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Transformations and Transfer: Preschool Children Understand Abstract Relations and Reason Analogically in a Causal Task

Mariel K. Goddu
University of California, Berkeley

Tania Lombrozo
Princeton University

Alison Gopnik
University of California, Berkeley

Previous research suggests that preschoolers struggle with understanding abstract relations and with *reasoning by analogy*. Four experiments find, in contrast, that 3- and 4-year-olds (N = 168) are surprisingly adept at relational and analogical reasoning within a *causal* context. In earlier studies preschoolers routinely favored images that share thematic or perceptual commonalities with a target image (*object matches*) over choices that match the target along abstract relations (*relational matches*). The present studies embed such choice tasks within a cause-and-effect framework. Without causal framing, preschoolers strongly favor object matches, replicating the results of previous studies. But *with* causal framing, preschoolers succeed at analogical transfer (i.e., choose relational matches). These findings suggest that causal framing facilitates early analogical reasoning.

"*Glove* goes with *hand*, so *sock* goes with _________" is a puzzle that we solve by attending to the relation between the first pair (i.e., gloves *go on* hands) and extending it to the second pair (i.e., socks *go on* feet). This kind of analogical reasoning plays an important role in cognition: recognizing the common relational structure between two exemplars can facilitate learning and deepen conceptual understanding (e.g., "an atom is like a solar system"; "electrical currents flow like water"; Alexander, 2016; Gentner & Gentner, 1982; Jee et al., 2010, 2013; Vendetti, Matlen, Richland, & Bunge, 2015). It can also generate novel insights, as exemplified by many classic examples in the history of science (e.g., "the force that draws the apple to Earth is the same as the force that keeps the moon in orbit"; Gentner, 1983, 2002; Gentner et al., 1997; Nersessian, 1996, 2002). Given the usefulness of analogical reasoning, it would seem that this powerful cognitive ability might be present in young children, who construct complex knowledge systems from sparse data and undergo radical conceptual change over brief periods of time (Carey, 1985, 2009; Gopnik, 2012; Gopnik & Meltzoff, 1997; Keil, 2011). Instead, many studies have found that preschoolers routinely fail to privilege abstract relational information over surface similarities without guidance from explicit social or linguistic cues. Below, we review prior work on young children's analogical reasoning before motivating the hypothesis that we go on to test: that children can succeed in privileging abstract relational information over surface similarities in the context of a causal reasoning task.

Most research on the development of analogical reasoning has used matching tasks with stimuli such as static shapes or images. One version of this Relational Match to Sample task tests participants' preferences for relational matches versus object matches. Children see a target image that demonstrates a relation between two objects, and are

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Correspondence concerning this article should be addressed to Mariel K. Goddu, Department of Psychology, 2121 Berkeley Way West, Berkeley CA 94720. Electronic mail may be sent to marielkgoddu@gmail.com.

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asked to choose between two potential matches to that target. While relational matches share the same abstract structure—but no perceptual features—with the target, object matches share some of the target's features, but not its relational structure (see Figure 1). If young children prioritize attention to superficial commonalities over relational commonalities, they will prefer object matches to relational matches in these tasks.

Several decades of research find that young children have precisely this preference. One relational-match-to-sample (RMTS) study evaluated 3- and 4-year-olds' preferences for matching illustrated images of animals in novel relational configurations (e.g., bigger than/smaller than; color relations; reflections over the *x* and *y* axes). Without scaffolding, preschoolers chose object matches over relational matches at a rate greater than nine times of ten (Christie & Gentner, 2010). Another study used images of everyday objects, where the relational matches belonged to categories with which children are familiar—for example, "things to play on." This study found that children favored even very far-flung perceptual matches to the categorical matches: for example, they chose to match a target image of a bicycle with round wheels to an image of eyeglasses with round lenses, instead of to a scooter (Gentner & Namy, 1999). Another task investigated children's ability to attend to common relational *roles* between familiar objects—for example, to choose a match to go with *paper* in the same way

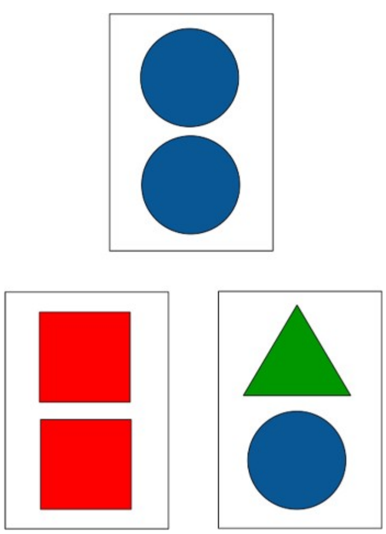

Figure 1. Relational-match-to-sample task with object match (bottom right). Preschoolers strongly favor the object match over the relational match (Christie & Gentner, 2010). [Color figure can be viewed at wileyonlinelibrary.com]

that *ax* goes with *tree* and *knife* goes with *watermelon*. Here, 3- and 4-year-olds strongly preferred thematic matches, such as "pencil," over the relational match, "scissors" (Gentner, Anggoro, & Klibanoff, 2011). The results of these and a variety of other studies using noncausal stimuli show that preschoolers strongly prefer to match based on superficial similarities (e.g., Anggoro, Gentner, & Klibanoff, 2005; Baldwin, 1992; Gentner, Loewenstein, & Hung, 2007; Gentner, Simms, & Flusberg, 2009; Graham, Namy, Gentner, & Meagher, 2010; Imai, Gentner, & Uchida, 1994; Kotovsky & Gentner, 1996; Landau, Smith, & Jones, 1988, 1998; Loewenstein & Gentner, 2001; Namy & Gentner, 2002; Rattermann & Gentner, 1998a; Uttal, Gentner, Liu, & Lewis, 2008).

Many studies that demonstrate children's consistent failure at spontaneous relational reasoning find, however, that *explicit sociolinguistic cues*—namely, *linguistic labeling* and *invitations to compare* exemplars—can improve children's relational reasoning. For example, giving exemplars the same label dramatically improves young children's performance on a spatial reasoning task. Without labels, 3-year-olds struggle to find a prize hidden on a target shelf after its location is demonstrated on a very similar "model." But with prepositional labels for the shelves, such as "middle" or "top," their performance increases from chance responding to 72% correct (Loewenstein & Gentner, 2005). Other studies find that explicit adult invitations to *compare* exemplars also facilitate children's performance: for example, when an experimenter provides children with images of both a bicycle *and* a tricycle in the categorical matching task and encourages the children to compare them, children strongly prefer the scooter over the eyeglasses (Namy & Gentner, 2002). Other tasks require *both* labeling and comparison. For example, children who see two labeled exemplars sequentially, without prompts for comparison, still strongly favor object matches in the animal images task (27% relational responding). It is only with both novel linguistic labels *and* comparison between multiple exemplars—for example, "Look! This is a jiggy. This is also a jiggy. Can you see why these are both jiggies? Now, which one of these [choices] is also a jiggy?"—that children favor the relational match, at 72% (Christie & Gentner, 2010; Gentner et al., 2011). In short, young children—who largely fail to perform spontaneous analogical transfer—appear to be more likely to detect relational commonalities within the same sets of stimuli when they receive explicit sociolinguistic scaffolding.

Are there other routes by which analogical reasoning might emerge in the course of young children's everyday experiences? And more broadly: how can we square children's sophisticated abilities for other forms of abstract thinking with their apparent deficiency in spontaneous relational reasoning and analogical transfer?

