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The early emergence and puzzling decline of relational reasoning: Effects of knowledge and search on inferring abstract concepts

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ABSTRACT

We explore the developmental trajectory and underlying mechanisms of abstract relational reasoning. We describe a surprising developmental pattern: Younger learners are better than older ones at inferring abstract causal relations. Walker and Gopnik (2014) demonstrated that toddlers are able to infer that an effect was caused by a relation between two objects (whether they are the same or different), rather than by individual kinds of objects. While these findings are consistent with evidence that infants recognize *same-different* relations, they contrast with a large literature suggesting that older children tend to have difficulty inferring these relations. Why might this be? In Experiment 1a, we demonstrate that while younger children (18–30-month-olds) have no difficulty learning these relational concepts, older children (36–48-month-olds) fail to draw this abstract inference. Experiment 1b replicates the finding with 18–30-month-olds using a more demanding intervention task. Experiment 2 tests whether this difference in performance might be because older children have developed the general hypothesis that individual kinds of objects are causal – the high initial probability of this alternative hypothesis might override the data that favors the relational hypothesis. Providing additional information falsifying the alternative hypothesis improves older children's performance. Finally, Experiment 3 demonstrates that prompting for explanations during learning also improves performance, even without any additional information. These findings are discussed in light of recent computational and algorithmic theories of learning.

1. Introduction

A growing literature indicates that children as young as 16 months of age are able to learn specific causal properties from contingency information and can act on that knowledge to bring about novel effects in the world (see Gopnik & Wellman, 2012 for a review). But when and how can children learn more abstract causal principles? The ability to quickly learn abstract and specific relations in tandem might explain how children acquire the impressive amount of causal knowledge evident in their early intuitive theories about the world.

In the current paper, we examine children's developing ability to infer an abstract causal principle – a *relation* between objects that causes an effect (i.e., the relation "same" or "different") – from a limited set of observations. Walker and Gopnik (2014) recently demonstrated that toddlers (18–30-month-olds) are surprisingly adept at learning and using these relational concepts in a causal relational match-to-sample (RMTS) task. In this study, children were assigned to either a *same* or *different* condition, and observed as four pairs of objects (two "same" pairs and two "different" pairs) were placed on a toy that played music. In the *same* condition, pairs of identical objects activated the toy while pairs of different objects did not. This pattern of activation was reversed for the *different* condition. During test, children were given a choice between two novel pairs: one pair of *same* and one pair of *different* objects, and asked to select the pair that would activate the toy. Children overwhelmingly selected the pair that was consistent with their training. These results suggest that the ability to reason about abstract relations is in place very early – emerging spontaneously only a few months after the first evidence of children's ability to learn about the specific causal properties of individual objects.

Walker and Gopnik's (2014) results are consistent with some research demonstrating early competence in abstracting *same-different* relations in infancy. In particular, research relying on looking-time and visual search measures suggest that infants as young as 7- and 9-months-old may be able to recognize data that

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involve *same-different* relations in visual displays from very few trials (Dewar & Xu, 2010; Ferry, Hespos, & Gentner, 2015; Tyrrell, Stauffer, & Snowman, 1991; see also, Hochmann, Mody, & Carey, 2016).

Intuitively, it might seem plausible that more abstract hypotheses, such as *same* and *different*, would be acquired later than lower-level, concrete ones based on specific features of objects. However, theoretical advances drawing on Bayesian accounts of the "blessing of abstraction" (Goodman, Ullman, & Tenenbaum, 2011) combined with empirical research on early learning (Dewar & Xu, 2010; Schulz, Goodman, Tenenbaum, & Jenkins, 2008) suggest that children's ability to learn abstract principles need not progress in a bottom-up manner. Instead, Hierarchical Bayesian Models formalize how it may be possible to infer relations between objects and events among multiple levels of abstraction simultaneously (Griffiths & Tenenbaum, 2009; Tenenbaum, Griffiths, & Kemp, 2006).

In fact, there is experimental evidence supporting the claim that children are able to grasp certain abstract principles at the same time, or even *before* they learn the specific causal relations underlying them (Gelman & Gottfried, 1996; Kemp, Perfors, & Tenenbaum, 2007; Lehrer & Schauble, 1998; Mansinghka, Kemp, Tenenbaum, & Griffiths, 2006; Rozenblit & Keil, 2002; Schulz et al., 2008; Tenenbaum & Niyogi, 2003; Tenenbaum et al., 2006). For example, decades of evidence from developmental studies of psychological essentialism (e.g., Gelman, 2003; Keil, 1989) has demonstrated that children assume that animals from similar species are likely to share internal structures. Importantly, they can do this well before they can identify just what those internal structures actually are.

This account may help to explain the growing evidence that basic relational concepts are available much earlier than previously believed. On the other hand, these results contrast with a much larger body of research demonstrating that older, preschool-aged children consistently experience difficulty with relational matching (e.g., Christie & Gentner, 2007, 2010, 2014; Gentner, 2010). If relational learning is indeed a continuous process, as has been proposed (e.g., Gentner & Medina, 1998; Gentner & Namy, 1999; Mix, 2008; Richland, Morrison, & Holyoak, 2006), and *same-different* concepts are already available very early in development (Ferry et al., 2015; Smith, 1984; Tyrrell et al., 1991; Walker & Gopnik, 2014), why do older children often fail to demonstrate this knowledge? How might we interpret this apparent developmental reversal in which abstract reasoning seems to emerge in the first two years of life, but then decline in early childhood?

First, it is possible that older children failed to exhibit relational reasoning in previous studies because of methodological problems – the tasks were simply too difficult. The toddlers in Walker and Gopnik (2014) may have succeeded because the novel causal procedure simply made the task easier (see also, Smith, 1984). Similarly, there is a large literature indicating the dissociation between children's knowledge as measured in looking-time tasks and their ability to act on this knowledge across a variety of developmental domains (e.g., Hood, Cole-Davies, & Dias, 2003; Kirkham, Cruess, & Diamond, 2003; Zelazo, Frye, & Rapus, 1996). These possibilities may account for differences between younger (Ferry et al., 2015; Walker & Gopnik, 2014) and older (Christie & Gentner, 2014) children's performance on *same-different* relational reasoning tasks.

