Don’t throw the (associative-learning) baby out with the bathwater just yet: Backwards-blocking reasoning with *multiple* candidate causes in human children

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Abstract

Causal reasoning is a fundamental cognitive ability that enables humans to learn about the complex interactions in the world around them. However, the available evidence suggests that the mechanism or set of mechanisms that underpin causal reasoning are not well understood. It is unclear, for example, whether causal reasoning is underpinned by a Bayesian mechanism, an associative mechanism, or both. Some theorists have argued that a Bayesian mechanism underpins causal reasoning because it can better account for backward-blocking (BB) and indirect screening-off (IS) findings in children and adults (e.g., Sobel, Tenenbaum, & Gopnik, 2004). However, the evidence is mixed about the extent to which learners engage in both kinds of reasoning. Here, we report three experiments that examine to what extent adults engage in BB and IS reasoning using the blicket-detector design (e.g., Gopnik et al., 2001), what mechanism best explains their behavior in this task, and under what conditions are adults’ causal ratings consistent with the predictions of the three competing computational and analytical models. The results of Experiment 1 revealed that adults’ causal ratings in the backwards-blocking condition (as well as in the indirect screening-off condition) were consistent with the predictions of the traditional and modified Rescorla-Wagner models when asked to reason about two objects. The results of the present study suggest that adults use associative processes to reason about two objects but a Bayesian-inference-like process to reason about three or more objects.

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

There is perhaps no ability that is more central for learning about how the world works than causal reasoning or the capacity to reason about cause-and-effect relations. This is a key cognitive ability because it enables human learners to encode causal relations to inform prediction and inference (e.g., Oakes & Cohen, 1990; Rakison, Smith, & Ali, 2016; Schlottmann & Shanks, 1992), to intervene on those relations to generate new effects (e.g., Gopnik et al., 2001), and counterfactually to reason about causal events to determine what would have happened if the chosen intervention had not been undertaken (e.g., Harris, German, & Mills, 1996; Sobel, 2004).

Despite consensus among researchers about the importance of causal reasoning, there is much less consensus among theorists about the cognitive mechanism that underlies this capacity. For example, it is unresolved whether domain-general mechanisms such as associative learning underpins causal reasoning or whether—as has recently been suggested by some theorists (e.g., Gopnik et al., 2004; Walker, Lombrozo, Williams, Rafferty, & Gopnik, 2017)—causal reasoning is grounded in a Bayesian-inference mechanism. One empirical finding about which domain-specific and domain-general theorists have disagreed considerably concerns whether an associative-learning mechanism or a Bayesian-inference mechanism subserves human beings’ capacity to engage in a form of retrospective reevaluation called backwards-blocking reasoning. This form of reasoning involves learning blocking or discounting redundant causal cues when other cues are shown unambiguously and in isolation to produce effects (e.g., Blaser, Couvillon, & Bitterman, 2004; Shanks, 1985; Shanks & Dickinson, 1987; Sobel et al., 2004). The aim of the experiments reported here was twofold. First, it was designed to examine whether and to what extent human children engage in backwards-blocking reasoning in a new context. Specifically, in contrast to previous studies on backwards-blocking reasoning in human children that has tended to ask children to reason about two objects, here we examined whether children could engage in this form of reasoning when asked to reason about multiple objects. Second, this study was designed to illuminate whether an associative-learning mechanism or a Bayesian-inference mechanism underlies children’s backwards-blocking reasoning performance in the current situation.

**The** **emergence of BB reasoning**

The ability to reason about causal events is thought generally to emerge between 18 months and 5 years of age (e.g., Benton, Rakison, & Sobel, 2021; Gopnik & Sobel, 2000; Gopnik et al., 2001; Kimura & Gopnik, 2019; Meltzoff, Waismeyer, & Gopnik, 2012; Sobel & Kirkham, 2006, 2007; Sobel & Munro, 2006; Walker & Gopnik, 2014; cf. Sobel & Kirkham, 2005). Although researchers have used a variety of paradigms to examine causal reasoning in human children (for a review see Bullock, Gelman, & Baillargeon, 1982), here we focus on research that has used the blicket-detector design. We focus on this paradigm for three reasons. First, it has been used most extensively to test children’s causal-reasoning abilities as well as to assess their ability to engage in backwards-blocking reasoning. Second, variations on this design have been used to evaluate adults’ causal reasoning abilities (e.g., Griffiths et al., 2011), which may support cross-study and between-age comparisons. Third, we focus on this paradigm because the notion that human reasoners use Bayesian inference to reason about causal events was introduced within the context of the blicket-detector studies and in concert with key advances in computer science, philosophy, machine learning, and statistics (for a review, see Gopnik et al., 2004).

