

# Additivity Pretraining and Cue Competition Effects: Developmental Evidence for a Reasoning-Based Account of Causal Learning

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The effect of additivity pretraining on blocking has been taken as evidence for a reasoning account of human and animal causal learning. If inferential reasoning underpins this effect, then developmental differences in the magnitude of this effect in children would be expected. Experiment 1 examined cue competition effects in children's (4- to 5-year-olds and 6- to 7-year-olds) causal learning using a new paradigm analogous to the food allergy task used in studies of human adult causal learning. Blocking was stronger in the older than the younger children, and additivity pretraining only affected blocking in the older group. Unovershadowing was not affected by age or by pretraining. In experiment 2, levels of blocking were found to be correlated with the ability to answer questions that required children to reason about additivity. Our results support an inferential reasoning explanation of cue competition effects.

*Keywords:* causal learning, blocking, reasoning, associative learning, cognitive development

Theories of human causal learning and animal Pavlovian conditioning have frequently been evaluated on their ability to explain the cue competition effect of blocking and the factors that influence this effect (Dickinson, 2001; Mitchell, De Houwer, & Lovibond, 2009; Shanks, 2010). In human causal learning tasks designed to measure blocking effects, an individual cue A (the element) is paired with an outcome (usually summarized as A+). A compound of two cues (AB+) is also presented. Blocking occurs when the element cue A blocks or prevents learning that B is causally efficacious. A series of recent studies has shown that the magnitude of blocking effects can be strongly affected by particular types of pretraining given before the blocking training itself, although the pretraining involves different cues. During pretraining in studies of additivity effects, the intensity of the outcome that is paired with two causally efficacious cues is varied (Beckers, De Houwer, Pineño, & Miller, 2005; Lovibond, Been, Mitchell, Bouton, & Frohardt, 2003; Vandorpe, De Houwer, & Beckers, 2007a). In additive conditions, the outcome is stronger than when an efficacious cue is given on its own (if the element cues F and H are each paired with an outcome +, the compound FH is paired with ++); in nonadditive conditions the outcome strength is the same for both the individual cues and their compound (if the element cues F and H are each paired with +, the compound cue FH is also paired with +). Blocking effects are

much more marked under additive conditions, and this is true for both humans (Beckers et al., 2005) and animals (Beckers, Miller, De Houwer, & Urushihara, 2006).

The fact that human causal learning and animal Pavlovian conditioning show additivity effects has been taken as an important reason to assume that both are underpinned by the same mechanisms (although see Penn & Povinelli, 2007; Shanks, 2010). However, much controversy surrounds the interpretation of additivity effects, with Beckers et al. (2006) arguing that such effects are best explained in terms of a higher-order theory of learning that stresses the role of effortful reasoning processes and that additivity effects are not predicted by associative models of learning. An inferential reasoning account of the effect of additivity pretraining on blocking explains this effect in terms of a chain of conditional reasoning. Mitchell, Lovibond, and Condoleon (2005) describe the additivity effect as recruiting a conditional inference as follows: "A is causally efficacious and gives outcome +. If A and B are both efficacious, then the outcome is ++. The outcome is +. Therefore B is not efficacious." Note that this is a variety of modus tollens inference (if p then q, not q, therefore not p). Engaging in this chain of reasoning will disambiguate B's causal status, giving low causal ratings for B and thus producing a blocking effect. Such reasoning is not available when causal outcomes are not additive; thus, blocking effects after nonadditive training are likely to be much weaker or nonsignificant (Beckers et al., 2005, 2006; Lovibond et al., 2003).

Associative models of causal learning do not easily predict additivity effects on blocking: The cues presented during pretraining never appear at test; thus, associative learning concerning such cues would not be expected to affect what is learned in the test period. However, the claim that associative models cannot explain additivity effects has recently been challenged (Haselgrove, 2010; Schmajuk & Larrauri, 2008), with Haselgrove (2010) arguing that it is possible to model such effects by assuming that cues used in training are sufficiently similar to cues used at test to result in some generalization of learning (i.e., by assuming that training and

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test cues share a common element). In his account, the result of this generalization is that, after nonadditive pretraining, no new learning about cue A occurs during the element phase, the consequence of which is that blocking is then not observed after the compound phase. However, new learning about element cues, and thus blocking, is assumed to be possible after additive pretraining.

Effects of additivity on blocking are also compatible with recent hierarchical Bayesian models of causal learning (Lu, Rojas, Beckers, & Yuille, 2008; Lucas & Griffiths, 2010), although for quite different reasons. These models essentially assume that additivity pretraining leads to the learning of an abstract principle that then modulates how likelihoods (i.e.,  $p(D|H)$  values) are computed from incoming data. Therefore exactly the same data can yield blocking after one sort of pretraining but not after another. However, most researchers regard such Bayesian models as computational-level theories (i.e., normative accounts of optimal performance) rather than as descriptions of cognitive processes (Gopnik et al., 2004; Griffiths & Tenenbaum, 2009). Thus, even if additivity effects can be modeled in other ways, it is still important to consider whether explicit inferential reasoning processes are or are not necessary for such effects to occur. This issue is particularly pertinent for comparative researchers because of the implications for how animal cognition is characterized, that is, whether rats should really be described as rule-based reasoners as Beckers et al. (2006) have claimed (see, e.g., Kunder & Fountain, 2010; Wills et al., 2009; and Urcelay & Miller, 2009, for discussion of the conclusions of Beckers et al., 2006).

In this study, we took a different approach toward examining whether or not additivity effects on blocking should be explained in terms of the involvement of reasoning processes. If the effect of additivity on blocking is due to the involvement of reasoning, then we might expect to see it vary according to the cognitive abilities of the population being tested (see also Castro & Wasserman, 2010). Thus, in our study we compared causal learning in children of different ages who might be expected to differ in terms of their ability to engage in the necessary chain of reasoning. It is well established that the ability to engage in conditional reasoning, such as the ability to make modus tollens inferences, improves in early childhood (Braine & Rumin, 1983; Byrnes & Overton, 1986, 1988; Greenberg, Marvin, & Mossler, 1977). Thus, if the additivity effect is due to this reasoning process, then we would expect to see it, and indeed blocking itself, show marked developmental changes.