In Experiment 1a below, we therefore present participants with exactly the same reasoning task used in Walker and Gopnik (2014). After replicating this previous work with 18–30-month-olds, we also assess an additional group of 18–30-month-olds, using another test of toddlers' causal understanding of the relational concepts (Experiment 1b). In addition to coding which pair of blocks the children selected (by pointing) to activate the toy in the causal RMTS task, we also coded whether the children themselves put the correct novel pair of blocks on top. This ability to design a new intervention, and to act on a cause in order to produce its effect has been argued to be a particularly telling signature of true causal understanding (Pearl, 2000; Woodward, 2003).

Centrally, Experiment 1a also compares performance of 18–30-month-olds with that of older children (ranging from 30 to 48-month-olds) on exactly the same task. We include the full range of ages from 18 to 48 months to test if there is a continuous developmental trajectory. If the toddlers in Walker and Gopnik (2014) indeed succeeded because of the particular methodological features of the task, then we would expect that older children would succeed as well. If they fail, however, this decline cannot be explained as a result of the methodological differences between tasks assessing the presence of relational concepts in toddlers, and those assessing older children.

There is at least one reason why younger children might genuinely outperform older children in learning these causal relational concepts, independent of method. It may be that while 3-year-olds are able to reason on the basis of relations, they are less likely to infer relational causes because they have learned that the properties of individual objects are especially likely to have causal powers. This leads to a bias. When they see a block on the toy they assume that some feature of that individual object, its color or shape or weight, was responsible for the effect, rather than the relation between blocks. Indeed, preschool-aged children often demonstrate a bias to attend to individual object kinds, which has been proposed to interfere with relational processing (e.g., Christie & Gentner, 2007, 2010, 2014; Gentner, 1998; Gentner & Medina, 1998; Gentner & Rattermann, 1991). A parallel bias has been observed in a variety of causal learning tasks, in which preschool-aged children assume that causal powers are inherent to individual objects (e.g. Gopnik & Sobel, 2000).

Why would this bias affect older learners and not younger ones? In probabilistic model accounts, learners explain newly observed evidence by searching through a space of potential hypotheses and testing these hypotheses against the data (e.g., Gopnik & Wellman, 2012). To do this, learners combine two probabilities: the "prior" – the probability of a particular hypothesis being true before any data are observed, and the "likelihood" – the probability of the observed data given that a particular hypothesis is true. Combining these two probabilities with Bayes rule produces the "posterior" – the probability of the hypothesis being true given the observed data. A learner can then compare the posteriors of different hypotheses, settling on the ones with the highest probabilities.

These models predict that if the prior probability of one hypothesis is high, then it will take stronger data to overturn it in favor of another hypothesis. But in addition to formulating specific hypotheses, learners can also formulate "overhypotheses" or "framework principles" (Goodman, 1955; Goodman et al., 2011; Kemp et al., 2007). Having an overhypothesis leads the learner to assign a higher prior probability to certain types of hypotheses, and so constrains children's interpretation of new data (Kemp et al., 2007). As a result, in order for the learner to consider a hypothesis that is inconsistent with the overhypothesis, the learner would need more evidence supporting this competing hypothesis than if she began with no prior expectations and assigned all possible hypotheses an equal prior probability (i.e., a "flat" prior).

From a probabilistic models perspective, then, we might say that younger children have a "flatter" prior distribution: they are equally likely to entertain hypotheses about individual object properties and about relations. In the case of Walker and Gopnik's (2014) causal reasoning task, an abstract principle of simplicity, as proposed by Lombrozo (2007), might lead toddlers to initially prefer a relational hypothesis over an individual object hypothesis, since a relational hypothesis proposes fewer causes to account for the data. Indeed, previous work demonstrates that young children show such simplicity preferences (Bonawitz & Lombrozo, 2012). However, as children get older, they acquire more and more evidence for the general principle that individual object kinds are likely to be causal, and their prior distribution becomes more skewed. This in turn makes children more likely to privilege individual properties over relational ones, and accept specific object hypotheses (e.g., the red square block causes the toy to play music) over specific relational hypotheses (e.g., two blocks that are the same cause the toy to play music), even when relational hypotheses are simpler. Indeed, this is a robust bias in adult learners (e.g., Lucas, Bridgers, Griffiths, & Gopnik, 2014).

In other words, with increasing knowledge, learners develop expectations that make some kinds of hypotheses more probable than others. Although privileging certain hypothesis-types allows learners to more quickly and accurately acquire information that is consistent with the general principles they have already inferred, it makes learning new information that is *inconsistent* with these general principles more difficult (see Gopnik, Griffiths, & Lucas, 2015). In fact, recent research suggests that in some cases, apparent limitations in younger children's knowledge may lead them to be better learners than older children and even adults, who may be more biased by their prior expectations (Gopnik et al., 2015; Lucas et al., 2014; Seiver, Gopnik, & Goodman, 2013).

In Experiments 2 and 3, we therefore adapt the causal RMTS procedure to test the proposal that older children are able to reason about abstract relations, but have learned the overhypothesis that individual kinds of objects are more likely to be causal. There are at least two ways that we might induce children to override this individual object overhypothesis, and so be more likely to accept the relational hypothesis instead. One is simply to give them additional information that weighs against the individual object hypothesis. In Experiment 2 we provide older children with explicit negative evidence for the causal efficacy of individual objects. Because this evidence is inconsistent with the individual object hypothesis, it might serve to lower the probability of this alternative. In other words, observing evidence that weighs *against* the prevailing hypothesis may lead older children to reject it, even though it is more consistent with their prior knowledge.

In Experiment 3, we scaffold the relational inference using a different mechanism. Rather than giving the children additional information or evidence, we change the way that children search through the hypothesis space, and decide which hypotheses to consider. Although traditional accounts of Bayesian reasoning offer a method for evaluating and updating particular hypotheses, there remains a very large space of possible hypotheses that may all be compatible with the observed evidence. It would be impossible for a child (or even a machine learning algorithm) to enumerate the probability of each one. How do children decide which hypotheses to evaluate? To address this question, more recent accounts of Bayesian reasoning have focused not only on the learning mechanisms underlying human inference, but also the "search problem" – that is, the problem of selecting which hypotheses to test in the first place (see Gopnik & Wellman, 2012 for a review). As a result, the traditional Bayesian picture of learning has been revised to include an account, at the algorithmic level, for how children and adults may *approximate* ideal Bayesian inference using various "sampling" techniques. In these procedures, learners generate a few hypotheses to test at a time, adjusting the probabilities of those hypotheses as they acquire more data, in order to discover the most likely option(s) (e.g., Bonawitz, Denison, Griffiths, & Gopnik, 2014; Denison, Bonawitz, Gopnik, & Griffiths, 2013; Sanborn, Griffiths, & Navarro, 2010; Ullman, Goodman, & Tenenbaum, 2012).