In studies that use this design, children are introduced to a machine called the "blicket detector" and told that it lights up and plays music when certain objects—namely, "blickets"—are placed on it but not when other objects are placed on it. Following a series of events in which the detector activates (or not), children are then asked to determine which objects are blickets and to “make the machine go” by placing the blicket on the machine. Of the findings that have been reported by researchers who have used the blicket-detector methodology, perhaps none have been more controversial than that by Sobel, Tenenbaum, and Gopnik (2004). They showed that 4-year-old children—and to a lesser extent 3-year-old children—can engage in BB reasoning and IS reasoning. Children were shown initially that two novel objects A and B together caused the detector to activate and then that object A alone either failed to activate the detector (i.e., AB+ A-; IS condition) or activated the detector when placed on it (i.e., AB+, A+; BB condition). 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. It is worth noting that the BB condition is so called because after observing that A alone can activate the detector, children who engage in this form of reasoning are thought to disregard or block retrospectively object B as a potential cause because A was shown unequivocally to produce the effect. In contrast, the ISO condition is so called because B is assumed indirectly to "screen off" or to block object A as a potential cause given that A alone failed to activate the machine.

Sobel et al. (2004) found that when children were subsequently asked to make the machine go, the 4-year-olds during the ISO trial—and to a lesser extent the 3-year-olds during the same trial—responded by placing object B on the machine. In contrast, during the BB trial these same children responded by placing object A on the machine. Subsequent research by Sobel and Munro (2009) found that 3-year-olds, like the 4-year-olds in Sobel et al. (2004), could engage in BB and ISO reasoning if the activation of the detector represented desires rather than a physical effect: the 3-year-olds categorized object B as a blicket in the ISO condition but were less likely to do so in the BB condition but only when the machine was called “Mr. Blicket” and said to like blicket objects. These findings have since been interpreted not only as evidence that human children can engage in backwards-blocking reasoning but as evidence that this form of reasoning is underpinned by a Bayesian-inference mechanism rather than by an associative-learning mechanism. The crux of the Bayesian-inference account is that human learners use a simple form of Bayes’ rule to reason about causal events and to choose the causal hypothesis—within a space of hypotheses that is potentially super-exponentially large—that is most consistent with the observed data (e.g., Sobel et al., 2004; Gopnik & Wellman, 2012). More specifically, this process involves combining prior beliefs about each hypothesis with observed data to update the (posterior) probabilities of each of the hypotheses in the psychological hypothesis space.

One specific kind of associative-learning model that has received some criticism in the developmental causal literature is the traditional Rescorla-Wagner (henceforth, RW) model (e.g., Rescorla & Wagner, 1972; Griffiths et al., 2011; Sobel et al., 2004). The previous findings challenge the RW model for three key reasons. First, this model predicts that B should be treated equivalently across the BB and ISO conditions, which is a prediction that is at odds with participants’ actual treatment of object B across these conditions. The reason the RW model predicts that participants should treat B equivalently across the BB and ISO trials is because the association between object B and the outcome was identical across both conditions; that is, B was shown to produce the effect (in combination with object A) twice in both conditions. This model also only makes weighted adjustments to cues that are present, which B was not during the "A" phases in both the BB and ISO conditions. This means that because object B is absent during the A phases of the BB and ISO tasks, the RW model predicts that the associative strength between object B and the blicket effect should remain unchanged across the experimental trials in both conditions, and thus further predicts that participants should treat B equivalently across both conditions. Second, the RW model requires many learning trials for reliable associations to be established (assuming modestly set values for the salience parameters) and used to make causal inferences. In contrast, in the studies cited above participants engaged in BB (and ISO) reasoning based on only a handful of learning trials. Finally, the BB and ISO findings challenge the RW model because this model does not naturally encode base rates to which children have been shown to be sensitive.

Despite these valid criticisms, caution should be exercised either before accepting these criticisms or arguments that stipulate that children use Bayesian inference to reason causally. One reason to exercise caution is because there are problems with Sobel et al.’s (2004) operationalization of BB reasoning (although for alternative operationalizations see De Houwer, Beckers, & Glautier, 2002; Larkin, Aitken, & Dickinson, 1998; Griffiths et al., 2011; Kruschke & Blair, 2000; Lovibond et al., 2003; Shanks, 1985; Van Hamme and Wasserman, 1994). These authors operationally defined BB reasoning as greater B choices in the ISO condition than in the BB condition. This way of operationally defining BB reasoning was presumably motivated by two key factors. First, if the causal status of object A—which can be determined unequivocally when object A is placed alone on the machine—causes participants retrospectively to reevaluate the causal status of object B, then participants should consider B to be less of a blicket in the BB condition (and thus retrospectively “block” it) than in the ISO condition. This is because A by itself fails to produce the effect in the ISO condition but produces the effect by itself in the BB condition. Second, proponents of this operationalization of BB reasoning have used the fact that participants do treat object B differently between the BB and ISO conditions as evidence against rudimentary associative-learning models such as the RW model given that this model predicts equivalent treatment of object B across the BB and ISO conditions.