Cue competition phenomena have previously been examined in children using the blicket detector task (Gopnik & Sobel, 2000; Gopnik, Sobel, Schulz, & Glymour, 2001; Sobel, Tenenbaum & Gopnik, 2004). In this paradigm children observe an experimenter placing a series of objects onto a "blicket detector" (an electronic box). If an object is a "blicket" the box will light up and play a tune. After children have seen some objects being placed on the machine they are asked whether or not an object is a blicket or to select an object that will cause the machine to turn on. Children are typically given a substantially less complex task with fewer repetitions of trials than in causal learning tasks used with adults. Although this task has been used to examine cue competition effects, there is no consensus on their developmental profile, in part because of differences between studies in the use of appropriate control trials (Beckers, Vandorpe, Debeys, & De Houwer,

2009; McCormack, Butterfill, Hoerl, & Burns, 2009; Sobel et al., 2004). Additivity effects have not been studied in children.

In the study presented here, we used a new causal learning task that was a child-friendly version of the well-known allergy task used in studies of additivity with adults (Beckers et al., 2005). This task involves children watching an experimenter feed a robot a series of individual or pairs of plastic foodstuffs. Some foodstuffs make the robots tummy light up and make a noise; children are subsequently asked to make causal judgments about foodstuffs. The experimenter can designate whether the robot's tummy lights up partially or fully, and the volume of associated noise, thereby controlling the strength of the outcome. Table 1 shows the trials that participants in experiment 1 received during pretraining and training using this paradigm. This paradigm allows a closer comparison to be drawn between the findings of child and adult studies. However, it differs from those used with adults in that children are not asked to rate the causal strength of cues on a scale because of potential problems with young children using such a response mode. Rather, we ask children to judge whether particular foodstuffs were or were not foods that made the robot's tummy light up and to make a forced choice between experimental and control foods as to which food would make the robot's tummy light up. The latter forced-choice measure has been previously found to be a more sensitive measure of cue competition effects in children (Beckers et al., 2009).

As can be seen from the outline of trials in Table 1, we assessed the cue competition effect of unovershadowing in addition to blocking. This was of particular interest because a reasoning account gives predictions about the effects of age and additivity on unovershadowing that contrast with the predictions such an account makes regarding blocking. A reasoning account specifically predicts that additivity should affect the magnitude of blocking effects, but not unovershadowing. In unovershadowing, the element A is shown not to cause an outcome (A+), and the compound of two cues is paired with an outcome (AB+). Under these circumstances, B is highly likely to be judged as causally efficacious. A chain of reasoning involving a simple disjunctive inference can support this judgment: "Either A or B must be causally efficacious. A is not efficacious, therefore B must be." Note that this chain of reasoning holds regardless of whether the outcome is additive or nonadditive, and, consistent with this, additivity has been shown not to affect the magnitude of unovershadowing in

Table 1  
*Pretraining and Element and Compound Training*

(a) Pretraining design		
Additive group	F+/G-/H+/I-/FG+/FH++	
Nonadditive group	F+/G-/H+/I-/FG+/FH+	
(b) Element and compound training		
Task	Phase 1	Phase 2
Forward blocking	A+, E-	AB+/CD+
Forward unovershadowing	A-, E+	AB+/CD+
Backward blocking	AB+/CD+	A+, E-
Backward unovershadowing	AB+/CD+	A-, E+

*Note.* - = no response; + = weak response, ++ = strong response. C items were controls; E items were fillers and ensured that there were some trials in which the outcome did not occur per task. During pretraining each trial was shown twice. During element and compound training, each trial was shown three times.

adults (Beckers et al., 2005). Moreover, evidence from recent developmental studies suggests that children may be competent at simple disjunctive reasoning from an early age (Halberda, 2006). Thus, a reasoning account might predict that unovershadowing does not show the same developmental profile as blocking because it involves a simpler inference within the grasp of preschoolers.

The developmental predictions regarding additivity and cue competition effects generated by an inferential reasoning account are straightforward. However, it is not clear what developmental predictions would be generated by either Haselgrove's (2010) account of additivity effects or a Bayesian account. In principle, it is possible to generate Bayesian models of causal learning that would predict developmental change (Shultz, 2007). However, the general thrust of developmental theorizing in this area has been to argue that the learning mechanisms that actually underpin children's sensitivity to statistical patterns of data are intact from early in development, perhaps even from birth (Goodman, Ullman, & Tenenbaum, 2011; Gopnik et al., 2004). Thus, as they stand, such accounts do not generate the specific pattern of developmental predictions made by the inferential reasoning account.

## Experiment 1

In this experiment, children were assigned to either an additive or nonadditive pretraining condition, with pretraining trials administered as summarized in Table 1. In addition to varying additivity, we also varied the order in which participants received the element and compound cues, so that backward as well as forward blocking was examined. Unovershadowing was also examined under forward and backward presentation conditions. A reasoning account readily predicts cue competition effects under both orders of presentation because the information upon which inferences are made does not vary with the order of the presentation of cues. However, we might expect that backward blocking would be more cognitively demanding, particularly for children, than forward blocking (although see McCormack et al., 2009). This is because in backward conditions, participants do not have the relevant information to make the inference until after they have seen the element cue and must retrieve the compound cue from memory before making a retrospective judgment (i.e., at test). Forward conditions may make fewer demands on working memory because participants have the relevant information in mind to make the inference while the compound cue is being presented (i.e., during training; Vandorpe, De Houwer, & Beckers, 2007b).

