the backwards blocking control trials and the model’s predictions for these trials. The connectionist model predicted that participants should treat the four objects equivalently, which the behavioral data supported. In contrast, the Bayesian model predicted that participants should treat object A differently than the other objects, which the behavioral data did not support.

Given that the connectionist model instantiated associative learning, these results suggest that participants may have used associative learning rather than Bayesian inference to process the present events. We discuss below the exact nature of this associative learning.

General Discussion

This study had two aims. The first was to determine whether 5- and 6-year-olds would engage in backwards blocking reasoning for 3 and 4 objects. This departs from the typical convention of using two objects to study causal reasoning in human children. The second aim was to clarify how exactly (i.e., the cognitive mechanism by which) children reasoned about the present causal events. We were specifically interested in whether children’s causal inferences best conformed to the predictions of a simple Bayesian model or a connectionist (associative learning) model.

With respect to the first aim, we found evidence of backwards blocking reasoning under the old operationalization of backwards blocking reasoning but only minimal evidence of such reasoning under a new and more valid measure of backwards blocking reasoning. This finding extends previous research to show that when children are asked to reason about three objects and a more valid of operationalization of backwards blocking reasoning is used, children minimally engage in backwards blocking reasoning.

With respect to the second aim, the data were most consistent with the connectionist (associative learning) models. However, a question that we have not yet answered concerns the exact nature of the connectionist models’ associative learning. Specifically, how did these models—via associative learning—arrive at their causal judgements? To understand how the connectionist model’s judgements arose mechanistically, consider the backwards blocking (i.e., ABC+ D+) control trial. The rationale for focusing on this condition is that the connectionist uniquely predicts participants performance during the backwards blocking control condition. During the simulation of this trial, when all four objects were first presented to the model, the resulting difference at the output layer between the activation of the single output unit and the predicted activation of that unit was equivalent for all four objects. Thus, because the difference between the observed and predicted activation of the single output unit was equivalent for all four objects, the network made the same weight adjustments both in sign and magnitude to the connections (which encode associations) between each object and the single output unit. This explains why the network responded equivalently when “asked” whether each object (i.e., objects A-D) was a blicket. Given that participants’ causal responses mirrored the predictions of the connectionist model, this suggest that children arrived at their causal judgements via a similar associative-learning process. This finding is significant because it has been suggested that causal reasoning in human children is best explained by Bayesian inference and rational processes rather than by associative processes. The present data add nuance and context to this debate by suggesting that whether children engage in Bayesian inference or associative learning may depend on how causal reasoning is measured and the number of objects about which they are asked to reason.

These aims aside, some potential criticisms are worth noting. One such potential criticism is that the results are inconsistent with the findings from previous studies on backwards blocking reasoning in human children. Such previous research showed that children unequivocally engage in backwards blocking reasoning when asked to reason about two objects; in contrast, the current study only provided equivocal evidence for backwards blocking reasoning when three and four objects were used. However, we believe that the present results extend rather than are at odds with such previous research. Specifically, the present study likely demonstrates that when children’s information-processing capacities are stretched such as when they are asked to reason about multiple potential causes, they may deploy and rely on simpler associative processes. Although the numerical difference between three and four objects is miniscule, by contrast the corresponding increase in the size of the underlying psychological hypothesis space is substantial. Such an increase in the size of the underlying psychological hypothesis space may have important ramifications on the cognitive mechanism that gets deployed by children, especially if children are sensitive to and affected by this increase. For example, children who are asked to reason about two candidate causes need only to represent and choose among *four* candidate causal hypotheses. Four candidate causal hypotheses may well be within the information-processing capacities of 5- and 6-year-olds. In contrast, children who are asked to reason about three candidate causes must now consider *eight* candidate causal hypotheses—this may exceed their restricted information-processing capacities.

It turns out that there is a wealth of data that is consistent with this general proposal (Doebel & Zelazo, 2015; Frye, Zelazo, & Palfai, 1995; Zelazo, Frye, & Rapus, 1996; Zelazo et al., 2003). One recent study by Kenderla and Kibbe (2023) showed that when 8- and 10-year-old children’s information-processing abilities were stretched in a virtual memory game—such as when children were asked to find three cards that shared one feature and differed on another feature—they relied less on working memory and more on manual exploration. Given that children were not required actively to maintain information in memory when manually exploring, manual exploration was an ostensibly simpler and less cognitively effortful strategy than one that required working memory. In a similar vein, Richland, Morrison, and Holyoak (2006) found that 3- and 4-year-old children made more featural and relational errors when asked to reason about multiple relations or when the task included a salient distractor than when asked to reason about a single relation without a distractor. Finally, there is evidence that preschool-age children's performance on theory-of-mind and social-problem-solving tasks was adversely affected when they first completed tasks that taxed their information-processing abilities compared to when such capacities were not taxed (Caporaso & Marcovitch, 2021; Powell & Carey, 2017; Steinbeis, 2018).

Together, this research demonstrates that although children can process information at higher levels, if the task that they are given requires information-processing abilities that extend beyond what they possess, then there will be a tendency for them to process information at lower levels and to rely on less sophisticated strategies and cognitive mechanisms. This may provide a developmental explanation for why children in the present study did not engage in backwards blocking reasoning or show evidence that they relied on Bayesian inference. A testable prediction of this account is that there should be a point at which children go from using a simple associative-based counting mechanisms in contexts like the present one to more rationale processes like Bayesian inference. This issue should be explored more fully in future research.

A second potential criticism is that we cannot be sure that a simple Bayesian-inference mechanism underpinned participants’ performance in the present study. For example, if participants assumed that blickets were common in the present context—which is plausible given how frequently the detector activated in the present study—then participants should be *less* likely to block redundant causes; in other words, participants should be *more* likely to treat all potential blickets (expect for the ones that are explicitly shown not to be causal) equally. This could explain participants’ performance in the backwards blocking control condition—in that condition, participants treated all objects equally. However, this explanation cannot explain *all* the present data. This is because this explanation predicts that participants should have also treated objects A-C equivalently in the backwards blocking experimental condition as well, but this was not the case: Participants treated object A differently than either objects B or C in the backwards blocking experimental condition. This explanation is also unlikely given that, over all the Bayesian models provided a poorer fit to the behavioral data than the connectionist models. This would not be expected if participants relied on Bayesian inference. Nonetheless, because we did not systematically manipulate base-rate information, this alternative explanation cannot be ruled out entirely. However, if we are correct that participants do not rely on Bayesian inference when asked to reason about multiple causes, we predict that their performance in this proposed future study would not differ from participants’ performance in the current study. However, if children’s causal judgements are affected by base-rate information, such that, overall, how they process backwards blocking event changes with changes to base-rate information, then this would suggest that participants may use Bayesian inference after all to reason about multiple candidate cause, at least when a Bayesian-inference mechanism is primed by explicitly and systematically manipulating base-rate information.

**Conclusion**

These potential criticisms notwithstanding, this study constitute one of the first systematic attempts to examine backwards blocking and indirect screening-off reasoning in human children in the context of three and four objects. A longstanding view has been that the cognitive mechanism by which human beings reason about causal events is Bayesian inference (e.g., Gopnik et al., 2004) rather than associative processes. The experiments reported here support a different conclusion: associative learning is sufficient to explain 5- to 6-year-old children’s reasoning about multiple potential causes.

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