However, this operationalization of BB reasoning has a notable shortcoming. Specifically, by operationalizing BB in terms of the difference in treatment of object B across the BB and ISO conditions, it is logically possible that participants treated object B differently between the BB and ISO conditions because they observed a positive effect during the elemental (i.e., A+) phase in the BB condition but a negative effect during the elemental (i.e., A-) phase in the ISO condition. This would mean that participants’ differential treatment of object B across the two conditions could have resulted from the fact that the two conditions differed in terms of their low-level perceptual features rather than from a true retrospective reevaluation of object B by participants based on A’s *relation to and effect* *on* object B across both conditions.

Given this limitation, we argue that a more (construct) valid operationalization of BB reasoning is to compare the treatment of object B following an AB+ A+ sequence of events (i.e., the BB experimental condition) to the treatment of B following an AB+ C+ sequences of events (i.e., the BB control condition). These two conditions differ in terms of the object that is shown during the elemental phase (i.e., A or C) and that object’s *relation* to B (and thereby the potential impact that this object has on how B is treated). For example, in the BB experimental condition, a dependency is presumably established between objects A and B because both objects appear together during the compound phase of the condition. This means that A’s causal status that is established during the subsequent elemental phase *should* affect participants’ (retrospective) treatment of B; that is, whether object A is shown to activate the machine should affect how participants treat object B. In contrast, in the BB control condition, object C never appeared with object B, which necessarily means that C’s causal status should not (retrospectively) impact how participants treat object B. Crucially, the blicket effect itself is held constant across the BB experimental and control conditions such that participants observe blicket-detector activation in both cases. If participants engage in BB reasoning in this context, then this would provide stronger evidence that participants have access to such a mechanism. In particular, if BB reasoning is treated as an indirect measure of the operation of a Bayesian-inference mechanism as has typically been the case (e.g., Griffiths et al., 2011; Sobel & Kirkham, 2006; Sobel et al., 2004), then demonstrating that participants treat object B differently across the BB experimental and control conditions would suggest that participants have access to and use Bayesian inference to reason causally.

**An open question**

A second reason to exercise caution before accepting the claim that human beings use Bayesian inference to reason about causal events is that it is not known whether human children engage in BB reasoning for three (or more) objects. The is because most, if not all, of the studies on BB reasoning in human children have tended to use two objects; that is, participants are shown an AB+ A+ sequence of events and then asked whether each object is a blicket. This research is important because it has revealed that BB reasoning may emerge by 3 years of age, but it leaves unaddressed whether children can engage in BB reasoning when asked to reason about three or more objects. It also remains unknown whether participants engage in BB reasoning when the elemental phase (i.e., the A+ phase in the BB condition or the A- phase in the ISO condition) consists of two rather than one object. These are important questions to answer because if a Bayesian-inference mechanism is assumed to underpin human causal reasoning—and it is further assumed that BB reasoning is an indirect measure of the operation of such a mechanism—then it is crucial to show that participants continue to engage in BB reasoning (and thus make use of Bayesian inference) even when they are asked to reason about three (or more) objects or even when the elemental phase consists of two rather than one object. In other words, if one of the goals of the larger research community is to elucidate the cognitive mechanisms by which human children reason about causality *in the real world*, then it is imperative to understand better how causal reasoning unfolds in situations that more closely approximate those that may be found the real world such as ones in which children must reason about more than two objects.

One may question whether the difference between a setting in which participants are asked to reason about two candidate causes and one in which they are asked to reason about three or even four candidate causes really is meaningful. This is because these two settings differ by one (or at most, by two) candidate causes. However, if Bayesian inference is the cognitive mechanism that underpins human causal reasoning, then the difference between these two settings is far from trivial. This is because in the two-candidate-cause setting, participants need only to determine which of *four* candidate causal hypotheses generates the observed data. However, in the three- or even four-candidate-cause setting, participants need to determine which of *eight* (in the case of 3 candidate causes) or *sixteen* (in the case of 4 candidate causes) hypotheses is the one that generates the observed data. Thus, in the four-candidate-cause setting, participants must consider four times as many causal hypotheses as participants in the two-candidate-cause setting, which is far from a trivial difference.

Crucially, this difference may have important implications for whether an associative-learning mechanism or a Bayesian-inference mechanism underlies causal reasoning in children. For instance, it is possible that when children’s information-processing abilities are taxed—such as when they are asked to reason about three (or more) objects—they may resort to simpler modes of causal reasoning such as reasoning that is consistent with the predictions of the traditional RW model. This perspective is consistent with a view that was put forward by Cohen and colleagues (Cohen, 1998; Cohen & Cashon, 2001; Cohen, Chaput, & Cashon, 2002; Oakes & Cohen, 1990; see also Oakes, 1994). The crux of this perspective is that there is a bias for children to process information at the highest level (and perhaps in terms of the most sophisticated available cognitive mechanisms and processes). However, if the task that children face requires information-processing abilities that extend beyond what they possess, then there will be a tendency for them to lower levels and less sophisticated cognitive mechanisms.