Previous research has proposed that generating explanations recruits specific constraints on the process of selecting which hypotheses to consider, even though the process of explanation, by itself, doesn't provide any additional evidence or information. Asking for explanations encourages learners to go beyond simple probability considerations. Instead learners privilege those hypotheses that offer the best explanation relative to alternatives, even if those hypotheses don't necessarily have higher posterior probabilities (e.g., Lombrozo, 2007, 2012; Lombrozo & Vasilyeva, in press; Walker, Lombrozo, Legare, & Gopnik, 2014; Walker, Lombrozo, Williams, Rafferty, & Gopnik, 2016; Williams & Lombrozo, 2010, 2013). More specifically (e.g., Bonawitz & Lombrozo, 2012; Frazier, Gelman, & Wellman, 2009; Lombrozo, 2007), hypotheses that are formulated in the context of explaining are likely to have certain characteristics, or "explanatory virtues." In particular, learners who explain tend to privilege hypotheses that go beyond highly salient surface features to those that are more inductively rich and robust. Explanatory hypotheses are more likely to be abstract, broad in scope, and applicable to a wide range of contexts and situations (Lombrozo, 2010; Lombrozo & Vasilyeva, in press; Walker et al., 2014, 2016; Williams & Lombrozo, 2010, 2013).

For example, Walker et al. (2014) demonstrated that a prompt to explain led children to generalize novel properties of objects on the basis of non-obvious causal affordances (over salient superficial similarities). In one study, children were presented with triads of blocks, including a target block that had a particular causal property (the block activated a toy), a block that looked identical to the target, but did not share the same causal property, and a block that looked distinct from the target but shared the same causal property. Children were then shown that the target contained a hidden internal feature, and were asked to generalize that feature to one of the two options (the perceptually similar block or the causally similar block). When children were prompted to explain, they were more likely to extend the novel property to the block that shared causal similarity, while those who were given a control prompt tended to generalize on the basis of perceptual similarity. In other words, explanation served to diminish the appeal of superficial object properties and highlight more generalizable patterns that served to inform subsequent inferences (see also Legare & Lombrozo, 2014).

We therefore applied this same approach to the current task in Experiment 3. If preschool-aged children are already able to reason about relational properties (as previous work suggests), but assign a higher probability to individual object hypotheses, then introducing a prompt to explain may impose a constraint on children's search procedure that will lead them to privilege more broadly applicable abstract properties instead. Unlike Experiment 2, Experiment 3 notably provides learners with no additional evidence. Instead, we aim to encourage relational reasoning another way. We use an explanation prompt to lead children to consider and privilege more abstract and general hypotheses.

To summarize, across the experiments that follow, we test the hypothesis that older children's "failure" on traditional relational reasoning tasks is due to the development of a *learned* overhypothesis that is not yet present in younger children. This overhypothesis serves to constrain their search to privilege those hypotheses that highlight individual objects, unless additional data or a change in the search procedures (e.g., via a prompt to explain) interferes with this inference.

2. Experiment 1a

2.1. Method

2.1.1. Participants

A total of 141 children participated in Experiment 1a, including 56 36–48-month-olds ($M = 41.6$ months; range = 36.0–48.2 months), 40 30–36-month-olds (M = 33.6 months; range = 30.1–35.8 months), and 45 18–30-month-olds (M = 25.1 months; range = 18.9–29.9 months). Half of the children in each age group were randomly assigned to one of two between subject conditions: *same* and *different*. An additional 10 participants were tested, but excluded. Six children were excluded due to experimenter error or toy failure, and 4 were excluded due to participants' failure to complete the experiment. Children were recruited from local preschools and museums, and a range of ethnicities resembling the diversity of the population was represented.

2.1.2. Materials and procedure

The procedure for Experiment 1a was an exact replication of the procedure used in Experiment 2 of Walker and Gopnik (2014) (see Fig. 1).

Children were tested individually in a small testing room, seated at a table across from the experimenter. During the training phase, children saw 4 pairs of painted wooden blocks (2 same and 2 different) placed on top of the toy. All blocks were unique shapes and colors, except for the identical blocks that constituted the "same" pairs. The toy was a 10- × 6- × 4-in. opaque white cardboard box that appeared to play music when certain blocks were placed on top. In reality, the box contained a wireless doorbell that the experimenter activated by surreptitiously depressing a button.

In the *same* condition, the pairs that activated the toy consisted of two identical blocks, while in the *different* condition the pairs that activated the toy consisted of two blocks that differed in both shape and color. The experimenter started the training phase by introducing the toy to the child, saying, "This is my toy! Sometimes it plays music when I put blocks on top and other times it does not. Should we try some and see how it works?" The experimenter then took out two blocks, saying, "Let's try these ones!" and placed both blocks simultaneously on the toy, and the toy played music. The experimenter responded to the effect by saying, "Music! My toy played music!" The experimenter then placed the two blocks on the toy a second time and said, "Music! These ones made my toy play music!" Next, the experimenter took out a new pair of blocks in the opposite relation as the first pair. The experimenter placed these two blocks simultaneously on the toy, and it did not activate. In response, the experimenter said, "No music! Do you hear anything? I don't hear anything." The experimenter placed this pair on the toy again and said, "No music. These ones did not make my toy play music." The experimenter then repeated this with two more pairs of blocks, one pair that activated the toy and one pair that did not. The presentation of all individual blocks were counterbalanced, however, the order of the presentation of pairs of blocks was fixed, beginning with a causal pair, and alternating between causal and inert pairs.