## Method

**Participants.** Ninety-nine 4- to 5-year-olds (mean age = 64 months, range = 56–71 months) and 73 6- to 7-year-olds (mean age = 80 months, range = 72–95 months) participated in the study. These children were recruited through local schools and newspapers and were tested either in their own classrooms or the School of Psychology's developmental laboratory. All participating children provided written parental consent. No information was available on parental income or educational attainment. Participants in both age groups were assigned to either a nonadditive or additive pretraining group; they were also assigned to either a forward or backward presentation group. Numbers of participants in each group were as follows:  $N = 25$  4- to 5-year-olds additive

forward group;  $N = 27$  4- to 5-year-olds additive backward group;  $N = 24$  4- to 5-year-olds nonadditive forward group,  $N = 23$  nonadditive backward group;  $N = 18$  6- to 7-year-olds additive forward group;  $N = 17$  additive backward group;  $N = 18$  nonadditive forward group; and  $N = 20$  nonadditive backward group.

**Apparatus and stimuli.** A purpose-built toy robot was used. The robot had a transparent Perspex center (described to the participants as the robot's tummy); along the right and left sides of the center were two semiopaque light boxes that contained battery-powered LED lights. The light boxes were divided in two; the bottom half was pink and the top half was red. The robot also contained a hidden speaker. Toy foodstuffs could be placed on a movable platform in the robot's mouth. Pressing the robot's nose caused the platform to move downward into the robot's tummy and tilt, and then the food(s) would drop into the robot's tummy. There were seven sets of five foods, one of which was a training set. Examples of the plastic foodstuffs were an egg, a piece of cheese, a piece of bread, and a banana. The tilting of the platform caused one of three responses to occur (either weak, strong, or no response). A weak response consisted of the bottom part of the robot's tummy lighting up accompanied by a quiet, low noise. A strong response consisted of all of the robot's tummy lighting up, accompanied by a loud, high noise. The lights and noise lasted for 3 s, and then the foodstuff(s) were removed from the robot's tummy by the experimenter through a hole at the back of the robot. These responses were predetermined by an input file selected by the experimenter from a computerized control program. The platform returned to the start position automatically.

## Procedure

**Pretraining phase.** Participants were shown the robot and introduced to the mechanism using one of the pretraining foods. Pretraining followed the protocol in Table 1a, dependent on whether the participant had been assigned to either the additive or nonadditive pretraining group. Trials were given in the fixed order shown in the table, and each trial was presented twice. Which foodstuff in the pretraining set was used for each cue (F-I) was varied between participants. When an outcome occurred, the experimenter described the robot's responses in the additive condition as "a bit of his tummy lighting up" when there was a weak outcome, and "all of his tummy lighting up" when there was a strong outcome. In the nonadditive condition, the outcome was simply described as "the robot's tummy lighting up." Throughout the pretraining session children were asked a series of comprehension questions in order to ensure that they understood what they had seen.

**Element and compound training phases.** Element and compound training followed the protocol in Table 1b, with each participant completing six sets of trials. In what follows, each set of trials (plus associated test questions) will be referred to as a task. Participants in the forward group completed three forward blocking tasks and three forward unovershadowing tasks; those in the backward group completed three backward blocking and three backward unovershadowing tasks. As in previous studies with children, but unlike in most studies with adults, the cue competition effects of blocking and unovershadowing were assessed in separate tasks to ensure that children did not have to sit through a large number of trials without a break. In each task, each trial was

shown three times, with the order of presentation of trials within each phase varied. For example, in a forward blocking task, in phase 1 participants would see a trial involving the robot being fed one foodstuff that made the robot's tummy light up (A+) and another trial in which a different foodstuff did not make the robot's tummy light up (E-). Participants saw each of these trials three times in a randomized order before being shown the compound cues in phase 2, with again each trial of compound cues (AB+ and CD+) shown three times in a varied order. Thus, for each task participants observed 12 trials in total before being asked test questions. The presentation order of blocking and unovershadowing tasks was counterbalanced. A new set of foodstuffs was used for each separate task. Within sets, foodstuffs were counterbalanced in terms of which element they represented (A-D); however, the foodstuff representing element E remained constant because this was a filler item that was included to ensure that there was at least one cue per blocking task that was not paired with an outcome.

**Test phase.** After the participant had observed all of the trials in one task the following questions were asked, to which children gave a yes or no answer: "Is (food name B, e.g., cheese) a food that makes the robot's tummy light up?" and "Is (food name C, e.g., bread) a food that makes the robot's tummy light up?" The order of the questions (B or C) was counterbalanced. Children were not asked about the causal status of cues A, E, or D because only responses to B and C are necessary for assessing cue competition effects. Then children were also asked a forced-choice question: "If you had to choose one of these foods to make the robot's tummy light up, which one would you choose (experimenter holds out B and C)?" Children either pointed to or named the food they chose. No feedback was given to participants. The identical process was repeated for all six tasks. Children were given a break after the third task to prevent fatigue and were provided with a brief reminder of the pretraining that they had experienced before

completing tasks 4–6. On completion of the third and sixth tasks, children were thanked for their participation and given a sticker of their choice.

## Results

### Difference Scores

In every task, for foods B and C, participants provided yes or no responses as to whether or not this was a food that caused the robot's tummy to light up. The maximum yes score for food B and for food C was 3 because participants had received three tasks of each type. To assess the effects of the independent variables, difference scores between ratings for foods B and C were calculated. These calculations were conducted in the following way for each participant: For blocking tasks, the number of yes responses to B were subtracted from the number of yes responses to C, whereas for unovershadowing tasks, the number of yes responses to C were subtracted from the number of yes responses to B. These difference scores give an indication of the magnitude of each cue competition effect; positive scores indicate a cue competition effect in the predicted direction and scores of zero indicate that no effect is present. Mean difference scores are shown in Figure 1. An initial analysis of variance (ANOVA) on difference scores showed a two-way interaction between pretraining type (additive vs. non-additive) and test type (blocking vs. unovershadowing),  $F(1, 168) = 5.02, p = .026, \eta_p^2 = .026$ . Thus, we analyzed difference scores separately for blocking and unovershadowing tasks.