Thus, if participants’ BB performance adheres to the predictions of the traditional RW model in a multiple-candidate-cause setting—which, here, would be in evidence if participants treated B equivalently across the BB experimental and control conditions regardless of the number of objects shown during the elemental phase—this would suggest that it may have been premature to conclude that the traditional RW model is an inadequate model of human causal reasoning. This would also support the contention that there is a tendency for children to use simpler cognitive mechanisms and processes to reason about causal events when their information-processing abilities are stretched. Thus, by understanding whether participants engage in BB reasoning in a multiple-candidate-cause setting, we can gain greater insight into *how* children reason about causal events and under what conditions they use one kind of cognitive mechanism in lieu of another.

**The present investigation**

The present investigation had five broad goals. The first goal of the experiments presented here was to determine whether 4-, 5-, and 6-year-olds could engage in BB reasoning when asked to reason about three objects (Experiments 1 and 2) and when the elemental phase consists of two rather than one objects. The second goal was to determine whether participants show evidence of BB reasoning when it is operationally defined as greater treatment of object B in the BB control condition compared to the BB experimental condition. The third goal was to gain greater insight into how—that is, by what cognitive mechanism—children reasoned about the present events. The fourth goal was to determine whether BB reasoning depends on whether one or two objects are shown during the elemental phase in the BB condition. Traditionally, the elemental phase in the BB condition has consisted of only a single object (i.e., object A). This means that it remains to be seen whether the BB effect is greater for object C (the object that is not shown when A and B are placed on the machine; object C is analogous to object B in the BB condition when two objects are used) when one object is shown during the elemental phase (i.e., object A) compared to when two objects are shown (i.e., objects A and B). Finally, because BB reasoning in previous research was operationally defined as greater treatment of object B in the BB condition compared to the ISO condition, here participants also experienced the ISO condition. It was important to demonstrate that participants who failed to show evidence of BB reasoning under the new operationalization of BB reasoning would nonetheless show evidence of it under the old operationalization. Failing to show BB reasoning under the new operationalization of BB as well as under the older operationalization of it would suggest that there were issues with the study rather than indicate a lack of BB reasoning in children.

**Experiment 1**

Experiment 1 assessed 4-year-old children’s ability to engage in BB when asked to reason about three objects. Participants were introduced to a computer-animated machine called the “blicket detector” and were told that their task was to determine which objects make the machine activate—and thus represent blickets—and which objects do not make the machine activate. Following this brief introduction phase, participants received two backwards-blocking trials and two backwards-blocking control trials and were asked to indicate whether the objects in each trial were blickets. In this experiment, only a single object was shown during the elemental portion of the BB experimental event.

**Materials.** The “device” used in the experiments presented here was a computer-animated version of the blicket detector. 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 became ocean blue. If the device was “off”, the white region remained white. In addition, a maximum of 4 differently colored circles were used, and each circle measured 2.67 cm × 2.67 cm (INCLUDE FIGURE OF MACHINE AND TOYS). The machine was designed such that it activated immediately when a circle that was predetermined to be a blicket contacted it. At the start of any given trial, three (for the BB experimental trials) or four equally spaced (for the BB control trials) circles appeared above the blicket machine. Finally, the videos contained a built-in script, which experimenters were instructed to read to ensure that all participants were given exactly same instructions and received the same text throughout the experiment (INCLUDE FIGURE OF MACHINE AND TOYS). All video events were created in Microsoft PowerPoint.

**Procedure.** Participants were either tested in a quiet room on campus or in quiet rooms in local children’s science museums. 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 that were used during the main portion of the experiment. The pretraining phase began with the triangle (object A) and pentagon (object B), which were located side-by-side and above the machine. Object A then descended until it contacted and immediately activated the machine (i.e., the white region changed from white to ocean blue). Object A then ascended until it 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 the machine, which immediately activated (ostensibly because object A contacted it). Participants were then asked whether each object was a blicket. This event was identical to the “one-cause” event in Gopnik, Sobel, Schulz, and Glymour (2001) and was included to ensure that participants could reason about blicket objects.

Following the pretraining phase, participants were given four test trials—two BB experimental trials and 2 BB control trials—in counterbalanced order using a Latin square. It should be noted that differently colored objects were used across all trials. This meant that no two events overlapped in the colors (for the objects) that were used.

The two BB experimental 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 ascended to their starting positions. The left- or right-most (counterbalanced) object (i.e., 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; that is, the text, “Is this one a blicket?” with a downward-facing arrow then appeared above each object, and participants were asked whether each object was a blicket. The first and second BB experimental trials were identical except that different colors were used for the objects.

The two BB 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 then descended by itself until it contacted and activated the machine. Children were then asked whether each object was a blicket. Note that object A descended with the remaining two objects in the BB experimental trials, whereas object D did not descend with the remaining three objects in the BB control trials. This means that D’s causal status should have no bearing on participants’ treatment of objects A-C. Note also that the BB control trials used the same text as the BB experimental trials. The first and second BB control trials were identical except that different colors were used for the objects.