The test phase began after all 4 pairs of blocks had been demonstrated on the toy. In both conditions, the child was given a choice between a novel same pair and a novel different pair to activate the toy herself. The pairs of blocks children observed on the toy and the pairs they were asked to choose between in the test phase were the same across conditions; the only difference between the two conditions was which relation activated the toy. The experimenter said, "Now that you've seen how my toy works, I need your help finding the things that will make it play music. I have two choices for you." The experimenter took out two trays, one supporting a novel same pair and one supporting a novel different pair, saying, "I have these," (holding up one tray) "and I have these" (holding up the other tray). Once the child looked at both trays, the experimenter continued, saying, "Only one of these trays has things that will make my toy play music. Can you point to the tray that has the things that will make it play?" The experimenter then placed both trays on opposite sides of the table just out of reach of the child, and prompted the child to point. The side of the correct pair was counterbalanced between children. Children's first point or reach was recorded.

Children received 1 point for selecting the pair of novel test blocks in the relation that matched their training (same or different) and 0 points for selecting the pair of test blocks in the opposite relation. A second researcher who was naïve to the purpose of the experiment recorded all responses. Inter-rater reliability was very high; the two coders agreed on 94% of the children's responses. Any disagreements were decided by discussion among the two coders and a third researcher.

2.2. Results

Replicating the results reported by Walker and Gopnik (2014), 18–30-month-olds in Experiment 1a selected the test pair that was consistent with their training, in both *same* (78%), $p = 0.01$ (two-tailed binomial) and *different* (77%), $p = 0.02$ (two-tailed binomial) conditions (see Fig. 2).[1] By contrast, however, the older children (3-year-olds) failed to select the correct test pair in either *same* (46%), $p = 0.85$ or *different* (43%), $p = 0.57$ conditions (see Fig. 2), with younger children outperforming older children in both cases (*same*: $\chi^2(1) = 5.37$, $p = 0.02$; *different*: $\chi^2(1) = 5.99$, $p = 0.02$). The performance of 30–36-month-olds fell between these younger and older groups, selecting the correct test pair marginally above chance (70%) in the *same* condition, $p = 0.06$ (one-tailed binomial) and at chance (50%) in the *different* condition, $p = 1.0$.

These results demonstrate a surprising decline with age on the causal RMTS task. To provide additional support for this developmental trajectory, we combined children across age groups and conducted a logistic regression, treating age as a continuous factor and correct selection (collapsing across *same* and *different*) as the dependent variable. Results of the logistic regression show a significant decrease in children's tendency to select the pair of blocks in the correct causal relation between 18 and 48 months, $\chi^2(N = 141, df = 1) = 3.96$ (Wald), $p < 0.05$ (intercept = 1.95). According to the fitted model, the probability of picking the correct pair at age 18 months is 76%, while the probability of picking the correct pair at 48 months is only 44%. The youngest children in our sample are therefore 32% more likely to select the correct pair than the oldest children in our sample.

3. Experiment 1b

Experiment 1a suggests a surprising decline in older children's ability to learn the abstract relations "same" and "different." In Experiment 1b, we sought to assess 18–30-month-olds a second time, using an additional test of causal reasoning: In addition to replicating 18–30-month-olds' selections (by pointing), we examined the outcome of their own interventions to produce the novel effect. This ability to intervene with the appropriate pair of objects and to act on a cause in order to produce its effect is a benchmark of causal understanding (Pearl, 2000; Woodward, 2003). Would the children who pointed to the correct pair of blocks also actively intervene to activate the toy with those blocks?

3.1. Method

3.1.1. Participants

Forty 18–30-month-olds (M = 23.6 months; range = 17.9–31.0 months) were randomly assigned to one of two conditions: *same* (n = 20, M = 24.3 months, range = 17.9–30.0 months) and *different* (n = 20, M = 23.1 months, range = 17.9–31.0 months). An

[1] All statistical tests in all experiments are two-tailed, unless otherwise stated in the text.

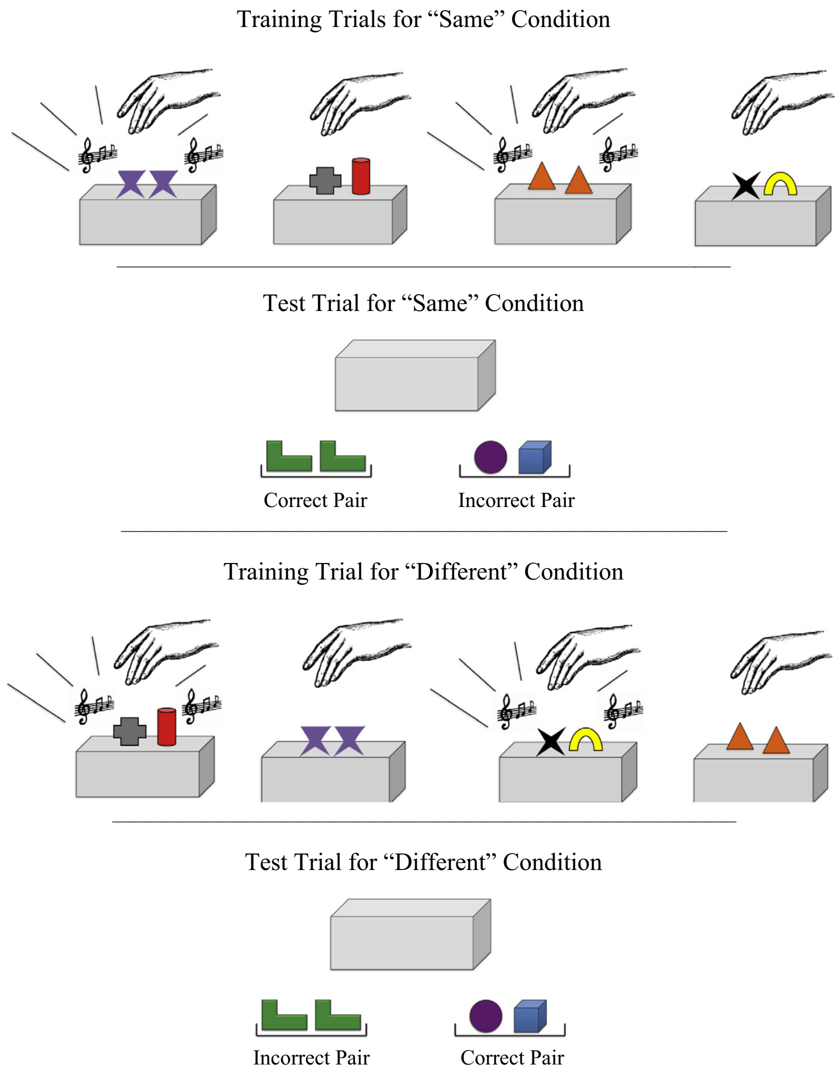

Fig. 1. Schematic representation of training and test trials in the *same* and *different* conditions in Experiments 1a and 1b. Participants observed four training trials (two causal and two inert pairs). During each of the training trials, the pair was placed on the toy twice. On each test trial, a novel pair of "same" blocks and a novel pair of "different" blocks were presented. The child was asked to select the pair that would activate the toy.

