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The early emergence and puzzling decline of relational reasoning: Effects of prior knowledge and search on inferring “same” and “different”

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Abstract

We explore the developmental trajectory and underlying mechanisms of relational reasoning. We describe a surprising developmental pattern: Younger learners are better than older ones at inferring abstract relations. Walker and Gopnik (2014) demonstrated that toddlers are able to infer the relations “same” and “different” in a causal system. However, these findings appear to contrast with the literature suggesting that older children have difficulty inferring these relations. Here we manipulate the data and children’s search procedure to assess the influence of these factors. In Experiment 1, we find that while younger children have no difficulty learning these relational concepts, older children fail to draw this abstract inference. In Experiment 2, we demonstrate that older children have learned the hypothesis that individual kinds of objects lead to effects. Finally, Experiment 3 indicates that including an explanation prompt during learning also improves performance. Findings are discussed in light of computational theories of learning.

Keywords: cognitive development, causal learning, relational reasoning, Bayesian inference.

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 (e.g., Gopnik & Wellman, 2012). But when and how can children learn abstract principles *about* causal structure? Higher-order generalizations, “framework theories” (Gopnik & Wellman, 1992), or “overhypotheses” (Goodman, 1955), provide the learner with information about the types of specific hypotheses that are likely to be true. Recent computational work suggests that these generalizations in turn might help children learn new specific causal relationships from perceptual data more quickly and accurately (e.g., Goodman, Ullman, & Tenenbaum, 2011). The ability to quickly learn abstract relations might explain how children acquire the impressive amount of causal knowledge evident in early “intuitive theories.”

Here we explore the mechanisms underlying the ability to infer a particularly fundamental abstract relation – the ‘sameness’ or ‘difference’ between objects. This type of reasoning is a particularly distinctive feature of human cognition – it has even been proposed to be a central dimension on which humans differ from other primates

(Penn, Holyoak, & Povinelli, 2008). Intuitively, it might seem plausible that these abstract, relational hypotheses 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 et al., 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 does not necessarily depend on extensive prior experience. In fact, recent research suggests that in some cases, younger children may actually be *better* at learning new abstract causal relations than older children and adults (Lucas, Bridgers, Griffiths, & Gopnik, 2014).

In the current paper, we examine children’s developing ability to infer an abstract causal principle – a relation between objects (i.e., “same” and “different”) causes an effect – from a limited set of observations. Walker and Gopnik (2014) demonstrated that toddlers (18-30-month-olds) are surprisingly adept at learning and using the relational concepts “same” and “different” in a causal relational match-to-sample (RMTS) task. Children were randomly assigned to *same* or *different* conditions, 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 specific causal properties.

However, Walker and Gopnik’s (2014) results contrast with a large body of research and a long-standing theory that active and explicit relational reasoning is a late developing ability (e.g., Gentner, 2010). In particular, preschool-aged children appear to have difficulty inferring abstract relational principles, and instead consistently demonstrate a bias to attend to individual object kinds (e.g., Christie & Gentner, 2014; Gentner & Medina, 1998). These

robust findings have led some to conclude that reasoning about relations depends on direct instruction, language, and other social input (e.g., Gentner, Anggoro, & Klibanoff, 2011). This type of experience has been proposed to explain the differences in relational reasoning abilities between human and non-human primates (e.g., Gentner, 2010).

How might we interpret this contrast? First, it is possible that older children failed to engage in 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. In Experiment 1, we therefore used exactly the same reasoning task as Walker and Gopnik (2014). In addition to replicating the earlier study with 18-30-month-olds, we also assessed relational reasoning performance in older children (ranging from 30-48-month-olds) using the same task. If the toddlers in Walker and Gopnik (2014) succeeded because of the particular methodological features of the task, then we would expect that older children would succeed as well.

There is at least one reason, however, why younger children might indeed genuinely outperform older children in learning these causal relational concepts. It may be that 3-year-olds have difficulty inferring such relations because they have learned a different overhypothesis namely, that individual kinds of objects, rather than relations between them, have causal powers. According to probabilistic models of cognitive development, learners search through a space of potential hypotheses and test them against the data (e.g., Gopnik & Wellman, 2012). To do this, learners combine two probabilities: the “prior” – the probability of a particular hypothesis before any data are observed, and the “likelihood” – the probability of the data given the hypothesis. Combining the two probabilities with Bayes rule produces the “posterior” – the probability of the hypothesis given the data. A learner can then compare the posteriors of different hypotheses, settling on the ones with the highest probabilities. Therefore, if the prior probability of one hypothesis is high, it will take stronger data to overturn it.