Finally, the ISO experimental and control conditions were identical to the BB experimental and control conditions except that objects A and D failed to activate the machine in the ISO experimental and control trials, respectively. The schematic for this experiment is shown below in Table 1.

|  |  |  |  |
| --- | --- | --- | --- |
| Schematic of Experiment 1 | | | |
|  | Compound | Elemental | Test |
| BB experimental trial | ABC+ | A+ | Is A/B/C a blicket? |
| BB control trial | ABC+ | D+ | Is A/B/C/D a blicket? |
| ISO experimental trial | ABC+ | A- | Is A/B/C a blicket? |
| ISO control trial | ABC+ | D- | Is A/B/C/D a blicket? |

Table 1. The +/- signs corresponds to whether the machine activates (+) or not (-)

**Results**

All analyses were conducted in R (R Development Core Team, 2008). All *p* values were supplemented with Bayes Factors. *BF*H1 quantifies support for the alternative hypothesis compared with the null hypothesis. *BF*s close to 1 indicate equal support for both hypotheses, whereas *BFH0*s≥ 3 and < 10 indicate moderate and strong evidence for the alternative hypothesis, respectively (Lee & Wagenmakers, 2014).

**[Add Exp. 1 results here]**

**Discussion**

[INSERT EXPERIMENT 1 DISCUSSION HERE]

**Experiment 2**

Experiment 2 was similar to Experiment 1 except that 5- and 6-year-old children were tested.

**Method**

**Participants.** Participants were X 5-year-olds (X boys and X girls; *Mage* =X months, range = X-Y) and X 6-year-olds (X boys and X girls; *Mage* =X months, range = X-Y). Although most children were from white, middle-class backgrounds, a range of ethnicities that resembled the diversity in the population were represented.

**Materials & Procedure.** The materials and procedure for Experiment 2 was identical to that for Experiment 1.

**Results**

Separate logistic mixed-effects models were fit to participants’ responses for the 5- and 6-year-olds as well as for the BB and ISO conditions, with participant as the random-effect factor in all models.

**5-year-olds.** Given that there was no effect of 5-year-olds’ pretest performance on their choices for any of the objects, we collapsed across this variable. The analysis revealed that the 5-year-olds were equally likely to indicate that object A was a blicket during the BB experimental trials (126 “yes” responses out of 148 total responses) compared to object D during the BB control trials (55 out of 73), odds ratio (OR) = 0.59, *p* = .26, *BF*H1= 0.14, bootstrapped 95% CI[-2.29, 3.49]. Likewise, participants were as likely to say that objects B and C were blickets during the BB experimental trials compared to the BB control trials, both ORs < .73, both *p*’s > .20, both *BF*H1’s = 0.25. Crucially, this was not the result of a decision by participants to respond equally to all objects across the BB and ISO experimental and control conditions. In fact, participants were much less likely to respond that object A was a blicket in the ISO experimental condition (3 out of 10) than in the BB experimental condition (58 out of 64), OR = .04, *p* < .0001, *BF*H1= 502.82. Similarly, participants were much less likely to respond that object A was a blicket in the ISO control condition (3 out of 10) than in the BB control condition (52 out of 63), OR = .09, *p* < .005, *BF*H1= 28.32. **[ADD THE DATA FOR THE ISO CONDITION. NOTE THAT THE R SCRIPT IS READY TO BE USED]**

The final analysis examined whether participants treated the objects that were shown unequivocally to produce the effect (i.e., object A in the BB experimental condition and object D in the BB control condition) differently the redundant causes. In terms of the BB condition, although participants treated object D equivalently with objects B and C in the BB control condition, both ORs < 1.24, both *p*’s > .64, both *BF*H1’s < 0.09, during the BB experimental trials participants were more likely to consider object A to be a blicket than objects B or C, both ORs < 0.32, both *p*’s < .03, both *BF*H1’s < 1.14. **[ADD THE DATA FOR THE ISO CONDITION. NOTE THAT THE R SCRIPT IS READY TO BE USED]**

**6-year-olds.** Similar to the analysis above with the 5-year-olds, we examined whether there was an effect of 6-year-olds’ pretest performance on their choices for any of the objects revealed. This analysis revealed no such effect. Thus, we collapsed across this variable for the 6-year-olds. The analysis revealed that the 6-year-olds, like the 5-year-olds, were equally likely to indicate that object A was a blicket during the BB experimental trials (134 out of 192) compared to object D during the BB control trials (57 out of 98), OR = .54, *p* = .15, *BF*H1= 0.24, bootstrapped 95% CI[-1.79, 2.87]. Likewise, participants were as likely to say that objects B and C were blickets during the BB experimental trials compared to the BB control trials, both ORs < .67, both *p*’s > .06, both *BF*H1’s < 0.62. Importantly, and similar to the analysis above, the 6-year-olds were sensitive the causal status of the objects. This is because they were much less likely to respond that object A was a blicket in the ISO experimental condition (14 out of 50) than in the BB experimental condition (40 out of 48), OR = .08, *p* < .0001, *BF*H1> 10000. Similarly, participants were much less likely to say that object D was a blicket in the ISO control condition (22 out of 50) compared to the BB control condition (35 out of 48), OR = .29, *p* < .005, *BF*H1= 7.33.

