Developmental Science

Developmental Science 12:1 (2009), pp 114–122 DOI: 10.1111/j.1467-7687.2008.00738.x

PAPER

What makes relational reasoning smart? Revisiting the perceptual-to-relational shift in the development of generalization

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Abstract

Development of reasoning is often depicted as involving increasing use of relational similarities and decreasing use of perceptual similarities ('the perceptual-to-relational shift'). We argue that this shift is a special case of a broader developmental trend: increasing sensitivity to the predictive accuracy of different similarity types. To test this hypothesis, we asked participants (3-, 4-, 5-year-olds and adults) to generalize novel information on two types of problems – offspring problems, where relational matches yield accurate generalizations, and prey problems, where perceptual matches yield accurate generalizations. On offspring problems, we replicated prior findings of increasing relational matches with age. However, we observed decreasing relational matches on prey problems. Provided feedback on their responses, 3-year-olds showed the same trend. Findings suggest that the relational shift commonly observed in categorization and analogical reasoning may reflect a general increase in children's sensitivity to cue validity rather than an overall preference to generalize over perceptual similarity.

Introduction

A hallmark of human intelligence is the ability to generalize flexibly over different types of similarity (Gentner, 2003). Two types of similarity are clearly important: *perceptual similarity*, degree of overlap in perceptual features; and *relational similarity*, degree of overlap in common roles (Medin, Goldstone & Gentner, 1993). In some situations, generalizing over *features of individual entities* is important. For example, given the relation between fins and ocean living, the fact that dolphins and swordfish both have fins suggests that they, unlike bears, live in the ocean. Sometimes different patterns of generalization are warranted, based on *relations among different entities*. For example, given the relation between mammals and nursing, the fact that both dolphins and bears are mammals suggests that they, unlike swordfish, nurse their young. Although generalization by either type of similarity alone has been found in animals and human infants (Marcus, Vinjayan, Bandi Rao & Vishton, 1999; Hauser, Weiss & Marcus, 2002; Shepard, 1987; but see Cohen, 2003; Thompson & Oden, 2000), whether children can ignore perceptual similarities and generalize over opposing relational similarities is at the heart of a lively debate in cognitive development (Gelman, 2003; Gentner & Toupin, 1986; Goswami, 1992; Opfer & Bulloch, 2007; Sloutsky & Fisher, 2004).

Evidence from category-based induction, where children's categories often map onto shared taxonomic, functional, and social relations more closely than onto perceptual similarities, indicates that young children can generalize over common relations rather than just common features (Brown & Kane, 1988; Goswami, 1995; Opfer & Siegler, 2004; Springer, 2001). For example, 5-year-olds generalized properties to a bat-like bird from a flamingo (same relation, different features) rather than from a bat (different relation, similar features) (Gelman & Markman, 1986). On the other hand, reports of children's early ability to ignore perceptual similarity have also been challenged. Preschoolers' apparent use of taxonomic relations in categorization might be explained instead as reflecting differential weighting of exemplar features (Jones & Smith, 1993), or stemming from feature–feature correlations (McClelland & Rogers, 2003; Rakison, 2000; Rakison & Hahn, 2004), or even from preschoolers' treatment of taxonomic labels as perceptual features (Sloutsky & Fisher, 2004).

Evidence regarding the development of children's analogies has invited a similar debate. While there is widespread agreement that toddlers can make analogies as early as they represent relevant relations (Gentner & Rattermann, 1991; Goswami, 1996), it is unclear whether generalization over irrelevant perceptual similarities is a necessary step in the development of analogical reasoning (Rattermann & Gentner, 1998) or merely a performance factor (Goswami, 1996). This issue is important because the idea that children's generalization undergoes a perceptual-to-relational shift has had a long