Having an overhypothesis, or general principle, leads the learner to assign a higher prior probability to particular types of specific hypotheses. As a result, the learner would need more evidence for a competing hypothesis than if they began with no prior expectations and instead assigned all possible hypotheses an equal prior probability (i.e., a “flat” prior). In other words, with increasing knowledge, learners develop a set of expectations that constrain the hypotheses they consider. This makes it more difficult to learn new information that is inconsistent with the general principles learners have already inferred (see Lucas et al., 2014).

A principle of simplicity such as the “Bayesian Occam’s razor” (Jefferys & Berger, 1992) would lead toddlers to prefer the relational hypothesis. The relational hypothesis proposes fewer causes to account for the data, and previous work demonstrates that young children show such simplicity preferences (Bonawitz & Lombrozo, 2012). However, if older children have learned the general

principle that individual object kinds are more likely to be causal, this may serve to constrain their interpretation of the data, leading them to privilege individual properties over relational ones, in spite of simplicity considerations.

In Experiment 2, we adapted the causal RMTS procedure to test the hypothesis that older children are able to reason about abstract relations, but have learned the overhypothesis that kinds of objects are more likely to be causal. Experiment 2 provided older children with explicit negative evidence that would lower the probability of an individual object kind hypothesis. By providing evidence *against* the individual cause hypothesis, 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.

Finally, in Experiment 3, we aim to scaffold the relational inference using a different mechanism. Rather than changing the data, we change the way that children search through the hypothesis space. In particular, previous work has demonstrated that asking children to explain patterns of events imposes top-down constraints on their search procedure, leading them to privilege more general and inductively rich hypotheses (e.g., Lombrozo, 2012; Walker, Lombrozo, Legare, & Gopnik, 2014; Walker, Williams, Lombrozo, & Gopnik, 2012). If preschool-aged children are already able to reason about relational properties, but assign a higher probability to individual object kind hypotheses, then introducing a prompt to explain may lead children to privilege abstract properties instead.

Across studies, we test the hypothesis that older children’s “failure” on traditional relational reasoning tasks is due to their increasing knowledge about the importance of individual object kinds, rather than to their inability to represent relations.

Experiment 1

Methods

Participants A total of 141 children participated in Experiment 1, 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 due to experimenter error or failure to complete the study.

Materials and Procedure The procedure for Experiment 1 was an exact replication of the procedure used in Experiment 2 of Walker and Gopnik (2014) (see Figure 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. The toy consisted of a 10- x 6- x 4-in. opaque white box that

appeared to play music when certain blocks were placed on top. The box contained a wireless doorbell that was 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 one more time and said, “Music! These ones made my toy play music!” Next, the experimenter took out a second pair of blocks in the opposite relation as the first pair. The experimenter placed these two blocks simultaneously on the machine, and the toy 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 machine 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.

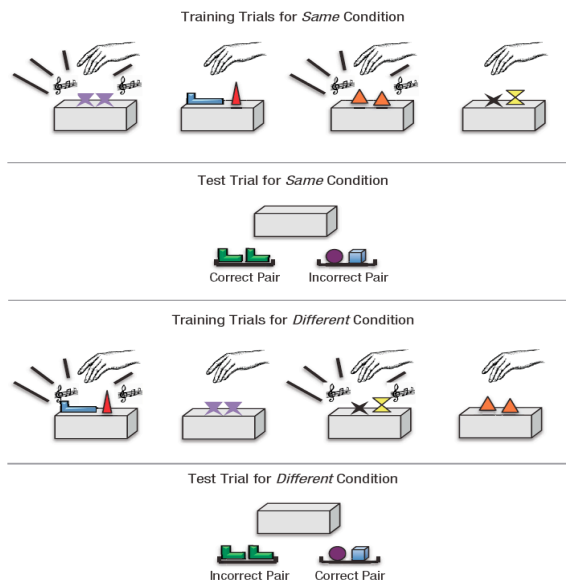


Figure 1: Schematic representation of training and test trials in the *same* and *different* conditions in Experiment 1.