### Blocking

A one-sample *t* test (using an expected chance value of 0, because scores resulting from forced-choice questions could range from -3 to +3) indicated that, overall, significant blocking was

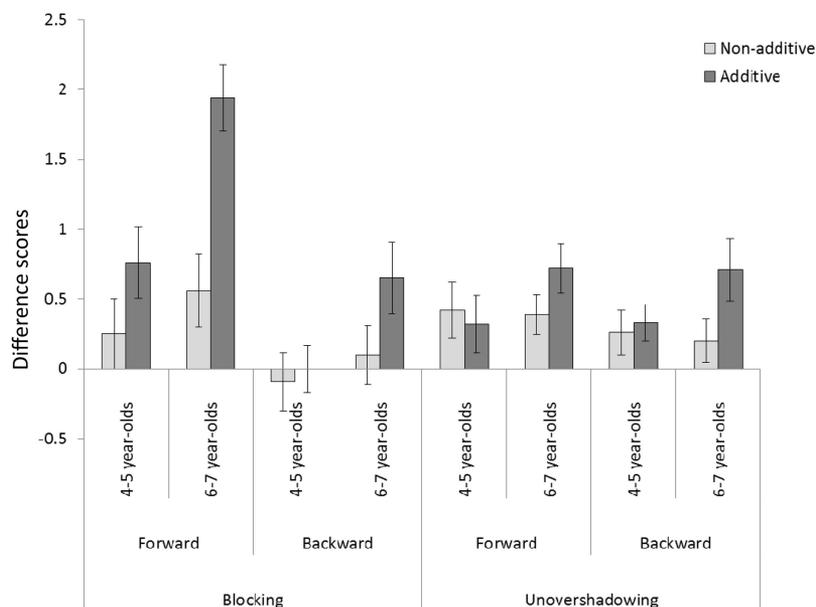


Figure 1. Difference scores in experiment 1 as a function of age group, training type, and order of presentation. Error bars show 1 SE.

observed,  $t(171) = 5.16, p < .001$ . ANOVA was conducted on the difference scores with between-subject factors of age group (4- to 5-year-olds vs. 6- to 7-year-olds), order (forward vs. backward), and pretraining (additive vs. nonadditive). There were significant main effects of pretraining,  $F(1, 164) = 14.81, p < .001, \eta_p^2 = .08$ ; age group,  $F(1, 164) = 12.47, p = .001, \eta_p^2 = .071$ ; and order,  $F(1, 164) = 18.75, p < .001, \eta_p^2 = .10$ . Difference scores were larger for the forward than the backward presentation condition, with significant blocking only for the forward condition,  $t(84) = 5.83, p < .001$ . Difference scores were also larger for the additive than the nonadditive training condition, with blocking being significant only in the additive condition,  $t(86) = 5.57, p < .001$ . In line with predictions, they were also larger for the older children, although both groups showed significant blocking,  $t(98) = 2.04, p < .05$  for the 4- to 5-year-olds and  $t(72) = 5.60, p < .001$  for the 6- to 7-year-olds. There was also a significant interaction between pretraining and age group,  $F(1, 164) = 4.14, p = .04, \eta_p^2 = .03$ . Further analyses indicated that there was no significant effect of pretraining for the 4- to 5-year-olds ( $p = .18$ ). However, this effect was significant for 6- to 7-year-olds,  $F(1, 69) = 16.54, p < .001, \eta_p^2 = .19$ , with larger difference scores observed in the additive pretraining condition than the nonadditive condition. A significant effect of age was observed in the additive pretraining condition,  $t(85) = -3.72, p < .001$ , but not in the nonadditive condition ( $p = .33$ ).

The interaction between order and pretraining was approaching significance,  $F(1, 164) = 3.69, p = .06, \eta_p^2 = .02$ . Further analysis revealed that there was a significant effect of pretraining for the forward presentation condition,  $F(1, 81) = 13.72, p < .001, \eta_p^2 = .15$ , with larger difference scores in the additive than the nonadditive pretraining condition. There was no significant main effect of pretraining for the backward presentation condition ( $p = .13$ ). There were no other significant interactions.

## Unovershadowing

A one-sample  $t$  test (expected chance value = 0) indicated that, overall, significant unovershadowing was observed  $t(171) = 6.41, p < .001$ . ANOVA was conducted on the difference scores with between-subject factors of age group, order, and pretraining for unovershadowing tasks. No significant main effects or interactions were observed.

## Choice Data

Participants were also asked to choose which food was the most likely to make the robot's tummy light up (choosing between food B and C). In blocking tasks, food C was more likely to be causal, food B was more likely in unovershadowing tasks, and participants were given one point for each correct choice. The maximum choice score was 3; mean choice scores are shown in Figure 2. An initial ANOVA on choice scores showed a two-way interaction between pretraining type (additive vs. nonadditive) and test type (blocking vs. unovershadowing),  $F(1, 168) = 10.73, p < .001, \eta_p^2 = .06$ . Thus, as with difference scores, we separately analyzed choice scores for blocking and unovershadowing tasks.