In terms of participants’ responses in the ISO condition, they were equally likely to indicate that object A was a blicket during the ISO experimental trials (54 out of 92) compared to object D during the ISO control trials (22 out of 28), OR = .58, *p* = .12, *BF*H1= 0.28, bootstrapped 95% CI[-0.47, 1.62]. Likewise, participants were as likely to say that objects B and C were blickets during the ISO experimental trials as during the ISO control trials, both ORs < 2.19, both *p*’s > .23, both *BF*H1’s < 0.22. As we indicated toward the end of the analyses for children in the BB condition, these results were not due to participants deciding to respond equally to the objects. This is because, as that analysis revealed, children treated object A differently between the ISO and BB experimental and control trials. Thus, children were sensitive to the causal status of the objects, most especially objects that were casually effective and ineffective.

Similar to the final analysis with the 5-year-olds, we next examined whether participants treated the objects that were shown unequivocally to produce the effect differently the redundant causes. In contrast to the results with the 5-year-olds, the 6-year-olds treated object A equivalently with objects B and C during the BB experimental trials, both ORs < 0.67, both *p*’s > .06, both *BF*H1’s < 0.62. Likewise, during the BB control trials, the 6-year-olds treated object D equivalently with objects A, B, and C, all ORs = .53, all *p*’s = .22, all *BF*H1’s = 0.22. Thus, for the BB experimental and control trials, the 6-year-olds treated all objects equivalently. However, during the ISO experimental trials, participants were more likely to choose objects B and C than object A, both ORs > 8.88, both *p*’s < .0001, both *BF*H1’s > 10,000. Likewise, during the IS control trials, participants were more likely to choose objects A, B, and C than object D, all ORs < 0.10, all *p*’s < 10,000, all *BF*H1’s > 800.

**Assessing participants’ treatment of redundant causes across the BB and ISO condition**

**5-year-olds.** Given that some previous research operationalized BB reasoning in terms of the difference in treatment of the redundant cause, object B, across the BB and ISO conditions, it was important to replicate that analysis here by comparing participants’ treatment of the redundant causes in this experiment (i.e., objects B and C, which were never shown alone on the machine) across the BB and ISO experimental and control conditions. It will be recalled that previous research indicated that participants did treat object B differently across the BB and ISO conditions (e.g., Sobel et al., 2004). Specifically, 4-year-olds were more likely to indicate that object B was a blicket in the ISO condition compared to the BB condition, and this finding was taken as evidence against the traditional RW model (which predicts equal treatment of object B across the conditions). This finding was interpreted to mean that these children engaged in BB reasoning. In contrast, in the present study participants treated objects B and C equivalently across the BB and ISO experimental and control conditions, all *p*’s > .17, all *BF*H1’s < 0.29.

**6-year-olds.** The analyses for the 6-year-olds indicated that although participants were more likely to indicate that object C was a blicket in the ISO experimental condition (40 out of 44) compared to the BB experimental condition (29 out of 45), OR = 5.75, *p* < .01, *BF*H1= 16.53, bootstrapped 95% CI[2.02, 9.48], participants treated object B similarly between the BB and ISO experimental and control trials, both OR’s = 1.05, both *p*’s > .91, both *BF*H1’s < 0.10.

**Discussion**

The results of Experiment 2 for the 5-year-olds revealed that the 5-year-olds did not show evidence of BB reasoning under either an old (e.g., Sobel et al., 2004) or new operationalization of it. Specifically, in terms of the new operationalization, the 5-year-olds treated objects B and C equivalently between the BB experimental and control conditions. Likewise, in terms of the old operationalization of BB reasoning, the 5-year-olds mostly treated objects B and C equivalently between the BB and ISO experimental and control conditions. Combined with the fact that the 5-year-olds’ causal inferences were mostly with the simple connectionist model that instantiated a formally equivalent version of the traditional RW model, these results suggest that the 5-year-olds may have relied on an associative-learning mechanism to reason about the present causal events.

In contrast, the present data do not rule out the possibility that the 6-year-olds used Bayesian inference to reason in the present context. Although it is clear that their performance is incompatible with the predictions of the traditional RW model as implemented in a simple connectionist (computational) model—based on the fact that participant neither distinguished object A from objects B and C in the BB experimental condition nor did they distinguish object D from objects A, B, and C in the BB control conditions—their causal responses may nonetheless be consistent with the predictions of a simple Bayesian model. Specifically, if participants assumed a priori that blickets were common in the present context—which is plausible given that the detector activated much more frequently in the present study than, say, in Sobel et al. (2004)—then they would be expected to treat the objects equivalently between the BB experimental and control conditions.