The test phase began after all 4 pairs of blocks had been demonstrated on the machine. In both conditions, the child was given a choice between a novel same pair and a novel different pair to activate the machine herself. None of the objects in the test pairs had been observed on the machine during the training phase. The pairs of blocks children

observed on the machine 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 helping 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.

Results and Discussion

Replicating results reported by Walker and Gopnik (2014), 18-30-month-olds in Experiment 1 selected the test pair that was consistent with their training, in both *same* (78%), $p = .005$ (one-tailed binomial) and *different* (77%), $p = .009$ (one-tailed binomial) conditions. However, 3-year-olds failed to select the correct test pair in either *same* (46%), $p = .85$ or *different* (43%), $p = .57$ conditions (see Figure 2), with 18-30-month-olds outperforming 3-year-olds in both cases (*same*: $\chi^2(1) = 5.37$, $p = .02$; *different*: $\chi^2(1) = 5.99$, $p = .02$). 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, $p = .06$ (one-tailed binomial) and at chance (50%) in the *different* condition, $p = 1.0$.

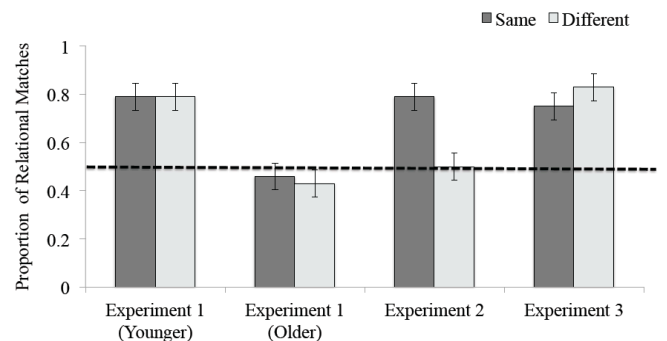


Figure 2: Proportion of correct relations selected for 3-year-olds following the manipulations in Experiments 1-3.

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 decline between 18 and 48 months, $\chi^2(N = 141, df = 1) = 3.88$ (Wald), $p < .05$

Experiment 2

Results of Experiment 1 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 hypothesized 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 in Experiment 2, we manipulated the data that children observed to provide direct evidence against the individual object kind principle. 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 1, with one 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.

Methods

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 (28 *same*, 28 *different*). An additional 4 participants were excluded for failure to complete the study.

Materials and Procedure Materials were identical to Experiment 1 and the procedure included the following changes. For each pair, the experimenter first placed each block on the machine *sequentially*, before placing them both on simultaneously (see Figure 3). 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 failed to activate the toy on its own). This was followed by a test phase, which was identical to Experiment 1.

Results and Discussion

Three-year-olds who were provided with negative evidence for the individual object kind hypothesis selected the correct relation significantly more often than chance (64%), $p = .045$ (exact binomial) (see Figure 2). However, this overall effect was entirely due to the improved performance of children in the *same* condition, in which 79% of children selected the correct pair, $p = .005$ (exact binomial). This performance was significantly better than children of the same age in the *same* condition in Experiment 1, $\chi^2(1) = 6.17$, $p = .01$, 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 (exact binomial), leading to a significant difference between *same* and *different* conditions, $\chi^2(1) = 4.98$, $p = .03$.

How might we explain this emerging asymmetry between the "same" and "different" conditions in older children? If 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, 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. 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 kinds of block are placed on the toy (i.e., when there is only one potential activator). In other words, given that 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 hypothesis than the data in the "different" condition. We intend to test this hypothesis in future work.

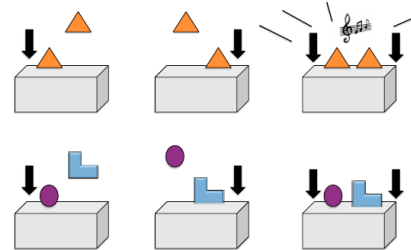


Figure 3: Schematic representation of two (of four) training trials in the *same* condition.

Experiment 3

In Experiment 3, we examined whether we could induce relational reasoning another way – by introducing a prompt to explain during 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. We hypothesized that generating an explanation may motivate a different search procedure, increasing the chance that children will accept the relational hypothesis.