## Blocking

A one-sample  $t$  test (using an expected chance value of 1.5 because scores from the forced-choice questions could range from 0 to 3) indicated that significant blocking was observed,  $t(171) = 5.13, p < .001$ . ANOVA was conducted on the choice scores with between-subject factors of age group, order, and pretraining. There was a significant main effect of order,  $F(1, 164) = 4.02, p = .047, \eta_p^2 = .02$ , and pretraining,  $F(1, 164) = 20.14, p < .001, \eta_p^2 = .109$ . Although there were higher scores in the forward compared with the backward presentation condition, blocking was significant

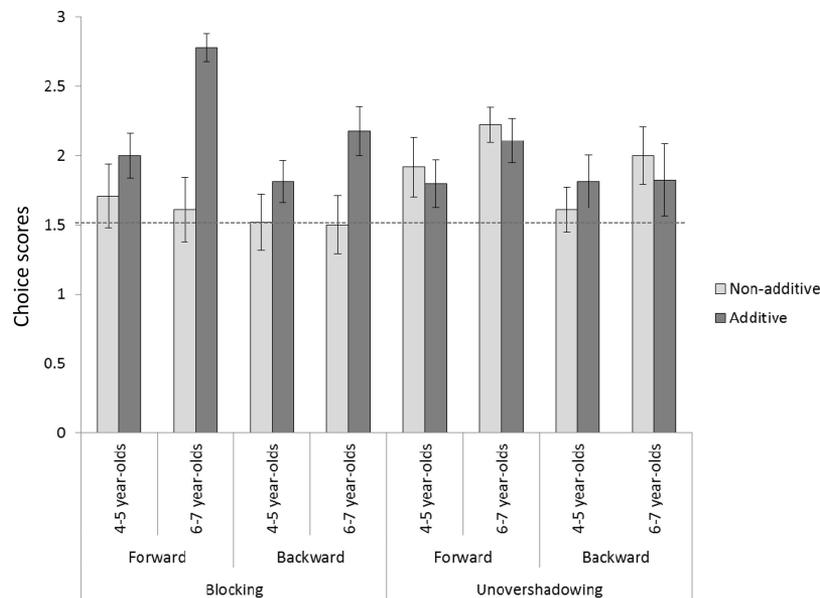


Figure 2. Choice scores in experiment 1 as a function of age group, training type, and order of presentation. Error bars show 1 SE. Dashed line shows chance level of performance.

in both conditions,  $t(84) = 4.72, p < .001$  for the forward condition and  $t(86) = 2.49, p < .02$  for the backward condition. Significant blocking was only observed in the additive condition,  $t(86) = 7.49, p < .001$ . The main effect of age was approaching significance,  $F(1, 164) = 3.56, p = .06, \eta_p^2 = .02$ . Although choice scores were higher for the older children, significant blocking was observed for both age groups, 4- to 5-year-olds:  $t(98) = 2.88, p = .005$ ; 6- to 7-year-olds:  $t(72) = 4.53, p < .001$ . There was a significant interaction between pretraining and age group,  $F(1, 164) = 5.41, p = .02, \eta_p^2 = .03$ . Further analyses indicated that there was no significant effect of pretraining for 4- to 5-year-olds,  $p = .12$ , but this effect was significant for 6- to 7-year-olds,  $F(1, 69) = 23.76, p < .001, \eta_p^2 = .26$ , with children choosing the control food more often if they experienced additive rather than nonadditive pretraining.

### Unovershadowing

A one-sample  $t$  test (expected chance value = 1.5) also showed significant unovershadowing,  $t(171) = 5.81, p < .001$ . ANOVA was conducted on the choice scores with between-subject factors of age group, order, and pretraining. Although 6- to 7-year-olds chose the experimental food more often than the 4- to 5-year-olds, the main effect of age group did not reach significance,  $F(1, 164) = 3.39, p = .067, \eta_p^2 = .02$ . The results of one-sample  $t$  tests indicate that 4- to 5-year-olds,  $t(98) = 3.08, p = .003$ , and 6- to 7-year-olds,  $t(72) = 5.61, p < .001$ , showed significant unovershadowing effects.

### Discussion

As predicted by a reasoning account, the magnitude of blocking effects increased with age, but no significant age change was observed for unovershadowing. Moreover, blocking, but not overshadowing, was modulated by additivity pretraining, but only for the older children. We interpret these findings as suggesting that the ability to engage in the chain of reasoning that is affected by additive pretraining—modus tollens reasoning—improves in the age period tested in this study, consistent with previous studies of children's reasoning (e.g., Byrnes & Overton, 1986, 1988). Unovershadowing is not predicted to be affected by additivity in a reasoning account. Moreover, because it involves the simpler disjunctive inference, it is not surprising that it is not affected by age. Furthermore, young children's relatively good performance on unovershadowing tasks suggests that they were paying attention to the task and keeping track of the causal status of items during trials.

Order of presentation of element and compound cues also selectively affected blocking, with more marked forward blocking observed than backward blocking. This contrasts with the findings of McCormack et al. (2009), who found no effect of presentation order on blocking in children. Indeed, in the study presented here, backward blocking was only apparent in children's answers to forced-choice questions in the additive condition, in which they were more likely to choose the control food than the experimental food to light the robot's tummy up. Backward blocking may have particularly taxed children's working memory capacity in that they had to retrieve cues and retrospectively make the appropriate inference. In unovershadowing trials, the necessary disjunctive

inference is likely to be less cognitively demanding, which may explain why order effects were not observed for this cue competition effect.

We have suggested that the age differences we have observed in blocking and the effects of additivity are due to developmental changes in ability to engage in modus tollens reasoning. However, it could be argued that these findings provide only indirect evidence for this suggestion because we did not actually explore why children's performance changed as they got older. More convincing evidence would come from demonstrating that the relevant age effects are related to changes in reasoning ability with age. Support would also be gained by investigating whether reasoning skills determined if children would demonstrate blocking in the additive condition. Our second experiment addressed this issue by introducing an additional measure that directly examined children's ability to make the relevant modus tollens inference.

### Experiment 2

In this experiment, children completed a cue competition task identical to that used in the forward additive condition in experiment 1. Only the forward condition was used because blocking was more marked in that condition. In addition, children were asked questions that could only have been answered if they were capable of engaging in the construction and evaluation of the appropriate modus tollens reasoning premises. We then looked at the relationship between performance on these modus tollens questions and performance on the cue competition task. Children were also asked to make judgments that involved simple disjunctive reasoning. The aim of this was to confirm that children were capable of making the appropriate disjunctive inferences from an early age, which may explain why no age effects were observed in levels of unovershadowing in experiment 1.