Notably, young children excel at *causal* reasoning, which requires learners to *relate* an initial state of the world to a later, end state via some causal process. Causal reasoning emerges early: children as young as 16–24 months can track patterns of statistical contingency between causes and effects, learn causal properties of objects, and intervene on causal systems to generate desired effects (e.g., Gweon & Schulz, 2011; Meltzoff, Waismeyer, & Gopnik, 2012; Sobel & Kirkham, 2006; for reviews, see Gopnik, 2012; Gopnik & Wellman, 2012). Causal reasoning is also highly sophisticated. After seeing only small amounts of data, children generate explicit causal judgments, counterfactuals, and novel causal interventions that they have never observed (e.g., Cook, Goodman, & Schultz, 2011; Gopnik & Sobel, 2000; Gopnik et al., 2004; Schulz, Gopnik, & Glymour, 2007; Schulz, Kushnir, & Gopnik, 2007; Sobel, Yoachim, Gopnik, Meltzoff, & Blumenthal, 2007). If children possess such formidable abilities in reasoning about the abstract relations between causes and effects, might they display analogical transfer for *causal events*, even if they do not do so for static, noncausal stimuli?

One recent line of research suggests that causal framing may indeed facilitate very young children's understanding of relations (Walker, Bridgers, & Gopnik, 2016; Walker & Gopnik, 2014, 2017). In these studies, 18- to 30-month-olds who saw that two "same" or "different" blocks made a machine play music were able to learn and transfer this relational rule to activate the machine with new blocks (Walker & Gopnik, 2014). Moreover, toddlers did not simply rely on perceptual features to solve this task, but genuinely attended to the relations (Walker & Gopnik, 2017). Comparing these results to the findings from traditional RMTS tasks—where even 3- and 4-year-olds' fail to master "same" and "different"—suggests that a causal framing could have powerful effects. However, these studies did not compare performance across causal and noncausal versions of the same tasks, which leaves open the possibility that it was other features of the task that improved performance. In addition, there are other indications that "same" and "different" may be easier than was previously thought, including data from early looking-time studies (Ferry, Hespos, & Gentner, 2015; Hochmann, Mody, & Carey, 2016). As a result it remains unclear whether it was causal framing, in particular, that allowed young children to succeed on these tasks, and whether this early success would emerge for other relations (beyond "same" and "different") recast in a causal context.

Across four studies, we test the hypothesis that causal framing can help preschoolers appreciate abstract relations over surface similarity. However, rather than tracking whether the relation can itself serve as a cause, as in the Walker and Gopnik studies, we ask whether children can track the abstract relations between the *beginning* and *end* states of causal events. For instance, a light switch reliably changes a room from being poorly illuminated to well illuminated, and learning this causal relation involves some representation of how the initial and end states are related (they differ in *level of light*). Understanding such relations can allow a learner to generalize from one causal event to another (Woodward, 2003). In the present studies, we therefore ask whether preschoolers can succeed in learning and transferring target relations when the relations are operationalized as the beginning and end states of a causal transformation.

Finding that preschoolers can succeed in learning and transferring abstract causal relations would be significant for a number of reasons. First, it would suggest that causal framing supports wide-ranging analogical transfer in preschoolers for a variety of abstract relations, beyond "same" and "different." Second, it would suggest a novel route by which analogical reasoning might develop in the course of young children's experience. Third, from the perspective of causal learning itself, it would show that children can formulate abstract relational hypotheses from data. That is, children can go beyond simply saying that "A causes B" to make inferences about the *kind* of causal relation that is involved in a given event.

The present studies build on previous work suggesting that young children are able to understand and track unusual causal transformations. There are two other studies that have shown that preschoolers can identify the causal "operator" linking two states of an everyday object (e.g., a knife linking a whole apple and a cut apple; Gelman, Bullock, & Meck, 1980) and that young children's analogical reasoning is enhanced for familiar physical causal processes (Goswami & Brown, 1990; cf. Rattermann & Gentner, 1998b, for the argument that this task did not contain true object matches). In contrast, our studies introduce transformations that are unfamiliar, such as a die becoming larger, borrowing many of the unfamiliar spatial configurations used in previous RMTS studies (e.g., changes in size, reflections across axes; Christie & Gentner, 2010). To succeed in our task, children must relate the beginning and end states of the transformation to identify a relevant relation, not rely on prior knowledge to provide an appropriate relation based on only the beginning or end state itself. While there is one recent study on novel "function learning" and compositionality demonstrating that preschoolers can reason about two transformations (i.e., changes in the color and pattern of an animated car), the participants in that study received extensive training, and their analogical transfer to *novel* stimuli was not assessed (Piantadosi & Aslin, 2016). Here, we closely adapt the classic RMTS task to directly pit a relational choice against an object match after only two sequential examples.

Experiment 1 explored whether 3- and 4-year-old children could learn and transfer novel relations between the beginning and end states of causal transformations, directly comparing the effect of causal versus noncausal framing on children's analogical reasoning. *Experiment 2* replicated the results of Experiment 1 using animated stimuli, and also investigated whether children could infer broader, more abstract hypotheses about the *kinds* of causal transformations that might occur. *Experiment 3* controlled for the possibility that children in Experiments 1 and 2 were succeeding due to a nonrelational strategy, such as choosing the novel object at test. *Experiment 4* investigated whether dynamically changing, yet noncausal, stimuli are sufficient to facilitate analogical transfer without causal framing.

Experiment 1

In Experiment 1, we presented 3- and 4-year-old children with a causally framed version of a RMTS task. Experiment 1 directly tested the effects of *causal* versus *noncausal* framing on children's analogical transfer by using traditional RMTS stimuli—that is, static images on flashcards—and manipulating causal framing experimentally.

Experiment 1: Method

Participants

Participants (N = 48) were 24 three-year-olds (M_{age} = 42.83 months, SD = 3.16, range = 36–47 months, 12 female, 12 male) and 24 four-year-olds (M_{age} = 54.04 months, SD = 3.97, range = 48–59 months, 11 female, 13 male). Eight additional children were tested, but excluded due to experimenter error (2), inattention (3), or unwillingness to complete the task as instructed (3). Children were recruited from university preschools and local museums in a large metropolitan area, and a range of ethnicities resembling the diversity of the local population was represented.

Materials and Procedure

Experiment 1 directly compared the effects of causal versus noncausal framing on analogical transfer using static images on flashcards, a method used for presenting stimuli to children in many previous RMTS studies. In both the Causal and Noncausal conditions, participants saw images of everyday objects printed on flash cards depicting relations previously tested in the literature. The six relations were: change in size (bigger/smaller), change in number (1:5), change in color, and reflections over the x- and y-axes (Christie & Gentner, 2010).

In the Causal condition (N = 24), each of the six sets of two exemplars were introduced in the context of six stories about magical wizards who caused transformations on everyday objects when they waved their magic wands. As such, the objects on each exemplar card were framed as the beginning and ending states of a causal transformation. Succeeding in analogical transfer thus required children to select the target card that portrayed the same relation between the initial and ending states of a novel object's "transformation" as had been illustrated by the previous two exemplars, rather than relying on shared features of previous exemplars, as in the object match. The wizards were each illustrated on an additional flashcard, which was laid next to the RMTS cards. For each of the six stories, the "transformation" portrayed in the object match card was similar to the dimension of change in the target transformation. So for the size transformations (bigger and smaller), the object match decoy transformations also took place within the two-dimensional plane (flattening horizontally and narrowing vertically); for reflections over x and y axes, the object matches were transformed over the y and x axes, respectively; for the multiplicative target transformation the object match underwent a *division*; and for the color transformation (yellow to purple) the object match turned a different color, blue (see Figure 2 for a summary of the stimuli in all six sequences).