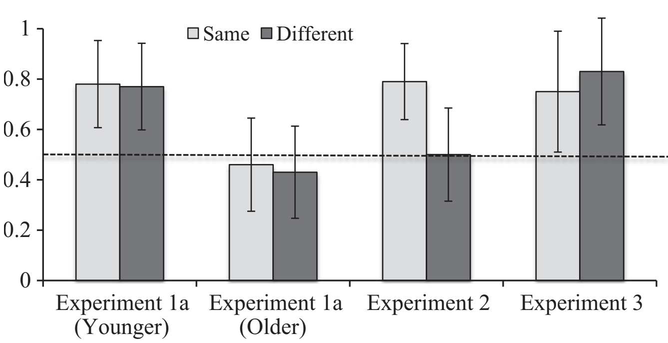

Fig. 2. Proportion of correct relations selected following the manipulations in Experiments 1–3. Error bars indicate 95% confidence intervals.

additional 8 participants were excluded for failing to complete the study. Recruitment methods and participant population was identical to Experiment 1a.

3.1.2. Materials and procedure

The procedure for Experiment 1b was nearly identical to Experiment 1a (refer to Fig. 1), except for the following critical change to the test trial. After the child pointed to the selected tray, the experimenter pushed both trays within reach and asked the child to intervene to make the toy play music. When necessary, children were encouraged to use the objects to activate the toy.

As in Experiment 1a, the experimenter recorded children's first point or reach. In addition, the experimenter coded the child's intervention. All children placed a block on the toy at least once. The experimenter coded whether the child initially placed two different blocks or two identical blocks on the toy, or whether they only placed one block on the toy.

3.2. Results and discussion

In Experiment 1b, 18–30-month-olds again pointed to the test pair that was consistent with their training, in both *same* (80%), $p = 0.02$ (binomial test) and *different* (75%), $p = 0.04$ (binomial test) conditions, replicating the results in Experiment 1a and in Walker and Gopnik (2014).

Sixteen children in the *same* condition pointed to the correct tray during their initial selection. Eleven (69%) of these children intervened with a pair of "same" novel blocks (rather than intervening with either the "different" pair or a single block), while only 3 (19%) of the children in the *different* condition who pointed to the correct tray did so, with a significant difference between conditions, $p = 0.01$ (Fisher's exact test). Similarly, 15 children pointed to the correct tray in the *different* condition and 10 (67%) of those children intervened with a pair of "different" blocks (rather than intervening with either the "same" pair or a single block), while only 3 (19%) of children in the *same* condition who pointed to the correct tray did so, with a significant difference between conditions, $p = 0.01$ (Fisher's exact test).

These results demonstrate that children are indeed making a causal inference when selecting between the test pairs of blocks – they select the pair they believe will make the toy play music. Children's intervention behavior, like their selection behavior, indicates that they have learned that the relations *between* the blocks in our experiment and not the individual blocks themselves carry causal power. However, because interventions were generally more variable, we focus exclusively on children's selections in Experiments 2 and 3.

4. Experiment 2

Results of Experiments 1a and 1b replicate Walker and Gopnik's (2014) findings that young children are already equipped with the capacity to infer relational properties, though older children fail. We hypothesize that older children may be expressing a learned bias to attend to individual object properties and ignore abstract relations between them. In an effort to assess this claim directly in Experiment 2, we manipulated the data that children observe to provide evidence against the individual object kind hypothesis. In particular, Experiment 2 provided older children with explicit negative evidence that would lower the probability of an individual object kind hypothesis. To do so, 3-year-olds observed the same procedure described in Experiment 1a, with one important change: Before the experimenter placed the pairs of blocks on the toy simultaneously, she first placed each block on the toy one at a time, and children observed that the toy failed to activate (see Fig. 3). By providing evidence *against* an individual object cause, these negative observations may prompt older children to override that hypothesis, even though it is more consistent with their prior knowledge, and instead consider the abstract relational principle that is more consistent with the evidence observed.

4.1. Method

4.1.1. Participants

A total of 56 3-year-olds ($M = 41.9$ months; range = 35.9–49.9 months) were randomly assigned to one of two conditions (*same*, $n = 28$, $M = 41.7$, range = 34.9–48.9 and *different*, $n = 28$, $M = 42.2$ months, range = 36.0–49.6 months). An additional 4 participants were excluded for failure to complete the study. Recruitment methods and participant population was identical to Experiment 1a and 1b.

4.1.2. Materials and procedure

The materials were identical to Experiment 1a and the procedure included the following critical changes. For each pair of blocks, the experimenter first placed each block on the toy *sequentially*, before placing them both on simultaneously (see Fig. 3). This sequential, followed by simultaneous, placement of the blocks on the toy was performed twice for each block pair. Therefore, in addition to observing positive evidence that pairs of same or different blocks (depending upon the child's condition) activated the toy together, children also observed negative evidence for the causal efficacy of individual blocks (i.e., each block

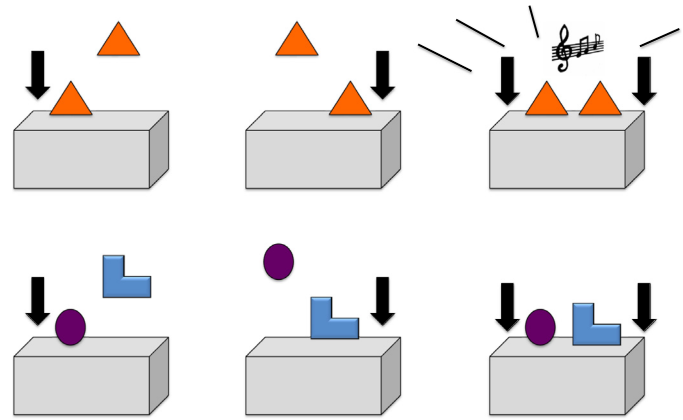

Fig. 3. Schematic representation of two (of four) training trials in the *same* condition. The pattern of activation was reversed for the *different* condition. All test trials were identical to those used in Experiment 1a.

failed to activate the toy on its own). This training phase was immediately followed by a test phase, which was identical to the test phase in Experiment 1a. Inter-rater reliability was very high; the two coders agreed on 93% of children's responses to the test questions. Any disagreements were decided by discussion among the two coders and a third researcher.