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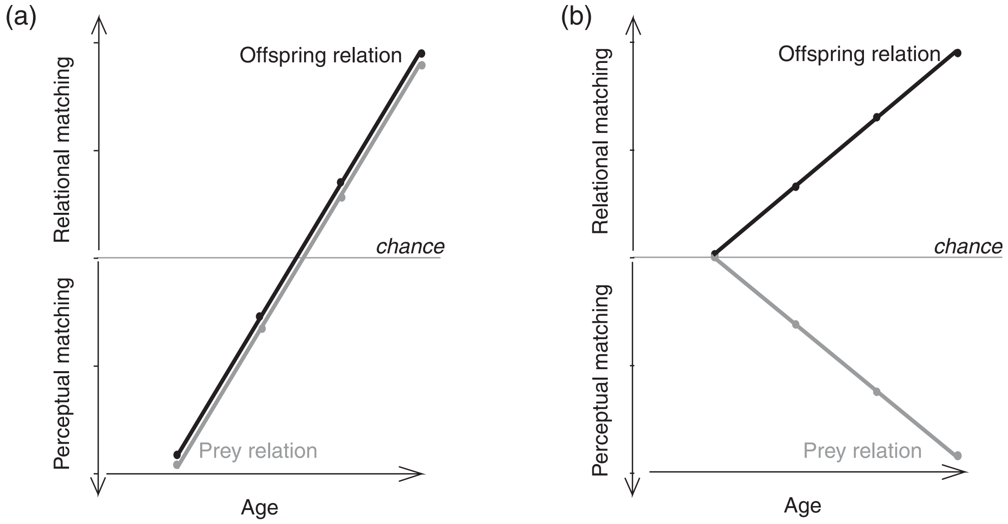


Figure 1 *Illustration of hypothetical developmental trajectories on problems where perceptual and relational similarities conflict. Panel A depicts a perceptual-to-relational shift across relations. Panel B depicts increasing sensitivity to reliability of different relations.*

tradition in developmental psychology (e.g. Vygotsky, 1962; Quine, 1977; Keil, 1989; Keil & Batterman, 1984; Gentner, 1988, 2003; Ratterman & Gentner, 1989), and although accounts differ in claims about domain-specificity, the notion that perceptual matching is the initial default in children's reasoning (Keil's 'Original Sim') is widely shared.

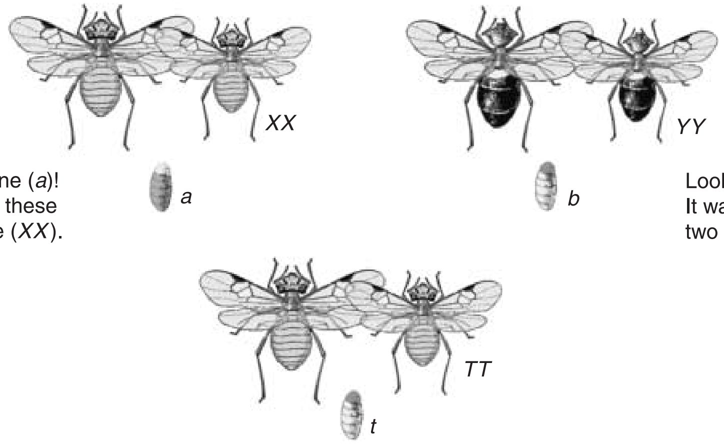
In this paper, we propose an alternative perspective on the roles of perceptual and relational similarity in the development of generalization. Rather than development proceeding from generalizations over perceptual similarities to generalizations over relational similarities (Figure 1a), the dominant developmental pattern is towards generalizing over highly predictive similarities, regardless of whether the similarities are perceptual or relational (Figure 1b). Within this latter view, the important developmental question is not *when* children learn to ignore irrelevant perceptual similarities in favor of relational ones, but how children learn the *contexts* in which they should ignore irrelevant perceptual similarities *and* irrelevant relational similarities. Moreover, if our account is correct, it has interesting implications for problems where perceptual and relational similarities conflict. Specifically, it predicts *increasing* use of relational matches with age for relations that reliably predict novel properties and *decreasing* use of relational matches with age for relations that do not reliably predict novel properties.