To see that this is the case, consider a formal—albeit extremely simple—Bayesian model. On a Bayesian-inference account, it is assumed that at the beginning of a learning task an ideal Bayesian learner represents all possible candidate hypotheses, *H*, whereby each hypothesis, *h* ∈ *H*, is assumed to have some prior probability, *p*(*h*), that is associated with it. This prior probability represents the learners’ confidence that the observed data were generated by a given causal hypothesis. Following observations of data, *d*, the learner then uses Bayes' rule to compute and assign posterior probabilities to each hypothesis, *p*(*h*|*d*),

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where *p*(*d*|*h*) represents the likelihood or the probability of the data *d* under a given hypothesis *h.* The denominator, which is a normalizing constant, ensures that sum of the posterior probabilities is 1.Because the hypotheses in the present experiments are assumed to be deterministic (i.e., objects either produce or do not produce detector activation), the likelihoods are set to 1 whenever a link (i.e., causal relation) exists in the hypothesis (Figure 1) and is consistent with the observed data; otherwise, they are set to 0.

Given that Bayesian inference operates over a fixed hypothesis space, it is also important to specify the hypothesis space *H* and the hypotheses *h* that comprise that space for the present context. This step is necessary before Bayes' rule can be used to determine the hypothesis with the largest posterior probability. Given that participants were asked to reason about three objects in the present study, the hypothesis space consists of eight hypotheses. The specific parameterization of each hypothesis in the space is specified by the activation law, which, for all three experiments, states that the blicket detector will activate if, and only if, a blicket object contacts it. The second step in defining this model is to specify the prior probabilities of each hypothesis in each of the three experiments. If we assume that the probability that a particular object is a blicket is independent of the probability that other objects are blickets, then prior probabilities for these experiments can be found in Table X. Once we have specified the prior probabilities, it is possible to use them to compute the posterior of each hypothesis when new data is observed, according to Bayes' rule.

Given that the present experiments used deterministic causes, that either did or did not activate the machine, whenever a link exists in the model and the data are consistent with that link, the likelihood of a particular hypothesis is set to 1; whenever a link does not exist the likelihood is set to 0. Once it is determined that a link exists for a particular object, we can compute the likelihood that object A, B, or C in Experiments 1 and 2 or object A, B, C, or D in Experiment 3 is a blicket by taking the product of the likelihood that a particular object activated the detector under each hypothesis and the prior probability of each hypothesis and then summing this product. To determine the probability that object B is a blicket, for example, we can compute the following equation:

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where is 1 if a causal link between *B* and *E* existsfor a specific hypothesis *h*; otherwise, is 0.

Taken together, these results suggest that when participants are asked to reason about three objects—which corresponds to a hypothesis space that consists of 8 candidate causal hypotheses—they do not engage in BB reasoning. Crucially, if BB reasoning is used as an indirect measure of the operation of a Bayesian-inference mechanism, then these findings are inconsistent with the notion that children use Bayesian inference to reason about three objects. It will be recalled that this perspective predicts that human reasoners should engage in BB reasoning irrespective of the number of candidate causes about which they are asked to reason. However, these data are consistent with the traditional RW model. As we discussed at the outset of this paper, this model does predict that participants should treat the redundant objects—that is, the objects that are not presented alone on the machine—equivalently. This is because the strength of the association between each redundant cue and the causal effect is equivalent for each cue. Crucially, these findings could not be explained by the fact that participants were insensitive to the causal status of each object and thus considered all objects to be blickets: Participants were more confident that object A was a blicket during the BB experimental trials than during the ISO experimental trials. Likewise, participants were more confident that object D was a blicket during the BB control trials than during the ISO control trials.

General Discussion

This study had two broad aims. The first aim was to examine whether 4-, 5-, and 6-year-olds would engage in BB reasoning when asked to reason about 3 objects. This study departs from previous research on BB reasoning in human children, which typically has involved asking children to reason about two candidate causes (e.g., Beckers et al., 2009; Griffiths et al., 2011; McCormack et al., 2013; Sobel et al., 2004). The second broad aim was to determine how or by what cognitive mechanism children reason about multiplate candidate causes. Specifically, we examined whether a Bayesian-inference mechanism or an associative-learning mechanism based on the traditional RW model better explained how children reasoned about multiple candidate causes in the present context. Experiment 1 showed that 4-year-olds treated the redundant causes equivalently regardless of whether the comparison was between experimental and control trials *within* the BB condition or between the experimental or control trials *between* the BB and ISO conditions as was done in previous studies. Experiment 2 replicated this finding with 5- and 6-year-olds. These children, like the 4-year-olds, showed no evidence of BB reasoning—they treated the redundant causes equivalently between the experimental and control conditions *within* the BB condition as well as between the BB and IS experimental and control conditions.