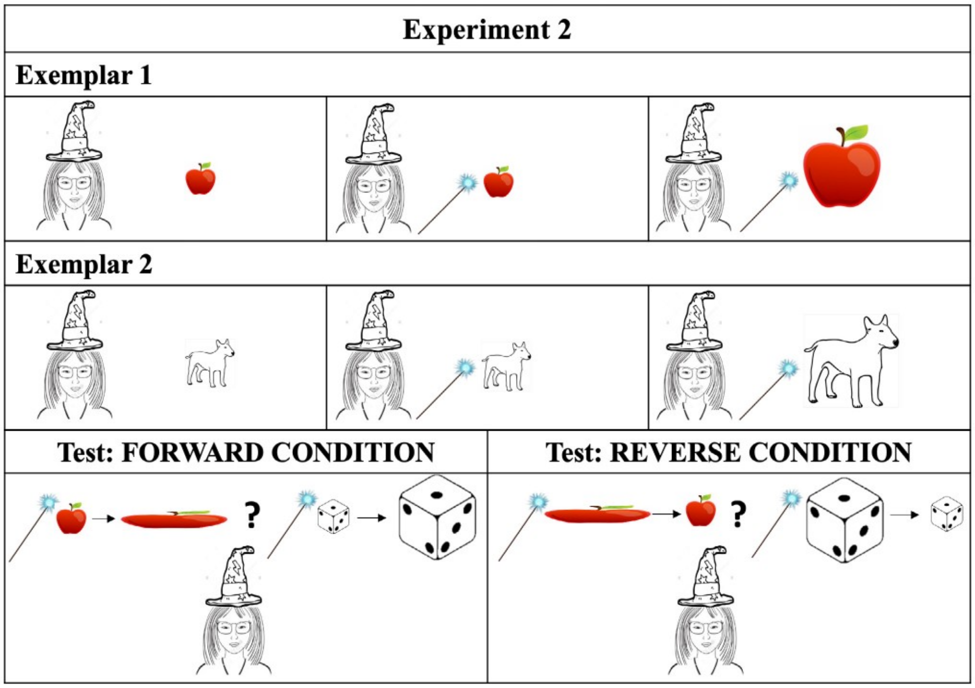

Figure 2. Schematic summary of the six causal transformations used in *Experiments 1 and 2*. The relations between the beginning and ending states of the causal transformations were adapted from traditional, non-causal relational-match-to-sample stimuli used in previous studies (Christie & Gentner, 2010). The stories were presented in a randomized order for each participant. The order of presentation of the object match and relational match was randomized and counterbalanced across participants. [Color figure can be viewed at wileyonlinelibrary.com]

The causal "narratives" consisted of minimal descriptions about the wizards and their actions. For example, in one story, the experimenter introduced the participant to Gwen:

> This is Gwen. Gwen is a magical wizard. Here is something that happens when Gwen waves her magic wand. She turns *this* [e.g., indicates apple with finger on exemplar flashcard] into *this* [e.g., indicates larger apple with finger on exemplar flashcard].

Then, the experimenter told the participant about the transformation again: "Yes, that's what happens: she turns this into this." Then the experimenter presented another card with the second transformation, and said, "Here's something else that happens when Gwen waves her magic wand. She turns *this* [e.g., indicates dog with finger on flashcard] into *this* [e.g., indicates larger dog]." The experimenter then placed the wizard card above two cards indicating the object match and the relational match choices (always side by side, order of presentation counterbalanced across subjects). The experimenter then asked,

> Now Gwen is going to wave her magic wand again. What do you think she's going to do next? Will she turn *this* into *this* [indicating images on first card]? Or will she turn *this* into *this* [indicating images on second card]?

The six stories were presented in a random order.

In the Noncausal condition (N = 24), the experimenter used the same stimuli as in the Causal condition, except for one difference: no wizard cards were employed. The experimenter used a script adapted from other RMTS samples, saying, "I have this card right here, with *this* and *this* [the experimenter pointed to each of the images, just as in the Causal condition]." The experimenter then repeated and re-indicated the images again, saying, "Yes, I have this card right here, with *this* and *this*." The second exemplar was then produced, and the experimenter said, "And I have this card right here, with *this* and *this* [indicating images with finger]. That's right, I have this card right here with *this* and *this*." Next, the experimenter showed the participant the two choices, saying, "Now, can you tell me which one of these

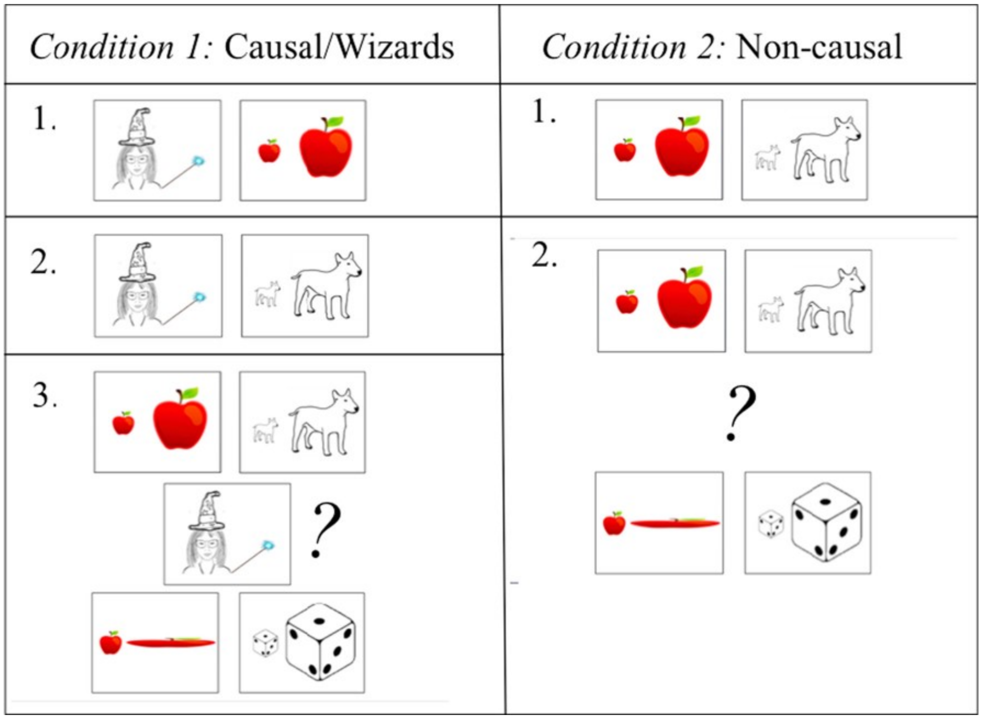

Figure 3. Stimuli for causal versus non-causal cards conditions in *Experiment 1*. The images were displayed to children on printed flash-cards. In the causal condition, children heard the magical wizards/causal transformation stories. Then, they were asked, "What do you think the wizard will do next? Will she turn [this] into [this], or [this] into [this]?" The Non-causal condition followed the same procedure as other relational-match-to-sample tasks using static, non-causal stimuli; at test, participants were asked, "Which one of these two cards goes best with these two cards?". [Color figure can be viewed at wileyonlinelibrary.com]

two cards *goes best* with the ones that we already saw?" This wording is standard for RMTS tasks (e.g., Christie & Gentner, 2014). The six sets of cards were presented in a random order, and the order of presentation of the two choices was counterbalanced and randomized across trials. Figure 3 depicts the presentation of stimuli in the Causal versus Noncausal conditions.

Experiment 1: Results and Discussion

Children were scored on the number of relational matches they chose out of six possible matches. The maximum score of six of six would show a preference for relational matches; the minimum score of zero of six would indicate a preference for object matches.

An analysis of variance showed that the effect of condition (causal vs. noncausal) was highly significant, $F(1, 45) = 29.20$, $p < .001$, $d = 1.48$. Age was also a significant factor: 3-year-olds performed worse than 4-year-olds, $F(1, 45) = 6.12$, $p = .02$, $d = 0.56$. However, there was no significant interaction between condition and age, $F(1, 44) = 0.07$, $p = .79$.