4.2. Results and discussion

Results of Experiment 2 are consistent with the proposal that older children have developed a learned bias to attend to individual objects (see Fig. 2). Once 3-year-olds were provided with negative evidence for the individual object kind hypothesis, they selected the correct relation significantly more often than chance (64%), $p = 0.045$ (binomial). However, this overall effect was due to the improved performance of children in the *same* condition, in which 79% of children selected the correct pair, $p = 0.005$ (binomial). This performance was significantly better than children of the same age in the *same* condition in Experiment 1a, $\chi^2(1) = 6.17$, $p = 0.01$, and no different than the 18–30-month-olds (78%). Children in the *different* condition did not differ from chance performance (50%), $p = 1.0$ (binomial), leading to a significant difference between *same* and *different* conditions, $\chi^2(1) = 4.98$, $p = 0.03$.

Interestingly, the performance of the 30–36-month-olds in Study 1 also suggests the asymmetry between same and different, although (due to small sample sizes) the difference between the two conditions did not reach significance ($p = 0.16$).

How might we explain this emerging asymmetry between the *same* and *different* conditions in older children? It is possible that the data patterns observed in these two conditions interacted differently with the strength of children's beliefs in "relational" vs. "individual" hypotheses. According to Bayes rule, if the prior probability for one hypothesis is very low and the other is comparatively high, the difference in likelihoods of the two data patterns might have little effect. In an intermediate case, however, where one hypothesis is slightly more probable than the other, the difference in the likelihoods might lead to a difference in the posterior probabilities for these hypotheses (after observing the data pattern) and thus a difference in performance. This may have led to differences in how older children's beliefs were updated in light of the evidence.

In particular, the presentation of negative evidence for individual blocks in Experiment 2 would provide stronger support for the relational inference in the *same* condition than in the *different* condition. Suppose older children (1) have developed the overhypothesis that individual kinds of objects are causal, (2) assume that the experimenter is randomly sampling blocks, and (3) assume that some fixed proportion of block types activate the toy, all plausible assumptions. Then the pattern of data that they observe in the *same* condition has a lower likelihood of occurring than the pattern of data in the *different* condition. This is because, given assumptions 1–3, the probability that the toy will activate on any given trial should be higher when two different kinds of blocks are placed on the toy (i.e., when there are two potential activators), than when two of the same kind of block are placed on the toy (i.e., when there is only one potential activator). Since there is only one kind of block presented in each positive evidence training trial in the *same* condition, these data offer stronger counterevidence to the individual object kind overhypothesis.

Another possible explanation for this asymmetry may be that children with an object kind overhypothesis must rely on similarities between individual properties of objects (color, shape, etc.). Given that there are many more possible features that might be responsible for the effect in the *different* condition compared to the *same* condition, the space of possible specific hypotheses is larger. It is therefore much more difficult to rule out object kinds in the *different* condition.

5. Experiment 3

In Experiment 3, we examined whether we could induce relational reasoning in another way – not by manipulating the data that children observe, but by introducing a prompt to explain the evidence observed during the training trials. Experiment 3 contrasted two conditions in which we asked 3- and 4-year-olds to either report *whether* the toy activated in each training trial or to explain *why* the toy did or did not activate in each case. Based on the previous literature reviewed above, we hypothesized that generating an explanation may lead children to consider different hypotheses and, in particular, to search for simpler and more general hypotheses (e.g., Lombrozo, 2012; Walker et al., 2014, 2016; Walker, Bonawitz, & Lombrozo, submitted for publication; Williams & Lombrozo, 2013; see also Bonawitz, van Schijndel, Friel, & Schulz, 2012). That might increase the chance that older children will accept the relational hypothesis, even though it has a lower prior probability than the individual hypothesis. The hypothesis that ‘‘sameness" or ‘‘difference" activates the machine is both simpler and more general than the alternative hypothesis that a different individual block was responsible for the effect on each trial.

5.1. Method

5.1.1. Participants

Forty-eight 3- and 4-year-olds (M = 45.1 months; range = 36.5–58.9 months) were randomly assigned to one of two conditions (*explain*: n = 24, M = 45.9 months, range = 37.0–58.9 months; *report*: n = 24, M = 44.2 months, range = 37.2–58.5 months). Half of the children in each condition (12 per condition) observed evidence that was consistent with the *same* relation and the other half observed evidence that was consistent with the *different* relation. An additional 3 participants were excluded for failing to complete the study. Recruitment methods and participant population was identical to the previous experiments.

5.1.2. Materials and procedure

The procedure for Experiment 3 was nearly identical to Experiment 1a (see Fig. 1), except for the following changes. Children in the *explain* condition were prompted for an explanation after the second placement of each training pair on the toy, asking, ‘‘Why did/didn't these ones make my toy play music?" In the *report* condition, the experimenter asked an almost identical question (framed as a ‘‘what" question, rather than a ‘‘why" question): ‘‘What happened when I put these ones on my toy? Did it play music?" (prompting a yes/no response). As in previous work, reporting was selected as a control task because it shares several commonalities with explanation: it draws children's attention to the causal relationship, it requires them to verbalize in a social context, and it roughly matches children's time engaging with each outcome.

In addition to coding children's selections, all explanations were categorized into 3 mutually exclusive types: (1) object-focused (e.g., *"because it's red*", *"because it has batteries*"), (2) relation-focused (*"because they are the same,*" *"because they are not the same*"), and (3) uninformative (*"I don't know,*" *"because it played music*"). Inter-rater reliability was again very high; the two coders agreed on 96% of children's responses to the test questions, and 89% of the explanation categories. Any disagreements were decided by discussion among the two coders and a third researcher.