Methods

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.

Materials and Procedure The procedure for Experiment 3 was nearly identical to Experiment 1 (see Figure 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 do you think these ones made/did not make my toy play music?” In the *report* condition, the experimenter asked, “What happened to my toy when I put these ones on it? Did it play music?” (prompting a yes/no response).

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%), $p = .007$ (exact binomial) (see Figure 2). Children in the *report* condition did not differ from chance (42%), $p = .54$, and there was a significant difference between *explain* and *report* conditions, $p = .017$. Unlike in Experiment 2, there was no significant overall difference between *same* (58%) and *different* (63%) relations, $p = .76$. 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 1, reveals no significant difference, $\chi^2(1) = 0.02$, $p = .88$, while 3- and 4-year-olds in the *report* condition performed significantly worse than the 18-30-month-olds, $\chi^2(1) = 9.0$, $p = .003$, and no differently from the 3-year-olds in Experiment 1, $\chi^2(1) = 0.06$, $p = .81$, replicating the pattern in Experiment 1.

General Discussion

Across three experiments, we assessed the influence of both the data that children observed (Experiments 1 and 2), as well as their search procedure (Experiment 3) on their relational reasoning ability. In Experiment 1, we replicated the finding that 18-30-month-olds are able to infer the relations “same” and “different” from very little data in a causal task. We also 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. Instead, we found evidence for a genuine decline 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: 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 the same and different conditions. This is consistent with previous work indicating that explaining prompts generalization 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. First, these results indicate that relational reasoning is not a late developing ability, as has been previously proposed (e.g., Christie & Gentner, 2010, 2014; Gentner, 2010). Instead, toddlers are able to infer the relational causal principles “same” and “different” from just a few pieces of evidence, and act based on this inference. These abilities are in place early – emerging spontaneously only a few months after the ability to learn specific causal properties. Although older children often fail to infer the relational hypothesis, this failure can be explained by appealing to the role of prior knowledge in constraining their judgments.

The earlier literature invoked a “relational shift” in the preschool period and attributed this to a number of factors, including an increase in relational knowledge (Gentner & Ratterman, 1991), exposure to relational language (Christie & Gentner, 2014), and various maturational variables (Halford, 1992; Thibaut, French, & Vezneva, 2010). While we agree that relations are learned through experience, we propose that this learning occurs much earlier, and need not proceed from local properties to more abstract ones. Our results 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 (e.g., Karmiloff-Smith & Inhelder, 1974-1975).

These findings are also relevant to the broader evolution of relational reasoning (Penn et al., 2008) and causal cognition in general. There is an ongoing debate in the comparative literature regarding whether differences in relational reasoning indicate a qualitative difference, or merely a quantitative gap (see Penn et al., 2008). The fact that very young human children already show the relational reasoning advantage, with no explicit prompting or cultural tutelage, may indicate that this is indeed a significant phylogenetic difference. Although it is possible that the younger children’s success is due to the use of a perceptual heuristic, as has been suggested for nonhuman primates (e.g., Wasserman et al., 2001), several features of the study design weigh against this possibility: children saw pairs of objects (rather than multi-element displays), they observed only two positive and two negative trials, they never acted on an object, and their behavior was never reinforced. Indeed, no other species has come close to demonstrating the first-trial performance of these human children after so few observations (see Penn et al., 2008).

Finally, these results are consistent with other cases in which younger children are more flexible learners than older ones (Defeyter & German, 2003; Lucas et al., 2014; Seiver et al., 2013). The very fact that children know less to begin with may, paradoxically, make them better (or at least more flexible) learners. In Bayesian terms, this flexibility results from a “flatter” initial prior. 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 conclusions when a new situation is consistent with their past experiences. However, experience can also be a double-edged sword – occasionally leading learners away from the correct hypothesis.

However, this flexibility may also reflect different search procedures, as well as different kinds of prior knowledge. In Experiment 3, asking children to explain the data led to better performance. There may therefore be a general shift from broader to narrower search procedures as children grow older, independent of their specific knowledge. Developmental differences in both prior knowledge and search procedures may help to explain why very young children are such extraordinarily powerful learners.

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