In the *Causal* condition, the average number of relational matches chosen was significantly above chance ($N = 24$; $M = 3.96$, $SD = 1.66$; $t(23) = 2.79$, $p = .01$, $d = 0.58$). By contrast, the *Noncausal* condition replicated the results of previous studies that use traditional, noncausal stimuli: In this condition, children strongly preferred object matches, averaging only one relational match ($N = 24$, $M = 1.13$, $SD = 1.25$). This performance was significantly *below* chance, $t(23) = -4.48$, $p < .001$, $d = 1.50$.

Although 3-year-olds' performance in the causal condition (55%) was not different from chance ($N = 12$; $M = 3.33$, $SD = 1.72$; $t(11) = 0.67$, $p = .52$)—the *proportion* of both age groups' relational preferences was dramatically larger in the causal condition relative to the noncausal condition. The difference between 3-year-old participants' performance in the Causal and Noncausal conditions was 2.33 relational choices out of six, or a boost in relational reasoning of more than 38% in the Causal condition. For 4-year-olds, the boost from causal framing was 2.58 relational choices, or 43%.

Notably, this relative improvement in children's relational reasoning occurred in the absence of the sociolinguistic scaffolds tested in prior research.

That is, although the causal descriptions that children heard in the Causal condition were verbal, children did not receive any of the explicit prompting that previous studies have employed as interventions to improve children's reasoning. In the present task, the experimenter did not give the exemplars the same label, and did not explicitly instruct participants to compare them.

In sum, the results of Experiment 1 suggest that with an appropriate causal framing, even 3- and 4-year-old children can succeed in identifying and generalizing an abstract relation.

Experiment 2

In Experiment 2, we sought to replicate the results of the Causal condition of Experiment 1 using a PowerPoint presentation with six short animated sequences. The animations made the causal nature of the sequences especially salient, and so might improve children's performance. This was particularly relevant for the 3-year-olds who were still at chance in the causal condition in Experiment 1. Children first observed two animations of causal transformations (i.e., a wizard making an object grow with her magic wand) and then had to indicate what they thought would occur when the same operation was performed on a novel object. As in Experiment 1, children were presented with a choice between a relational match, in which a novel object underwent a transformation with the same abstract relation between initial and ending states, and an object match in which a previously seen object underwent a change that did not reflect the relations depicted between the initial and ending states of the exemplar transformations. Success on the task once again required children to select an end state based on its *relation* to the given initial state, rather than relying on shared features.

Experiment 2 also included a condition in which children observed a given relation (e.g., a wand making a small object larger) and had to generalize to the reverse relation (e.g., the wand making a large object smaller) versus an unrelated transformation (e.g., reflecting the image over the x-axis). This condition tested whether children could learn from evidence to make broader inferences about types of relations—in this case, involving a shared dimension of change, albeit in different directions. Causal learning studies have found that 4-year-olds are able to learn and apply more abstract, general causal relations in making social causal attributions (Seiver, Gopnik, & Goodman, 2013) and in making inferences about the functional form of causal systems (Lucas, Bridgers, Griffiths, & Gopnik, 2014). Would children who had previously seen the wizard make things *smaller* now infer that she was more likely to effect change about *size*, in general?

Experiment 2: Method

Participants

Participants were 24 three-year-olds (M_{age} = 41.29 months, SD = 4.18, range = 34–46, 10 female, 14 male) and 24 four-year-olds (M_{age} = 53.45 months, SD = 3.26, range = 49–58, 15 female, 9 male). Three additional children were tested but excluded due to refusal to complete the task as instructed (1) or parental interference (2). The recruitment procedures and demographics were the same as those of participants in Experiment 1.

Materials

Participants saw a PowerPoint presentation with six short animated sequences about wizards who caused transformations on everyday objects when they waved their magic wands (see Supporting Information for sample animations). The images of the wizards and the objects in the sequences were identical to those printed on the static flash cards in Experiment 1.

Procedure

The experimenter introduced the task by telling each participant that they were going to play "The Wizards Game." In the game, children were told that they would learn about some magical wizards who could do some special things when they waved their magic wands. Then, the children would get to decide what they thought the wizard was going to do next, when she waved her magic wand again.

For each wizard, children saw two sequential PowerPoint-animated examples of causal events. In one story, the experimenter introduced the participant to Gwen: "This is Gwen. Gwen is a magical wizard. Are you ready to find out what Gwen can do when she waves her magic wand?" The experimenter then played through the first animated sequence in the PowerPoint. Each animated exemplar began with a slide in which the wizard image was displayed to the left of the object to be transformed, with a space in between them. The experimenter said, "Look! Here's Gwen, and here is an apple [pointing at each image in sequence]. Are you ready to find out the first thing that happens when Gwen waves her magic wand? Here she goes!" The experimenter then activated an animation sequence in which Gwen "waved her magic wand" at an apple, causing it to "grow" larger: first, a still image of a wand appeared between the images of Gwen and the apple; then, the apple faded out and was replaced by an identical, but notably larger, image of the same apple. In this way, the animated display suggested a dynamic causal sequence of events more than the flashcards in Experiment 1, yet did so without displaying any additional information (e.g., any intermediary "phases" of the object between the beginning and ending states). The experimenter then commented: "Wow! Did you see that? Let's see that again!" and then played the sequence a second time. The experimenter then repeated the procedure for the next exemplar: this time, Gwen waved her wand at a dog, which grew larger, too.

Next, the children were sequentially reminded of the two exemplars: "Ok, so first she did this [replay animation of the first exemplar]; let's put that up here so we can remember [sequence was posted, statically, in miniature at the top of the screen]; then she did this [played animation of second exemplar], let's put that up here so we can remember [sequence was again stored at the top of the screen]." At test, the experimenter asked, "What will happen when Gwen waves her magic wand again?" The magical wizard was displayed and her wand flashed. In this case, children were provided with the choice between two animations: a (familiar) apple becoming flat (*object match*) and a (novel) dice growing larger (*relational match*; see Figure 4).

In a separate, "Reverse" condition, half of the children (N = 24, 12 three-year-olds and 12 four-year-olds) saw the same display, but with one difference: at test, they chose between the same object match (apple becoming flat) and a new relational choice that matched the examples at a higher level of abstraction: the large die indeed changed *size*, but it grew *smaller*, not larger. This condition tested whether children could use evidence to draw broader inferences about the general *kinds* of transformations that a given wizard might perform.

Across both Forward and Reverse conditions, the wizards were presented in a randomized order for each child, and the order of the choices (relational and object matches) were counterbalanced between subjects.

Experiment 2: Results and Discussion

As in Experiment 1, children were scored on the number of relational matches they chose out of six possible matches. An analysis of variance showed that performance did not differ between 3- and 4-year-olds, $F(1, 45) = 0.05$, $p = .82$. Moreover, with the animated stimuli, both 3-year-olds and 4-year-olds performed at above chance levels: 3-year-olds ($N = 12$), $M = 4.33$, $SD = 1.23$; $t(11) = 3.75$, $p = .003$, $d = 1.52$; 4-year-olds ($N = 12$), $M = 4.42$, $SD = 1.16$; $t(11) = 4.21$, $p = .001$, $d = 1.71$.

Surprisingly, the effect of forward versus reverse transformation was not significant: children succeeded equally often in both the forward and reverse conditions, $F(1, 45) = 0.00$, $p = 1.00$. Given the choice between an object match—for example, an apple becoming flat—and a relational match—for example, a novel dice growing larger—children in the Forward condition ($N = 24$) chose the relational match at a high rate (73%), scoring more than four of six relational choices on average ($M = 4.38$, $SD = 1.17$). This rate of relational responding was significantly above chance, $t(23) = 5.74$, $p < .001$, $d = 1.18$. Participants in the Reverse condition performed nearly identically to the Forward condition, also choosing relational matches 73% of the time ($N = 24$; $M = 4.38$, $SD = 1.38$; $t(23) = 4.89$, $p < .001$, $d = 1.00$). Furthermore, the distribution of children's scores suggests that results were not driven by a competent subpopulation. Of the 48 participants tested, 37 (77.1%) scored 4/6, 5/6, or 6/6 relational matches. Only 11 of the 48 children (23.9%) scored at or below chance: five of 24 children in the Forward condition (three 3-year-olds and two 4-year-olds) and six of 24 (three 3-year-olds and three 4-year-olds) in the Reverse condition.