These findings are significant because they provide insight into how—that is, by what underlying cognitive mechanism—children reason about multiple candidate causes. As we mentioned at the outset, if BB reasoning is used as an indirect measure of children’s use of Bayesian inference, then the fact that participants showed no evidence of BB reasoning when asked to reason about multiple potential causes suggests that children were not relying on Bayesian inference. Instead, the present results suggests that children’s causal judgements were subserved by an associative-learning mechanism. In particular, the present results suggests that the traditional RW model—which has been argued to be unable to explain human causal judgements (e.g., Sobel et al., 2004)—is sufficient to explain the present results. This is because the RW model predicts that participants should treat the redundant causes equivalently across and within conditions, which aligns with participants’ actual performance.

These findings are broadly significant because they suggest that when children’s information-processing capacities are stretched, they rely on simpler cognitive mechanisms to reason about causal events. Specifically, when children are asked to reason about three causes, the current results suggest that their causal judgements align with the predictions of the traditional RW model. Although at the level of individual objects asking children to reason about three compared to two objects may seem trivial, by contrast the corresponding increase in the underlying psychological hypothesis space is substantial. For example, children who are asked to reason about two candidate causes—which is the approach that has been taken in most contemporary studies on BB reasoning in human children (e.g., Beckers et al., 2009; Griffiths et al., 2011; Kloos & Sloutsky, 2013; McCormack et al., 2009; McCormack et al., 2013; Sobel et al., 2004)—need only to represent and choose among *four* candidate causal hypotheses (i.e., 2n, where *n* is the number of potential causes). This may be within the limits of 3- and 4-year-olds’ information-processing capacities. However, children who are asked to reason about three candidate causes must now contend with *eight* candidate causal hypothesis. For the developing child, this may well be outside the limits of their restricted information-processing capacities. This view also aligns with previous theorizing both in the infant literature (e.g., Cohen, Chaput, & Cashon, 2002) as well as in the child literature (e.g., De Houwer & Beckers, 2003; Waldmann & Walker, 2005). This, in turn, may explain why their present causal judgements better aligned with an associative-learning mechanism than a Bayesian-inference once, whereas in previous studies on BB reasoning in children, their performance better aligned with a Bayesian-inference mechanism than an associative-learning one.

One open question that this study leaves unaddressed concerns what effect, if any, establishing the base rate of blickets would have on participants’ BB performance in this setting. For example, it is possible that participants would engage in BB reasoning—and thus show evidence of the use of a Bayesian-inference mechanism—if the base rate of blickets is established to be low. In contrast, if the base-rate of blickets is established to be high, it is possible that participants’ performance would mirror those of participants in the current study. Such a study, in combination with the results of the present study, would clarify what base rate, if any, participants default to when base rate is not explicitly manipulated. Although previous research has shown that children are sensitive to base rates and can integrate that information into their causal judgements about two potential causes (e.g., Griffiths et al., 2011; Sobel et al., 2004), it remains unknown whether participants would be sensitive to base-rate information in the present context.

Nonetheless, by examining whether participants are sensitive to base rate information in a context with multiple candidate causes, we can provide still further insight into the underlying causal mechanism that supports causal judgements in human children. For instance, if children’s causal judgements are shown to be affected by base-rate information, such that their BB reasoning performance changes as a function of changes to the base rates of blickets, then this would suggest that participants may use Bayesian inference to reason about multiple candidate cause after all. This is because Bayesian inference requires that learners combine the current data with our prior beliefs about how likely a given object is to be blicket to choose the causal hypothesis that is generating the data. Thus, participants who are insensitive to the base-rates of blickets cannot be said to be using Bayesian inference. Crucially, if participants continued not to engage in BB reasoning despite manipulations to the base rate of blickets—as evidenced by equivalent treatment of the redundant candidate causes within and between conditions—then this would further suggest that associative learning provides a better account of causal reasoning in human children.

Along these lines, one potential criticism of the present study is that it cannot be ruled out that participants were relying on Bayesian inference. For example, if participants assumed a priori that blickets were common in the present context—which is plausible given that the detector activated much more frequently in the present study than, say, in Sobel et al. (2004)—then participants should be less likely to block redundant causes. We are disinclined to accept this explanation for two reasons. First, the performance of the 4-year-olds and the 5- and 6-year-olds was equivalent. If possessing sufficient information-processing capacities and showing sensitivity to base-rate information are important prerequisites for using Bayesian inference, then the 4- and 5-year-olds might be expected to perform differently than the 6-year-olds. The results from Experiment 2 seem to support this supposition: The 5-year-olds’ performance suggested that they were more confident that object A was a blicket than the other redundant causes in the BB experimental condition and that object D was a blicket than the other redundant causes in the BB control condition.

Future research will need to manipulate the base rates of blickets, similar to what was done in Sobel et al. (2004), to determine whether the present results reflect the operation of a Bayesian-inference mechanism or a RW-model-like associative-learning mechanism