5.2. Results and discussion

Three- and 4-year-olds who were prompted to explain during the training trials selected the correct relation significantly more often than chance (79%), p = 0.007 (binomial) (see Fig. 2). Children in the *report* condition did not differ from chance (42%), p = 0.54, and there was a significant difference between *explain* and *report* conditions, p = 0.017. Unlike in Experiment 2, there was no significant overall difference between *same* (58%) and *different* (63%) relations, p = 0.76. There were also no differences found between *same* and *different* within each condition (*explain*: *same* = 75%, *different* = 83%; *report*: *same* = 42%, *different* = 42%). Comparing the overall pattern of responses of 3- and 4-year-olds who explained to the 18–30-month-olds in Experiment 1a, reveals no significant difference, $\chi^2(1) = 0.02$, $p = 0.88$, while 3- and 4-year-olds in the *report* condition performed significantly worse than the 18–30-month-olds, $\chi^2(1) = 9.0$, $p = 0.003$, and no differently from the 3-year-olds in Experiment 1a, $\chi^2(1) = 0.06$, $p = 0.81$, replicating the developmental pattern in Experiment 1a.

This is particularly notable since, as with the *report* control, the children in Experiment 1a heard almost the same description of the events as those in the *explain* condition (‘‘These ones made my toy play music/did not make my toy play music!"). The only difference was that the explanation condition included the additional phrase ‘‘why do you think" (‘‘Why do you think these ones made/did not make my toy play music?").

In order to analyze whether the content of children's explanations mattered for this pattern of responses, we classified the type of explanation (i.e., *object-focused*, *relation-focused*, *uninformative*) that each child produced most often, and analyzed their performance on the relational task. Children who provided *relation-focused* explanations as their modal response (N = 6) – the most relevant explanation for the task – always selected the correct relational pair (100%). Children who provided *object-focused* explanations (N = 9) were also highly likely to select the correct relational pair (89%). However, children who provided *uninformative* explanations or failed to provide an explanation at all (N = 9) selected the fewest number of correct relational pairs (56%). The children who provided relevant relational or object-focused explanations were significantly more likely to choose the correct relational pair than children who provided no explanation or uninformative ones (p = 0.047, Fisher's exact test). These data indicate that providing a meaningful explanation (regardless of its content) is sufficient to improve relational reasoning, but that simply being prompted for an explanation may not be.

This initially counterintuitive finding – that children need not produce the "correct" explanation for the act of explaining to take effect – is consistent with much of the previous research examining the cognitive impacts of explaining. In particular, previous research has found that preschoolers who are prompted to explain often show a more sophisticated pattern of responses on later inferences, even when the content of their explanations falls short (Edwards, Williams, Lombrozo, & Gentner, 2016; Walker et al., 2014, 2016; Williams & Lombrozo, 2010). Wilkenfeld and Lombrozo (2015) argue that it is the *process* of explaining that carries epistemic value, regardless of whether it results in the "correct" product. In other words, the effects of explanation cannot be reduced to the content of the verbal response. Instead, attempts to explain – particularly in children – yields cognitive benefits for learning even when the explanations they produce happen to be false. On the other hand, when children make no attempt to generate a reasonable explanation (i.e., children who provided *uninformative* explanations or none at all), they do not show these same learning benefits.

6. General discussion

Across four experiments, we assessed the influence of both the data that children observed (Experiments 1a, 1b, and 2), and whether they reported or explained that data (Experiment 3) on their abstract causal reasoning. In Experiment 1a, we replicated Walker and Gopnik's (2014) finding that 18–30-month-olds are able to infer the abstract relations "same" and "different" from very few observations in a causal task. We also included an intervention prompt in Experiment 1b, in which 18–30-month-olds further demonstrated their causal understanding of the relational concept. In addition, we contrasted toddlers' performance with a group of 30–36-month-olds and a group of 3-year-olds. As in previous work, older children failed to learn the relation. In fact, we found evidence for a decrease in relational reasoning between 18 and 48 months of age.

The findings of Experiment 2 help to further explain this decline. They suggest that children may learn to privilege individual kinds of objects as causally effective rather than relations between them: When provided with evidence against this hypothesis, 3-year-olds were able to infer the relation in the *same* condition. Finally, in Experiment 3, we demonstrated that prompting children to explain during learning leads 3- and 4-year-olds to privilege the abstract relational hypothesis in both *same* and *different* conditions. Importantly, Experiment 3 shows that a manipulation that provides no new evidence or additional information about the machine can nonetheless change participants' judgments. Results of Experiment 3 are also consistent with previous work indicating that generating explanations prompts generalization and abstraction in causal reasoning (e.g., Legare & Lombrozo, 2014; Walker et al., 2014).

Discovering when and how children learn relational concepts is important for understanding the processes underlying early causal learning, but it is also important for understanding the development of relational reasoning more broadly. The earlier literature on the development of relational reasoning invokes a "relational shift" from attending to individual, concrete object features to attending to more abstract, relations *between* objects. This previous literature attributes the observed shift to a number of factors, including an increase in relational knowledge (Gentner, 1988; Gentner & Rattermann, 1991), exposure to relational language (e.g., Christie & Gentner, 2014), and various maturational variables (Halford, 1992; Richland et al., 2006; Thibaut, French, & Vezneva, 2010).

Along with previous research relying on habituation measures (e.g., Ferry et al., 2015), our current behavioral findings suggest that the developmental trajectory of relational reasoning may be better characterized as a "U-shaped curve," in which early reasoning abilities are overshadowed by children's development of conflicting hypotheses (see e.g., Karmiloff-Smith & Inhelder, 1974–1975). In other words, the "relational shift" may not reflect an initial inability or difficulty to formulate or use relational concepts. Instead, children are equipped to reason about both objects and relations from a very early age, and the shift reflects a change in the probabilities assigned to the individual object kind and relational hypotheses over time.