Notably, participants' overall high rate of relational responding (73%) across both versions of this causally framed version of a classic RMTS task tracks very closely with children's rates of relational responding in previous, noncausal RMTS tasks that scaffolded children's reasoning with linguistic labeling and/or explicit prompts to compare exemplars (Christie & Gentner, 2010, 2014; Gentner et al., 2011). However, as in Experiment 1, in the present task no explicit labels or prompts to compare were offered.

In sum, the results of Experiment 2 replicated the results of Experiment 1, providing further evidence for the facilitative effect of causal framing on 3- and 4-year-old children's analogical reasoning. With the animated stimuli, which perhaps further

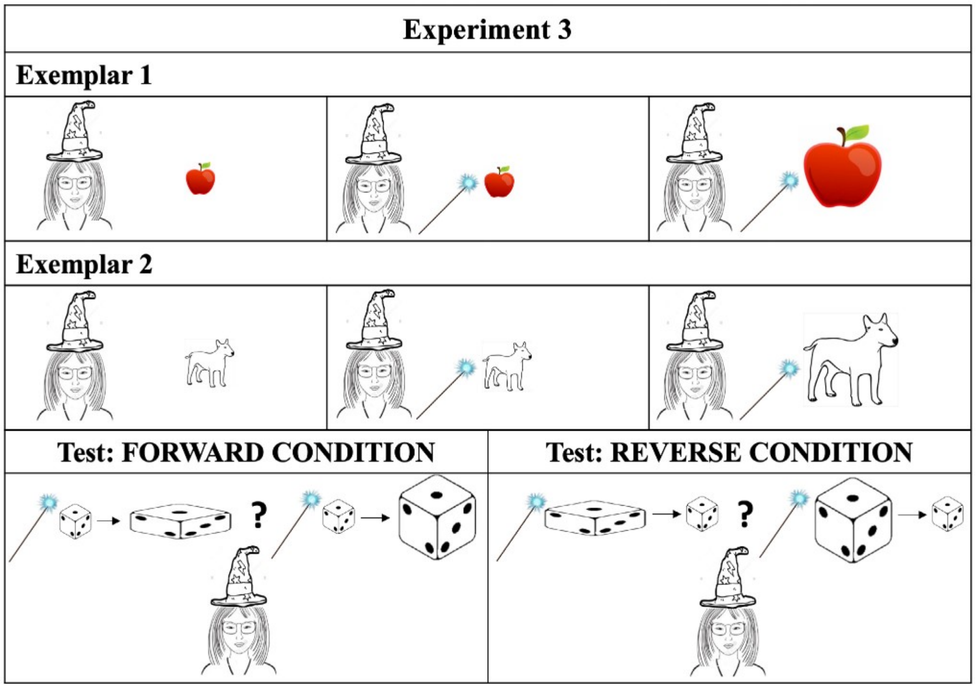

Figure 4. Schematic example of one of six trials in *Experiment 2*. Children saw the images on a laptop in a PowerPoint presentation (see Supporting Information). The images were identical to those on the flashcards in *Experiment 1*. [Color figure can be viewed at wileyonlinelibrary.com]

increased the salience of causality in the wizards narratives, both 3- and 4-year-olds favored relational over object matches. Experiment 2 went beyond Experiment 1 in showing that with a causal framing, children can engage in analogical reasoning even for higher order relations that involve change along a dimension in either direction (i.e., "forward" and "reverse"). A critical question, then, is why children succeed under these conditions, given their failures on noncausal versions of similar tasks. We return to this key question in the General Discussion, after reporting additional experiments that bolster and clarify our interpretation of these results.

Experiment 3

The results of Experiments 1 and 2 suggest that preschoolers were able to transfer the abstract relational information between the beginning and ending states of a causal transformation to novel exemplars. That is, they were able to reason analogically in order to override the object match in favor of the choice that shared the causal form of the transformations they had seen the wizard perform earlier (and, in the case of the 24 children in the Reverse condition, choose the option that shared an even higher order abstract similarity). However, it is possible that children were using a nonrelational strategy in their responding: for example, that they were choosing the novel object because it was novel, or because the wizard "hadn't done it yet." In Experiment 3, we control for the possibility of a novelty preference by repeating the Experiment 2 procedure, but with two of the same objects at test. In addition, by eliminating the object match, we directly test whether preschoolers are actually reasoning relationally, that is whether they choose the correct relation when the objects' identities are held constant.

Experiment 3: Method

Participants

Participants were 24 three-year-olds (M_{age} = 41.2 months, SD = 3.45, range = 35–47 months, 12 female, 12 male) and 24 four-year-olds (M_{age} = 53.5, SD = 3.84, range = 48–59 months, 14 female, 10 male). Four additional children were tested but excluded due to experimenter error (1), inattention (1), refusal to answer (1), or unwillingness to complete the task as instructed (1). The recruitment procedures and demographics were the same as those of participants in Experiments 2 and 3.

Materials and Procedure

Experiment 3 used the same PowerPoint stimuli and procedure as Experiment 2, but eliminated object match choices to control for the possibility that children were using a nonrelational strategy (e.g., choosing the novel object). At test, children chose between two identical objects that underwent different transformations: one relational match that mirrored the causal structure of the two exemplar transformations, and one decoy that underwent the same transformation as the corresponding object match in Experiments 1 and 2 (see Figure 5; see Supporting Information for sample animations). If children still perform above chance on this task, then we can infer that they are performing true analogical transfer—that is, that they are tracking and reasoning about the abstract relation between the beginning and the ending states of the causal transformations. As in Experiment 2, we again tested participants in both a Forward (N = 24) and a Reverse condition (N = 24) to see whether children would be able to infer more abstract generalizations about the dimension of change the wizard was likely to affect.

Experiment 3: Results and Discussion

An analysis of variance showed that performance again did not differ between 3- and 4-year-olds, F (1, 45) = 1.81, p = .19. The effect of forward versus reverse transformation was also not significant, F(1,