### Method

**Participants.** Sixty-four 3- to 6-year-old children participated in the study (mean age = 62 months; range = 44–78 months). All children were recruited through local schools or nurseries and were tested in their own classroom. No information was available on parental income or educational attainment.

**Apparatus and Stimuli.** The experimental setup for the robot task was identical to that in experiment 1.

**Procedure.** All participants experienced additivity pretraining (see Table 1a) and completed tasks in the forward condition only (see Table 1b). As in experiment 1, children completed six cue competition tasks with a break after the first three tasks. Children were also asked two pairs of reasoning questions, with each pair of questions containing a modus tollens and a disjunctive reasoning question related to the functioning of the robot. One pair was administered at the end of the first testing session and the other at the end of the second testing session. For each modus tollens reasoning question, children initially saw a new compound of two foods fed to the robot a single time, with only part of the robot lighting up. Children were then asked "Does only one of the foods make the robot's tummy light up, or do both of the foods make the robot's tummy light up?". The order in which the experimenter mentioned "one" or "both" of the foods in this question was counterbalanced. To answer this question, children

need to make the following inference: If both foods were foods that light the robot's tummy up, the whole of the tummy would have lit up. The whole tummy did not light up; therefore, both of the foods are not tummy-lighting foods. For disjunctive reasoning questions, children again saw the robot being fed with a pair of novel foods, and only part of the robot lit up. The experimenter then said "One of these foods doesn't make the robot's tummy light up. Is the other food one that makes the robot's tummy light up?" To answer this question, children had to reason that if one of the foods was not a tummy-lighting food, the other food had to be one. Children were thanked for their participation and rewarded with a sticker at the end of each testing session.

## Results

Mean scores are given in Table 2. It can be seen from the table that as a group, children performed well on the reasoning questions and indeed were at ceiling on the disjunctive questions.

### Yes Responses

As in experiment 1, difference scores between ratings for food B and C were calculated to assess the strength of forward blocking and unovershadowing for each child. Mean difference scores are summarized in Table 2. A one-sample  $t$  test (test value = 0) indicated that significant blocking was observed,  $t(63) = 5.11, p < .001$ . A separate one-sample  $t$  test (test value = 0) indicated that significant unovershadowing was also observed  $t(63) = 5.95, p < .001$ .

### Choice Data

Participants were also asked to choose which food was the most likely to make the robot's tummy light up (choosing between food B and C). The maximum choice score was 3; mean choice scores are summarized in Table 2. A one-sample  $t$  test (test value = 1.5) indicated that significant blocking was observed,  $t(63) = 2.55, p = .013$ . A separate one-sample  $t$  test (test value = 1.5) also showed significant unovershadowing,  $t(63) = 3.89, p < .001$ .

### Relationships Between Measures

Subsequent analyses examined relationships among age, scores on the modus tollens questions, and performance on the cue

Table 2  
*Experiment 2: Mean Difference Scores and Choice Scores for Forward Blocking and Unovershadowing Trials (Maximum Is 3) and Mean Modus Tollens and Disjunctive Reasoning Scores (Maximum Is 2)*

	<i>M (SD)</i>
Difference scores	
Blocking	0.66 (1.03)
Unovershadowing	0.69 (0.92)
Choice scores	
Blocking (choose C)	1.78 (0.88)
Unovershadowing (choose B)	1.95 (0.93)
Reasoning scores	
Modus tollens	1.39 (0.77)
Disjunctive	1.94 (0.30)

competition task. Relationships were not examined between scores on the disjunctive reasoning questions and other measures because performance was at ceiling on these questions. Correlations are shown in Table 3. Age was significantly correlated with all measures except blocking choice scores. The table indicates that blocking and unovershadowing difference scores were significantly correlated with performance on the modus tollens questions; in fact, this remained the case even when age was partialled out (blocking:  $r = .28, n = 61, p = .01$ ; unovershadowing:  $r = .35, n = 61, p = .002$ ). Performance on the modus tollens questions was also significantly correlated with blocking and unovershadowing choice scores, although this correlation did not remain significant when controlling for age (blocking:  $p = .09$ ; unovershadowing:  $p = .19$ ). Age itself was correlated with performance on blocking differences scores. However, when modus tollens reasoning performance was partialled out, the relationship between age and blocking difference scores was only marginally significant ( $r = .20, n = 61, p = .06$ , one-tailed). Finally, we also inspected individual scores to examine whether the ability to make the appropriate modus tollens inference was necessary for blocking. Difference scores could range from  $-3$  to  $+3$ . Table 4 shows the distribution of difference scores and modus tollens reasoning scores across the sample. It can be seen from the table that 100% of those children who unambiguously showed blocking (those with difference scores of 2 or 3) were correct on both of the modus tollens reasoning questions. Thus, there were no instances of children who definitely showed blocking but were unable to make the appropriate conditional inference.

## Discussion

The findings of this study are consistent with those from experiment 1 in that performance on blocking trials changed with age, with older children being more likely to show blocking. This study extended the findings of experiment 1 by showing that the effect of age on blocking scores failed to reach significance when the ability to make the appropriate modus tollens inference was controlled for. Furthermore, modus tollens reasoning performance was significantly correlated with blocking scores, and this was the case for blocking difference scores even when controlling for age. Taken together, these findings suggest that the age effects on blocking found in these experiments are at least in part due to age differences in the ability to make the appropriate conditional inference.