To examine this issue, we gave participants (3-, 4-, 5-year-olds and adults) two problem types (offspring/prey) to diagnose whether they used relational or perceptual similarity when generalizing information (category-membership, novel properties, and future appearances) to unlabeled targets (juvenile insects). For each problem, perceptual and relational similarity differed in predictive accuracy. On offspring problems, relational similarity had high cue validity (i.e. juveniles with the same parents were the same kind); on prey problems, perceptual similarity had high cue validity (i.e. juveniles that looked the same were the same kind). In Experiment 1, children were given no feedback so we could assess development of prior knowledge about the predictive accuracy of perceptual and relational similarities across problem types; in Experiment 2, we provided youngest children with feedback on their answers, such that they would maximize positive feedback by differentially matching by common relations or common features, to examine trial-to-trial changes in relational matching.

Cue validity and choice of similarity

Central to our account is the assumption that children's sensitivity to relevant information increases with age (Siegler, 1981). For example, on balance scale problems, most 5-year-olds predict that the side of the balance scale with greater weight will fall regardless of distance from fulcrum; more importantly, they fail even to encode distance of weights from the fulcrum, thereby failing to reproduce distance information when asked to recall the problems they encountered (Siegler, 1976; on boundary conditions, see Feretti & Butterfield, 1986, and Jansen & van der Maas, 2001). Older children, in contrast, do encode information about distance from the fulcrum, but they fail to integrate this information appropriately.

Another developmental difference in sensitivity to relevant dimensions is seen across a wide range of tasks that pit one dimension against another. On number conservation tasks (Piaget, 1952), young children ignore the (relevant) density of the objects in a row in favor of the (irrelevant) length of a row. On shadow-projection tasks (Inhelder & Piaget, 1958), young children ignore the



Look at this one (*a*)!
It was born to these
two bugs here (*XX*).

Look at this one (*b*)!
It was born to these
two bugs here (*YY*).

These two bugs (*TT*)
gave birth to this one
here (*t*).

Figure 2 *Offspring problem. Similarity (*TT, XX*) has high cue validity. Accuracy is maximized by selecting relational matches.*

(relevant) distance of the object from the light source in favor of the (irrelevant) span of the bar. On probability tasks (Piaget & Inhelder, 1951), young children ignore the (relevant) number of undesired colored marbles in favor of the (irrelevant) number of desired marbles. Across these tasks, young children's answers were sensible given that the dominant dimensions tended to be those that maximized accuracy on the tasks that they ordinarily faced (i.e. where dominant and subordinate dimensions were not put into conflict by creative experimenters). However, older children provided better responses – not because of an overarching weight-to-distance, length-to-density, bar span-to-distance to light source, or desired-to-undesired shift – but because they knew when to switch from commonly predictive to less commonly predictive dimensions. Consistent with this interpretation, children typically adopt premastery strategies in order of predictive accuracy (Siegler, 1983).

This same analysis can be applied to the 'career of similarity' in development of analogical reasoning and category-based induction. For the same reasons that young children attend initially to weight on balance scale tasks (or length of row on number conservation tasks), their choice of perceptual matches in analogy tasks and surface similarities in category induction tasks may reflect use of information that, although generally highly predictive, is less so on problems that pit (unreliable) perceptual similarities against (reliable) relational similarities. What distinguishes older children from younger children on these tasks, in this view, is simply their sensitivity to the situational reliability of less commonly predictive information (i.e. relational and taxonomic similarities). Moreover, this same principle can also explain why perceptual similarities with low inductive potential are given low weight by children when generalizing novel properties (Gelman & Coley, 1991) and why relational similarities that license almost no generalizations, such as *can be taken out of a burning house*, are seldom used by children of any age (Barsalou, 1985).