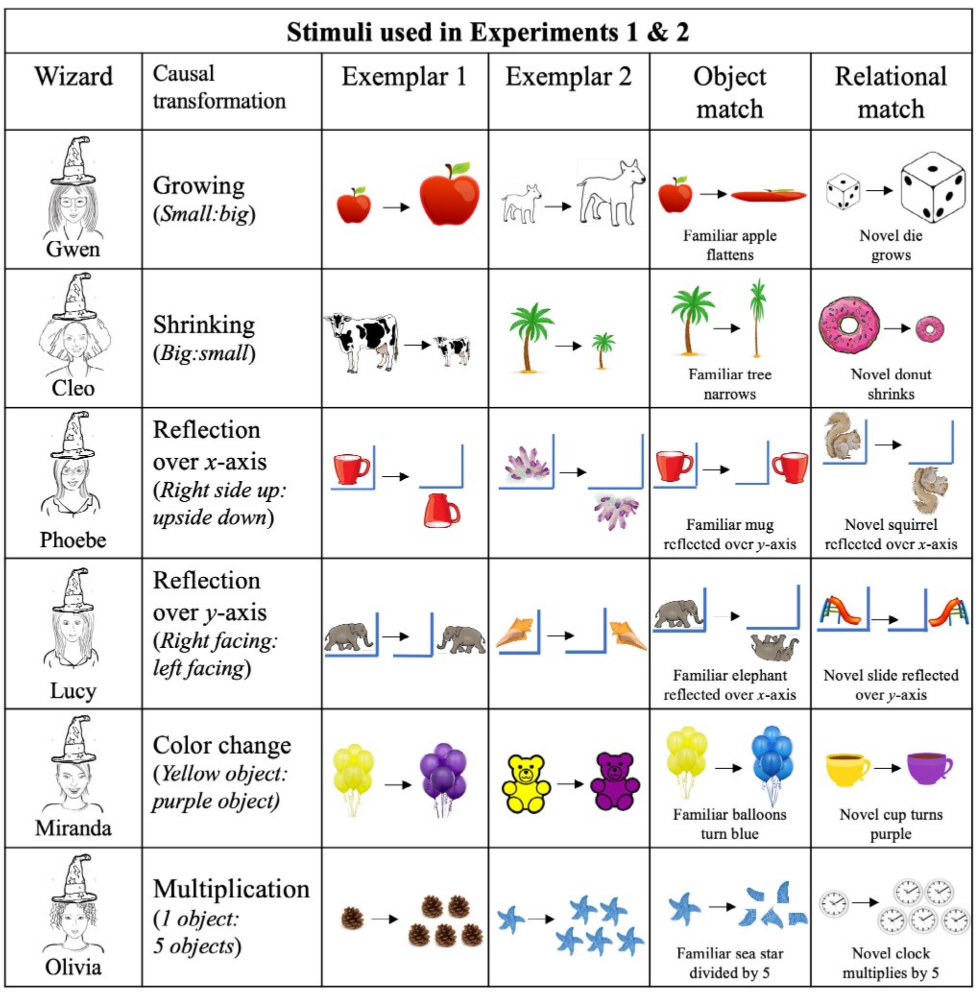

Figure 5. Schematic example of one of six trials in *Experiment 3* (see Supporting Information for samples from the animated PowerPoint presentations). Materials and procedure were identical to those in *Experiment 2*, with the one difference that at test, there were no object matches (test choices were between a relational match and an identical decoy object that underwent a different transformation). [Color figure can be viewed at wileyonlinelibrary.com]

45) = 1.21, $p = .27$. In both the Forward and Reverse conditions, performance was again significantly above chance ($N = 24$, $M = 4.25$, $SD = 1.22$, $p < .001$, $d = 1.02$; $N = 24$, $M = 3.71$, $SD = 1.15$, $p = .001$, $d = 0.61$). These results suggest that children were indeed reasoning relationally about the beginning and ending states of the causal transformations.

Strikingly, participants' performance in the Forward condition of Experiment 3, in which children ($N = 24$) chose between two of the same objects that underwent different transformations, was no different from performance in the Forward condition of Experiment 2 ($N = 24$), which pitted object matches against relational matches, $t(23) = 0.36$, $p = .72$). This suggests that 3- and 4-year-olds are actually reasoning about abstract relations in this causally framed RMTS task. Because there were no object matches in Experiment 3 stimuli, the only way for children to reason about the answer was by attending to the relations between the beginning and ending states of the provided exemplars, and then transferring that abstract knowledge to make the structurally relevant choice (novel relational match vs. novel decoy). Together with the results of Experiments 1 and 2, these findings provide strong evidence that children were indeed performing analogical transfer in this causally framed adaptation of the RMTS task.

In the Reverse condition, where two objects with different starting states (e.g., large die vs. flattened die) transformed into identical ending states, participants' rate of relational responding was 64.6% relational matches ($N = 24$; $M = 3.88$, $SD = 1.38$; $t(23) = 3.39$, $p = .006$, $d = 1.07$), which was no different from their performance in the Reverse condition of Experiment 2, $t(46) = -1.36$, $p = .18$. This suggests that children were again able to make more abstract generalizations about the "kind" of transformation the wizards were likely to perform—for example, that given two previous "shrinking" transformations the wizard was more likely to *grow* a novel object (but maintain its shape) than to flatten it.

The critical results in the Forward condition of Experiment 3—that is, those that map onto the original RMTS task, where the relation between the target and the relational match is the same, not reverse—replicate Experiments 1 and 2, suggesting that children were indeed performing analogical transfer for the relations between the starting and ending states of two sequential exemplars in a causal RMTS task. These results are remarkable due to their contrast with the results of a variety of previous, *non*causal RMTS tasks with preschool-aged children.

Experiment 4

Taken together, the results of Experiments 1–3 suggest that *causal framing* improves young children's analogical reasoning. However, Experiment 2—using dynamic stimuli—produced an even larger proportion of relational responses (especially for the 3-year-olds) than the Causal condition of Experiment 1, which used static stimuli. It was possible that the dynamic cues might be enough to support relational reasoning, even without causal framing. Experiment 4 thus seeks to replicate the results of the Noncausal condition of Experiment 1, but using the animated stimuli from Experiments 2 and 3. With these cues, but without causal framing, will children succeed in analogical transfer in a dynamic, yet noncausal, task?

Experiment 4: Method

Participants

Participants ($N = 24$) were 12 three-year-olds ($M_{age} = 43.67$ months, $SD = 3.23$, range = 38–47 months, 6 female, 6 male) and 12 four-year-olds ($M_{age} = 53.17$ months, $SD = 3.27$, range = 48–58 months, 6 female, 6 male). Two additional children were tested but excluded due to experimenter error (1) and unwillingness to complete the task as instructed (1). The recruitment procedures and demographics were the same as those of participants in Experiments 1–3.

Materials and Procedure

Experiment 4 used identical PowerPoint stimuli to the Forward condition of Experiment 1, with one difference: there were no wizards (i.e., no causal framing). This experiment was designed to replicate the results of the Noncausal condition of Experiment 1 and to investigate whether dynamic cues alone are sufficient to facilitate analogical transfer.

In this dynamic—but noncausal—paradigm, children saw exactly the same exemplar animations as they did in Experiment 1, and they saw the same choices. However, there were no wizards, and no stories or explanations about the images representing transformations (i.e., no discussion at all of the images "turning into" each other). At the beginning of the experiment, the experimenter told each participant, "In this game, we're going to decide which thing goes best with some other things that we see." For the first exemplar of each trial, the experimenter said, "Here's this thing right here [e.g., narrating while playing animation of small apple that disappeared, then was replaced by an identical larger apple]. Now here it is again [replaying the animation]." Then the experimenter said, "Here's the second thing [e.g., playing animation of small dog that disappeared, then was replaced by a larger dog]. Here it is again." Then the experimenter said,

> So, first we saw this [playing the first animation], with *this* and *this* [pointing to the objects in sequence, just as in Experiments 1]. Let's put that up here so we can remember [the images appeared in miniature at the top of the screen]. Then we saw this [playing the second animation], with *this* and *this*. Let's put that up here so we can remember. Now, which one of these two things goes best with the things that we saw before [playing relational match and object match choices]?

As in Experiment 1, children were offered the choice between an object match, which featured an object from one of the exemplar transformations, and a relational match, which featured a novel object that shared the same relational structure as the relation between the beginning and ending states of the causal exemplars (see Supporting Information for a sample trial).

Experiment 4: Results and Discussion

The results of Experiment 4 replicated the results of the Noncausal condition of Experiment 1, suggesting that dynamic cues alone—such as temporal and spatial contiguity—are insufficient for bringing about the facilitative effect of causal framing we observe in Experiments 1–3. Of the 24 children tested in this task, only 5 participants (2 three-year-olds and 3 four-year-olds) chose relational matches more often than chance. Overall, children's low rate of relational responding (33%) was significantly below chance ($N = 24$, $M = 1.96$, $SD = 1.68$; $t(23) = -3.04$, $p = .006$, $d = 0.88$). It was also significantly below performance in the Forward conditions of Experiment 1, $t(46) = -4.13$, $p < .001$, $d = 1.19$, and Experiment 2, $t(46) = -5.33$, $p < .001$, $d = 1.67$. Consistent with both the results from previous RMTS studies that used static, noncausal stimuli—and just as in the Noncausal condition of Experiment 1—Experiment 4's dynamic noncausal stimuli do not promote children's analogical transfer (see Figure 6 for comparisons across Experiments 1–4; see Table 1 for the proportions of relational matches for each of the six transformations across Experiments 1–4).