Performance on questions assessing the ability to make the appropriate disjunctive inference was at ceiling, consistent with our interpretation of the lack of age effects in experiment 1 on unovershadowing. However, age and modus tollens reasoning were unexpectedly related to unovershadowing scores in experiment 2. Modus tollens performance had not been predicted to be correlated with unovershadowing because we had argued that unovershadowing depends on making simpler disjunctive inferences. However, unovershadowing difference scores depend on two responses: the number of positive responses to the experimental cue (B) and the number of positive responses to the control cue (C). Only children who give more positive responses to B than C will have positive difference scores. We have suggested that a positive response to B depends on reasoning that because A is not causal, B must be causal—the disjunctive inference. However, children may arguably be more likely to give a negative response

Table 3

*Experiment 2: Correlations Between Reasoning Scores, Age, and Scores on Cue Competition Tasks*

	Age (months)	Blocking difference scores	Unovershadowing difference scores	Blocking choice scores	Unovershadowing choice scores	Modus tollens reasoning
Age (months)	—	.32**	.27*	.17	.31**	.41**
Blocking difference scores		—	.19	.55**	.33*	.37**
Unovershadowing difference scores			—	.19	.44**	.42**
Blocking choice scores				—	.07	.22*
Unovershadowing choice scores					—	.23*
Modus tollens reasoning						—

\*  $p < .05$ . \*\*  $p < .01$  (one-tailed).

to C if they can also engage in modus tollens reasoning. Children have observed that part of the robot's tummy lights up when C and D are fed to the robot together, but they never see C or D individually fed to the robot. When asked to make a judgment about C's causal status, they should realize that it is possible that C is not causal if they grasp that if C and D were both causal then the whole of the robot's tummy would have lit up. Making the appropriate modus tollens inference involves inferring that C and D cannot both be causal, and making this inference should increase the likelihood that negative responses are given to C.

To examine whether this interpretation of the relationship between modus tollens reasoning and unovershadowing difference scores is correct, we looked at whether modus tollens reasoning scores correlated with the number of yes responses to B or the number of yes responses to C in unovershadowing tasks. Consistent with this interpretation, reasoning scores correlated selectively with responses to the control cues but not the experimental cues (correlation with responses to C:  $r = -.35$ ,  $n = 64$ ,  $p < .01$ ; correlation with responses to B:  $r = .16$ ,  $n = 64$ ,  $p > .05$ ). Thus, modus tollens reasoning is related to unovershadowing, but only because unovershadowing is measured relative to responses to types of control trials used in these experiments.

Unlike in studies with adults, our child participants did not give causal ratings for cues, but they judged whether each cue was or was not causal (used to calculate difference scores) and chose whether B or C was the most likely to be causal (used to calculate choice scores). In experiment 2, it was found that these two measures of blocking correlate well (although not perfectly) with each other, as do the two measures of unovershadowing. However, it is not clear which of the measures is the more sensitive. In experiment 1, backward blocking was only apparent in choice scores, and it might be argued that choice scores are likely to be

more sensitive of blocking than difference scores because they directly measure the difference between children's causal assessments of B and C (Beckers et al., 2009). Indeed, McCormack et al. (2009) found that, when asked to judge whether an individual cue was or was not causal, children had a tendency to give yes responses to all cues unless a cue had been shown independently not to yield an outcome. This in itself could mask blocking. However, in experiments 1 and 2, age differences were more marked on difference scores than on choice scores, and indeed age and modus tollens reasoning scores were more strongly related to difference scores than choice scores. Thus, even for populations such as young children, who may have difficulty giving numerical causal ratings and thus give absolute yes/no causal judgments, calculation of difference scores seems to be the most appropriate way of measuring cue competition effects.

## General Discussion

Taken together, the findings from our two experiments indicate that our novel, child-friendly paradigm is appropriate for studying cue competition effects in young children. This paradigm is more closely aligned to those used with animals and adult humans than previous paradigms used to study such effects in children (McCormack et al., 2009; Sobel et al., 2004). As far as we are aware, this study constitutes the largest and most systematic examination of cue competition effects in children to be reported, and its findings provide new evidence for a reasoning account of such effects.

The age effects reported in experiment 1 were as predicted by a reasoning account. Blocking was modulated by additivity pretraining, but only for older children who may be capable of the conditional reasoning necessary for benefiting from additive pretraining. Unovershadowing was unaffected by age and additivity, which is also consistent with a reasoning account. Consistent with this lack of an age effect, experiment 2 demonstrated that the ability to make the simple disjunctive inference necessary for judging that the experimental cue is causal in unovershadowing trials appears to be intact from an early age. The results of experiment 2 indicated that age effects reported in blocking are, at least in part, due to children's ability to engage in modus tollens reasoning, a type of reasoning that improves with age over the period studied in these experiments. The ability to make the appropriate modus tollens inference was measured separately from blocking and found to be related to it. Blocking itself was only unambiguously observed in children who were clearly capable of

Table 4

*Experiment 2: Distribution of Blocking Difference Scores and Modus Tollens Reasoning Scores*

Blocking difference score	Modus tollens reasoning score		
	0	1	2
-1	1	2	2
0	7	10	11
1	3	5	12
2	0	0	6
3	0	0	5

modus tollens reasoning. In experiment 2, modus tollens reasoning was also found to be related to unovershadowing, but only because such reasoning was related to the likelihood that participants would give a negative response to control cues. We argued above that making modus tollens inferences would be expected to increase the likelihood that participants would judge a cue from a control pair to be noncausal.

However, we note that performance on the modus tollens reasoning questions was relatively good, and indeed there were several children who were able to answer these questions correctly who did not consistently show blocking after additivity pretraining in experiment 2. This suggests that modus tollens reasoning may not be the only cognitive factor that explains age and individual differences in blocking; that is, that this reasoning ability is necessary but not sufficient for blocking. A reasoning account would predict that cognitive resources such as working memory might be particularly important for cue competition effects insofar as such effects are underpinned by effortful higher-order processes. Making the necessary inferences in our cue competition tasks might be expected to be particularly taxing of working memory in young children; therefore, age differences might also be due to changes in working memory. Thus, some children may have performed well on the modus tollens reasoning questions but did not show blocking because of the additional working memory demands of the blocking task. The modus tollens questions themselves may have placed much lower demands on working memory than the blocking task because answering these questions involved making a single judgment that was based on observing single trial with one pair of cues. Therefore, we would speculate that children may need to be able to make the necessary modus tollens inference and, in addition, have sufficient working memory capacity to show blocking effects in our task.