This novel proposal also provides an explanation for the well-documented influence of scaffolding on relational abilities. For example, previous research has demonstrated that the use of labels (Christie & Gentner, 2007; Gentner & Rattermann, 1991; Loewenstein & Gentner, 2005; Namy & Gentner, 2002; Ratterman & Gentner, 1998; Son, Doumas, & Goldstone, 2010; see also Premack, 1983; Thompson & Oden, 2000; Thompson, Oden, & Boysen, 1997 for similar findings in chimpanzees) and prompts to compare (e.g., Christie & Gentner, 2014; Gentner, Anggoro, & Klibanoff, 2011; Gick & Holyoak, 1983; Kotovsky & Gentner, 1996) support relational competence. Similarly, we demonstrate (in Experiments 2 and 3) that the individual object kind hypothesis may be overcome in both the *same* and *different* conditions with relatively minimal intervention, by shifting the probabilities assigned to each hypothesis.

Of course, in order to propose the presence of a complete U-shaped curve, it would be necessary to provide evidence that adults (i.e., the right side of the "U") succeed on this task as well. While we believe that adults would have no problem inferring the relational hypothesis in the task used here, we cannot speak to the underlying mechanism based on the current study. In particular, because the current task was designed to be simple enough to be conducted with children as young as 18 months, we anticipate that adult success would be easily achieved on the basis of pragmatic cues alone (e.g., the non-random selection of pairs should prompt adult learners to infer that the experimenter is intentionally demonstrating the relational property).[2]

However, there remains an important empirical question regarding whether adults would succeed, in principle, on a parallel task that is better suited to adult learners. Indeed, it is possible that without the pragmatic cues, adults, like older children would fail to infer the relational cause. Given that overhypotheses tend to strengthen with additional experience, adults may not only maintain a similar object bias, but it may be even stronger than the one held by older children in the current studies. On the other hand, adults may have developed a more elaborate overhypothesis in which both object properties and relations are possible. Indeed, previous research examining relational reasoning in adult populations provides evidence that they hold both objects and relations in mind (e.g., Barnett & Ceci, 2002; Catrambone & Holyoak, 1989; Christie & Gentner, 2014; Christie, Gentner, Vosniadou, & Kayser, 2007; Gick & Holyoak, 1980, 1983; Markman & Gentner, 1993; Needham & Begg, 1991; Vendetti, Wu, & Holyoak, 2014). Ongoing research in our lab aims to directly address this point.

There also remain interesting open questions regarding the performance of younger children (the left side of the "U"). For example, it might be argued that younger children's success is due to the use of a perceptual heuristic rather than reasoning about abstract relations, as has been suggested for nonhuman primates (e.g., Fagot, Wasserman, & Young, 2001; Penn, Holyoak, & Povinelli, 2008; Wasserman, Fagot, & Young, 2001). In particular, it has been proposed that nonhuman primates learn to respond

[2] These pragmatic cues could not explain our developmental results, since it is unlikely that 18–30-month-olds would read pragmatic cues better than preschool-aged children.

based upon the amount of perceptual entropy (variance) in a display. However, at least two features of our study design weigh against this possibility. First, children saw pairs of two objects at a time, rather than the multi-element displays that are traditionally used in comparative work. According to previous research, as the number of elements in an array is systematically decreased, the magnitude of perceptual variability also decreases, preventing the use of perceptual cues in distinguishing *same* from *different* (see Wasserman & Young, 2010; Zentall, Wassermann, Lazareva, Thompson, & Rattermann, 2008 for reviews). Second, children observed a total of two positive and two negative evidence events with distinct block pairs (compared to the hundreds, or even thousands of trials with reinforcement used in the comparative literature). Indeed, no other species has come close to demonstrating the first-trial performance of these young human children after so few observations (see Penn et al., 2008). It therefore seems unlikely that children are computing the perceptual variance in the stimuli that we present. Nevertheless, additional research will be necessary to conclusively rule out this possibility.

Though it is unlikely that simple perceptual strategies like "entropy" could explain the pattern of our results, our study design may allow younger learners to entertain more or less abstract notions of "same," and there remain several open questions regarding how to define the scope of this early concept. For example, children may infer a concept that is task specific, applying only to instances of "the same two blocks." It is also possible that they infer a concept that includes a notion of two-ness (e.g., "it takes [at least] two of the same block") or a concept that includes both a notion of two-ness and a particular property (e.g., "[at least] two blocks that are the same shape"). However, it is unlikely that children are tracking a concept of quantity alone, since children are able to differentiate between "same" and "different" pairs, both of which include two blocks. Indeed, the only concept differentiating these pairs is whether or not the two blocks are members of the *same* kind, or share the *same* properties. Nevertheless, it is reasonable to assume the presence of a link between *same-different* relations and quantity (e.g., see Hochmann et al., 2016), and this represents an important avenue for future research. Of course, our results are also consistent with the possibility that children infer a general notion of same that does not depend upon specific quantity. Children may even be able to extend this notion of same to a set of three objects rather than two, or beyond the task materials to other items (e.g., "same toys"), or even other domains (e.g., "same sounds"). These are important questions for further research.

Despite these ongoing considerations, our results do appear to be consistent with other cases in which younger children are more flexible learners than older ones (Defeyter & German, 2003; Gopnik et al., 2015; Kuhl, 2004; Lucas et al., 2014; Seiver et al., 2013; Werker, Yeung, & Yoshida, 2012). The very fact that children know less to begin with may, paradoxically, make them better (or at least more flexible) learners. In particular, as we acquire abstract knowledge about causal structure, this experience provides a set of inductive biases that are usually quite helpful, allowing the learner to draw quick and accurate conclusions when a new situation is consistent with their past experiences. However, this experience can also be a double-edged sword – occasionally leading learners away from the correct hypothesis, particularly in cases in which the correct hypothesis is unusual or less consistent with previous observations. In Bayesian terms, children's flexibility results from a "flatter" initial prior than older children and adults.

In addition to simply accumulating more knowledge, children may search through their hypothesis spaces differently as they grow older. There may be a general shift from broader to narrower search procedures as children age, independent of their specific knowledge (Gopnik et al., 2015; Lucas et al., 2014). On this view, younger children might generally be more likely to come up with unlikely hypotheses than older ones, including hypotheses that are quite different from their current hypotheses. In computational terms, younger children might have a "high-temperature" search strategy, in which they move to hypotheses that are further away with less evidence to motivate those moves. Older children and adults might use a "low temperature" strategy in which their new hypotheses remain quite close to the hypotheses they currently entertain. Developmental differences in both accumulated knowledge and search procedures may help to explain why very young children are such extraordinarily powerful learners.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2016.07.008.

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