General Discussion

Previous research on the development of analogical reasoning has shown that preschoolers routinely fail to privilege abstract relational information over surface similarities in RMTS tasks. Without guidance from explicit social or linguistic cues, children prefer superficially similar "object matches" to "relational matches" that are perceptually dissimilar from the target yet share the same abstract structure. However, most of this research has used matching tasks with noncausal stimuli. The present experiments asked whether *causal framing* might facilitate young children's relational reasoning and analogical transfer.

Experiment 1 directly compared 3- and 4-year-olds' performance in a causally framed RMTS condition with a noncausal condition that used a traditional RMTS script. Both conditions used the same stimuli (static flashcards); however, children in the causal condition showed a large (40%) boost in relational responding compared with the noncausal condition. *Experiment 2* replicated the results of the Causal condition of Experiment 1 using novel, animated stimuli, and resulted in even stronger analogical reasoning performance in the younger children. *Experiment 3* used the same stimuli as Experiment 2, but the novel relational match was pitted against an identical novel decoy that underwent a different transformation, confirming that participants were indeed deciding on the basis of the relation rather than on a nonrelational heuristic (e.g., "choose the novel object"). Finally, *Experiment 4* used dynamic, yet noncausal stimuli—that is, PowerPoint animations from Experiment 1 with the causal framing removed—to replicate the results of the Noncausal condition of Experiment 1, and to test the extent to which dynamic perceptual cues by themselves may have contributed to children's success in Experiments 2 and 3. In the absence of causal framing, children again preferred object matches to relational matches, just as in traditional RMTS studies.

Taken together, the results of these four experiments strongly suggest that causal framing facilitates young children's analogical reasoning. When

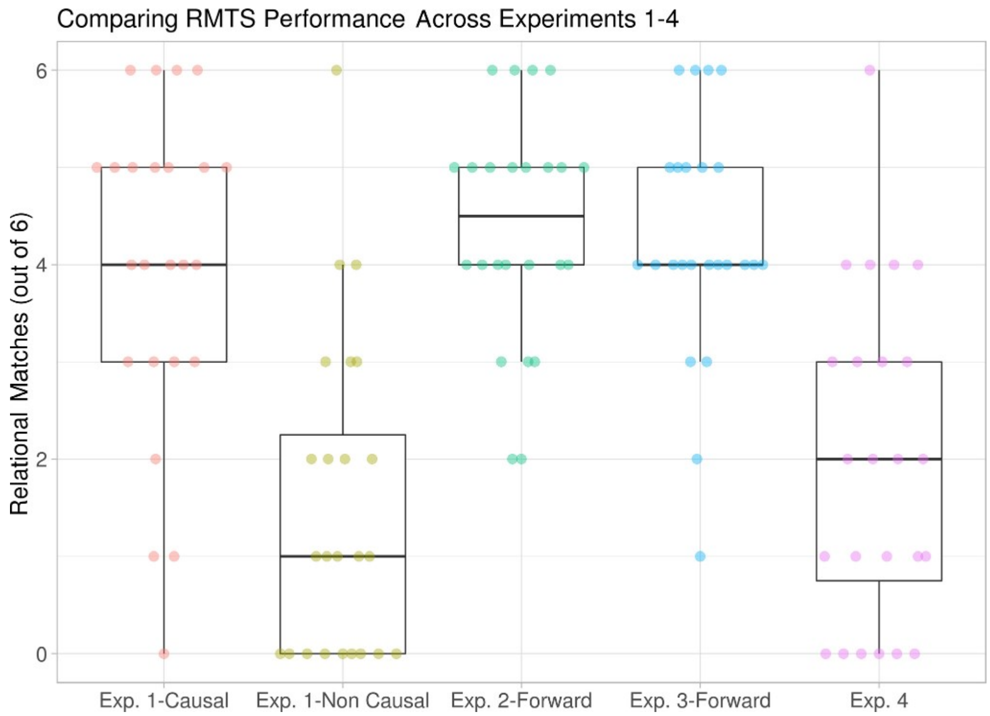

Figure 6. Results of Experiments 1–4. For each experiment, $N = 24$. Chance responding is 3 out of 6 relational matches. [Color figure can be viewed at wileyonlinelibrary.com]

Table 1
Summary of the Proportion of Relational Matches for Each of the Six Transformation Types Across Experiments 1–4

Transformation	Exp. 1 (causal)	Exp. 1 (non causal)	Exp. 2 (forward)	Exp. 3 (forward)	Exp. 4
Growing	0.57 (0.51)	0.21 (0.41)	0.57 (0.51)	0.75 (0.44)	0.43 (0.51)
Shrinking	0.92 (0.27)	0.38 (0.49)	0.79 (0.43)	0.83 (0.38)	0.36 (0.50)
Reflection *x*-axis	0.86 (0.36)	0.17 (0.38)	0.93 (0.27)	0.50 (0.51)	0.07 (0.26)
Reflection *y*-axis	0.86 (0.36)	0.17 (0.38)	0.71 (0.47)	0.71 (0.46)	0.29 (0.47)
Color change	0.71 (0.47)	0.33 (0.48)	0.57 (0.51)	0.58 (0.50)	0.36 (0.50)
Multiplication	0.57 (0.51)	0.25 (0.44)	0.57 (0.51)	0.88 (0.34)	0.29 (0.47)

novel abstract relations from traditional RMTS tasks are operationalized as the relation between the beginning and ending states of causal transformations, young children are quite capable of learning and transferring them. In addition, the present findings replicate the results of previous studies by showing that children *fail* to transfer these exact relations when they are presented using *non*causal versions of the same stimuli. The facilitative effect of causal framing on children's analogical transfer is comparable with the magnitude of the boost that previous work finds is provided by sociolinguistic cues such as labeling and explicit instructions to compare exemplars (Christie & Gentner, 2010, 2014; Gentner et al., 2011).

How Does Causal Framing Facilitate Analogical Transfer?

Two previous studies have shown that toddlers were able to learn the relations "same" and "different" when those relations were paired with a desirable causal outcome (Walker & Gopnik, 2014; Walker et al., 2016). While our studies bolster Walker et al.'s interpretation of their results in terms of causal framing, the present studies go beyond this work in several ways. First, our studies go beyond "same" and "different" to show relational generalization for a wide range of relations. Second, our studies show that children can generalize from a particular transformation in one direction (e.g., grow) to distinct transformations along that dimension (e.g., change in size, whether growing or shrinking), suggesting an ability to infer even higher order relations. Third, our Experiment 1 is the first to directly compare the effects of causal versus noncausal framing on children's performance in an RMTS task. This study shows that preschoolers—who regularly fail at RMTS tasks with static, noncausal stimuli—can learn exactly the same novel relations when they are embedded within the ordinary structure of a causal event.

How does causal framing facilitate relational reasoning and analogical transfer? One explanation for the causal framing effect may be that causal reasoning inherently involves attending to abstract relations—namely, the relation of "difference." Interventionist theories of causation in philosophy conceptualize "cause" in precisely this way: causes are "difference makers" (e.g., Woodward, 2003). In other words, to see that some cause *C* has resulted in some effect *E* is tantamount to noting that *C* has produced a *difference* in the state of the world (relative to which it would have been absent that cause).