Addressing this issue would involve examining the relationship between children's performance on working memory tasks and performance on the types of tasks used in these experiments, and we are currently conducting such a study. If our interpretation is correct, we should expect to see the ability to make modus tollens inferences and working memory capacity showing potentially separate effects on blocking. Working memory may also be implicated in explaining the effect of presentation order on blocking found in experiment 1, in which forward blocking was more marked than backward blocking. Making retrospective inferences involving previously presented cues, which is required in backward presentation conditions, might be expected to place a higher load on working memory (Vandorpe et al., 2007b).

Castro and Wasserman (2010) cast doubt on the reasoning account of additivity effects because they argue that it is unlikely that rats or young children can engage in the necessary inferential reasoning described by this account as underpinning blocking. We take it to be still an open question as to whether or not rats can engage in the necessary reasoning, and one that cannot be dismissed without empirical investigation. With regard to young children's abilities, Castro and Wasserman point to the work of Sobel and Kirkham (2006), who claim to have demonstrated backward blocking in children as young as 8 months (i.e., at an age at which it is indeed highly unlikely that the ability to make modus tollens inferences is present). However, we note that Sobel and Kirkham (2006) did not compare backward blocking with appropriate control trials (see Beckers et al., 2009; McCormack et al.,

2009), making it difficult to evaluate whether blocking was indeed observed in infants. Nevertheless, we take it to be an interesting and important challenge to establish if blocking, but, more specifically, additivity effects, can be observed in children who are not capable of making the conditional inference that a reasoning account holds to be necessary.

As we have pointed out in the Introduction, additivity effects on blocking can potentially be captured within the Bayesian approach to causal learning. For example, hierarchical Bayesian models (e.g., Lucas & Griffiths, 2010) would allow for the acquisition of more abstract constraints on learning during pretraining that would in turn shape how information about all subsequently presented cues is interpreted. Hierarchical Bayesian models have been recently applied in developmental contexts to capture infants and very young children's ability to learn from sparse data (Goodman, Ullman, & Tenenbaum, 2011; Kemp, Perfors, & Tenenbaum, 2007; Tenenbaum, Kemp, Griffiths, & Goodman, 2011). These are computational models, but much of this theorizing has assumed that the cognitive mechanisms that actually underpin this learning may be available from very early in development. On the basis of the current data, we would argue that, rather than assuming that such mechanisms are present early in development, it is important to consider how to characterize developmental changes in the underlying cognitive processes. In principle, it is of course possible to produce developmental versions of such Bayesian models that would allow, for example, age-related changes in the ability to abstract the relevant information during additivity pretraining and indeed subsequent causal learning. However, it is also necessary not just to consider whether such changes can be modeled computationally, but also how we want to characterize the underlying cognitive processes (Jones & Love, 2011). It is also important to question if they are processes that we would expect to be intact in young children or indeed other species.

The main focus of our study has been on exploring whether additivity effects on blocking are best explained by a reasoning account. Indeed, we found that blocking was not actually observed when pretraining was nonadditive in experiment 1. This finding is consistent with those of other recent studies with adults that suggest that blocking is either absent or greatly reduced when pretraining is nonadditive (Beckers et al., 2005; Lovibond et al., 2003). Nevertheless, we recognize that it is possible for blocking to occur after nonadditive pretraining conditions, particularly under forward presentation conditions, (Beckers et al., 2005; Lovibond et al., 2003), and indeed backward and forward blocking has previously been reported after nonadditive pretraining conditions in a study of 5-year-olds (McCormack et al., 2009). This raises the question of whether a reasoning account is appropriate to explain all instances of this cue competition effect. McCormack, Frosch, and Burns (in press) have argued that, even under nonadditive pretraining conditions, inferential reasoning (and counterfactual thinking in particular) may underpin blocking in humans. However, it may seem implausible to extend such an account to cover all examples of blocking in the animal kingdom. Demonstrations of blocking (or related phenomena) have been provided in various species (potentially including invertebrates such as snails, Acebes, Solar, Carnero, & Loy, 2009, and honey bees, although see Blaser, Couvillon, & Bitterman, 2006), and animal researchers would naturally be reluctant to assume that all of these species are capable of inferential reasoning. Beckers et al. (2005) and Lovi-

bond et al. (2003) allow for the possibility that there may not be a single set of processes underpinning blocking, and that, even in humans, lower-level associative processes may be involved under some circumstances. However, taken together, the findings of the current study strongly suggest that explaining the effects of additivity pretraining on blocking does require invoking a role for inferential reasoning. And, insofar as this pretraining effect has been demonstrated in an animal population (Beckers et al., 2006), they also imply that we need to take seriously the possibility that the description of Beckers et al. (2006) of rats as reasoners may indeed be correct.

Our focus on characterizing the cognitive processing underpinning additivity effects reflects the attention that these effects in particular have recently received in the human and animal causal learning literature (Penn & Povinelli, 2007; Shanks, 2010; Urcelay & Miller, 2009) and the challenge that such effects pose to associative models of learning. The central prediction underpinning the current experiments that arises from the characterization of such processes given by a reasoning account—that blocking and additivity effects should show individual and group differences because they depend on modus tollens reasoning—is one that is very difficult to test with adults because there is likely to be relatively little variability in adults' ability to make basic conditional inferences. Moreover, it is not clear how one would directly test whether other species such as rats can engage in conditional reasoning. Thus, we would argue that developmental studies provide us with a unique context in which to assess the role of reasoning abilities in explaining cue competition effects, and by extension, causal learning itself.

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