Might children's ability to notice differences between the beginning and the ending states of causal events underlie the causal framing effect on relational reasoning in the present experiments? How might this explanation fit with existing accounts of the facilitative effect of other scaffolding—namely, linguistic labels or comparison? Christie and Gentner propose that the underlying mechanism for success on their RMTS task with labeling is *comparison*. On this account, linguistic labels are "invitations to compare" (2014). For example, when an experimenter labels a target as a "truffet" and instructs the child to "Find the other truffet," the novel word prompts the participant to compare the target card to both the relational match and the object match. Instead of rapidly choosing the object match by privileging perceptual similarity, the label increases the likelihood that children will find the relevant abstract commonality. The labeling effect is further strengthened when an experimenter prompts the child to compare across multiple exemplars—for example, "Look, a truffet! Look, another truffet! Do you see why these are both truffets? Now, can you find me another truffet?" The common label leads children to expect that the exemplars share some commonality (Christie & Gentner, 2010, 2014).

"Comparison" could underlie children's success in the present, causally framed experiments, as well. First, causal framing could elicit spontaneous comparison between the beginning and ending states of each transformation, or between the actual transformation and a counterfactual state with no change. As with labeling two exemplars, this could invite learners to identify the commonalities, in turn bringing out the dimension of change (e.g., size, number). Secondly, although children were not explicitly instructed to compare each pair of transformations, our experiments did use two exemplars rather than one. However, it should be noted that any "spontaneous comparison" between multiple exemplars would also presumably apply to the Noncausal condition of Experiment 1, as well as to Experiment 4. There appears to have been little advantage for children's RMTS performance in either of those two conditions, in spite of the fact that they involved the same number of exemplars as in the causal condition. One final possibility for the role of comparison in the present experiments is that a common cause (e.g., wizard) might function similarly to common linguistic labels, prompting spontaneous comparison across sequential exemplars in which the cause appears.

A different reason why children may have succeeded in the present, causally framed studies could be that, in the causally framed tasks, the learner assumes that the posttransformation object is the *same* object as the pretransformation object. Previous work has shown that preservation of identity facilitates children's performance on spatial reasoning tasks (e.g., DeLoache, Miller, & Rosengren, 1997). Thus, perhaps the preservation of object identity across the beginning and ending states of a transformation explains children's success. However, it is important to note that any assumptions participants may have made about the identity of the objects in the present studies would seem to be inherent to the causal nature of the event itself, since the phrasing used in the "recap" portions of both the causal conditions in Experiments 1 and 2 ("First she turned *this* into *this;* then, she turned *this* into *this*") and the noncausal dynamic stimuli in Experiment 4 ("First we saw this, with *this* and *this;* then we saw this, with *this* and *this*") were ambiguous as to whether the pre and posttransformation objects were the same. And again, the noncausal dynamic stimuli in Experiment 4 were identical to those in the causal condition—in both cases strongly suggesting that a single object was involved. Nevertheless, children did not make the relational matches in these cases without causal framing. Further studies will be needed to determine whether the fact that a single object is transformed plays a role in these results.

Future Directions

In the present experiments, children were able to learn and apply complex relational concepts (such as reflections and multiplication) by noting the difference between the beginning and ending appearance of an object that underwent a causal transformation. If causal framing facilitates relational reasoning and analogical transfer, then this suggests that novel abstract relations might be acquired without pedagogy, testimony, or labeling. Because causal transformations are ubiquitous in everyday life, the present findings thus open the possibility for complex, prelinguistic relational representations in infants and other nonverbal animals. Further research should explore other ways in which very young children may use and apply the relations they have learned from causal events. One limitation of the present study is that the causal events were presented to children by an experimenter, rather than encountered in the course of children's naturalistic play; future experiments should explore whether children could learn and generalize novel relations they discover in the course of their own unguided actions.

Future research might also explore whether the facilitative effect of causal framing on preschoolers' relational reasoning extends to even more abstract relations, such as those involved in patterning. Learning abstract patterns, which lack the type of semantic familiarity that is perhaps inherent to our stimuli (e.g., "bigger than"; "upside-down"), represent a substantial challenge for preschool-aged children. Furthermore, there is some work that suggests that relational labeling improves children's performance on patterning tasks (Fyfe, McNeil, & Rittle-Johnson, 2015); thus, a causally framed version of those tasks may provide yet another interesting point of comparison between the facilitative effect of linguistic labels versus causal framing. Thus, causally framed patterning tasks would expand the scope of the observed effects beyond any limitations imposed by the potentially semantically describable nature of our stimuli.

Experiments 2 and 3 provided a preliminary suggestion that 4-year-olds did, in fact, draw broader generalizations from the data they observed. In the Reverse conditions of Experiments 2 and 3, 4-year-olds inferred that the wizard would be more likely to perform a transformation that resulted in an abstract difference along the same dimension of change—for example, "size"—than to produce a completely different kind of effect. This suggests that children learned more abstract information from the exemplars than simply the specific difference relation between the beginning and ending states of the events. However, the present findings are limited by the fact that children were not provided with the information or the opportunity to extend their generalizations to further transformations beyond the forced-choice they were given. Future research might provide children with systematic evidence for a causal-functional relation between a feature of the cause and a feature of the effect (e.g., the *number of times* a wizard waves her wand determines the *magnitude* of a size change). If children learn only the specific data provided in exemplars, then they will be unable to extrapolate or interpolate to new values. However, if they encode the abstract functional relation between the cause and its effect, they will be able to make novel causal predictions. Two studies that have investigated compositional reasoning in preschoolers (Piantadosi & Aslin, 2016) and noncausal function learning in adults (Jones, Schulz, Meder, & Ruggeri, 2018) begin to suggest that this may well be the case.

The present findings contribute not only to understanding the development of relational reasoning, but also to understanding the development of *causal* reasoning. Research on early causal learning has focused primarily on exploring children's ability to track statistical contingencies between causes and effects (for a review, see Gopnik & Wellman, 2012). By contrast, the present experiments offer insights into a separate, complementary route by which children learn from causal events. These findings suggest that children track not only the statistical frequency of causal outcomes, but also the *abstract form* of those outcomes in relation to the state of affairs that precedes them. Tracking the abstract forms of causes and effects may enable children to produce new hypotheses in situations with limited data (Magid, Sheskin, & Schulz, 2015); the forced-choice paradigms in Experiments 1–3 demonstrate that children can quickly learn this type of information to decide which of two possibilities is more likely. Future investigations might explore potential interactions between learning about the abstract forms of causes and effects and learning about the mechanisms that underlie them.

Finally, future research might also manipulate the extent to which the facilitative effect of causal framing on young children's relational reasoning might be due to reasoning about goals. One limitation of the present studies is that the causal transformations in the present study were the result of goal-directed actions by agents—the wizards. Although the present procedures did not specify any information regarding the wizards' psychological or social motivations for performing their transformations, anecdotally some children did provide justifications that involved the wizards' mental states (e.g., "She'll do that one next because she *wants* to"; "She'll do this because she *likes* it"). Given that children are highly sensitive to teleological information, agentic goals may be an especially powerful version of the causal framing manipulation (Kelemen, 1999). Moreover, there is some evidence that early causal inference can be particularly tied to goal-directed action (Bonawitz et al., 2010; Meltzoff et al., 2012). Further research will be necessary to disambiguate the potential relevance of agency and/or goal-directed causal intervention from a more general, facilitative effect of causal framing on relational reasoning. In particular, further research might investigate whether children would make the same inferences when a machine rather than a human caused the transformation.

Conclusion

Across four experiments with both causal versus noncausal stimuli, causal framing reliably facilitated young children's analogical transfer for novel relations in RMTS tasks. Further research will be required to better understand the nature of the representations that children learn in RMTS tasks (both causal and noncausal); however, causal framing may provide a uniquely promising avenue for future investigation into the development of relational reasoning skills. In the present experiments, the precise relations that children learned were determined entirely by the causal structure of an event. Unlike previous studies, the present experiments did not require linguistic labels or explicit prompts to compare, and yet the facilitative boost was on par with the boost provided by such sociolinguistic cues. Causal reasoning may be a route by which preverbal children can learn and use relational concepts.

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Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Appendix S1. Samples of Powerpoint stimuli (with experimenter audio) used in Experiments 2, 3, & 4.