The most direct implication of this analysis is that *when* the perceptual-to-relational shift occurs – like *when* the acquisition of conservation concepts occurs – should vary greatly depending on the relation in question, with highly predictive relations showing the earliest resistance to overshadowing by perceptual similarities. Research on development of analogical reasoning has demonstrated this point elegantly. For example, in children's early experience, the father/mother/baby relation predicts many novel facts, which 3- to 5-year-olds can map onto novel transitive relations (Goswami, 1992, 1995; for a simulation of this finding, see Leech, Mareschal & Cooper, in press). For relations that less reliably predict new facts in young children's experience, relational reasoning appears much later, sometimes at age 8 (Rattermann & Gentner, 1998), sometimes in college (Sternberg & Nigro, 1980; Sternberg & Downing, 1982). In category-induction, too, 5- and 6-year-olds can ignore perceptual similarity and use highly predictive relational information (e.g. parent/offspring) (Opfer & Bulloch, 2007). What has been left unclear across all these studies, however, is how children learn to make adaptive choices of similarity over the course of development.

The present studies

We sought to test our hypothesis about the development of generalization by examining children's use of relational and perceptual similarity on two perceptually identical problems: offspring problems, which could be solved accurately using relational matches, and prey problems, which could be solved accurately using perceptual matches. For offspring problems (Figure 2),

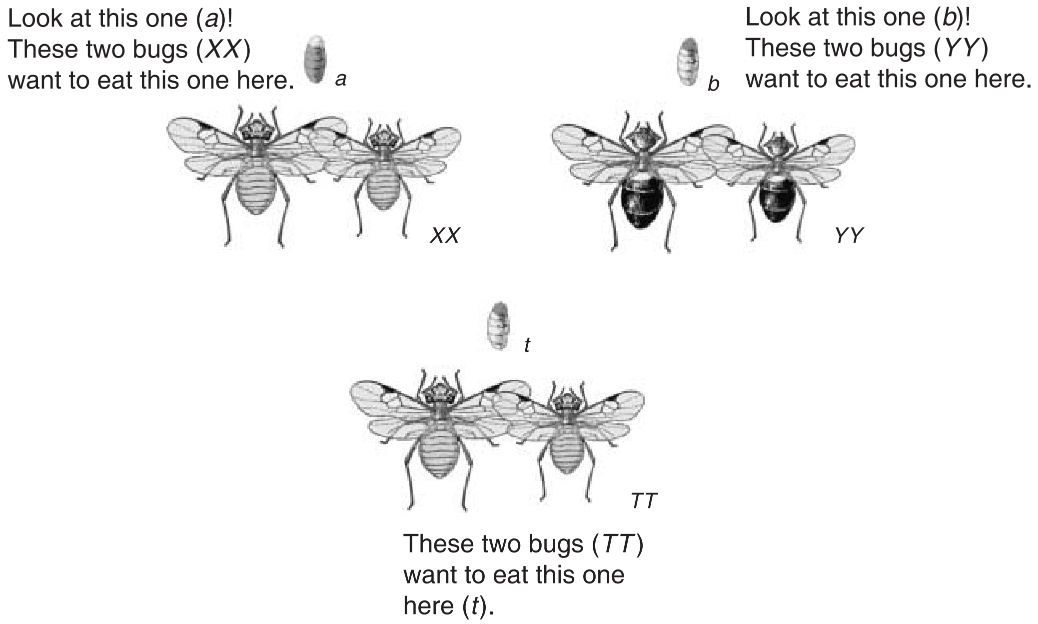


Figure 3 *Prey problem. Similarity (*t, b*) has high cue validity. Accuracy is maximized by selecting perceptual matches.*

the relational matches (i.e. juveniles that shared the *offspring-of* relation to adults-*TT* and -*XX*) provided the most reliably accurate choice because the identity of a juvenile generally can be determined by the identity of its parents; thus, offspring of the same parents (juveniles-*t* and -*a*) share category membership despite juveniles-*t* and -*a* having different perceptual features. For prey problems (Figure 3), however, relational matches (i.e. juveniles that shared the *prey-of* relation to adults-*TT* and -*XX*) provided the less accurate choice because the identity of juveniles generally cannot be determined by the identity of its predators; thus, matching juveniles by shared perceptual features would provide the most accurate approach for identifying their category membership.

These two types of problems invite competing predictions from the perceptual-to-relational shift hypothesis and our cue validity hypothesis. Specifically, the perceptual-to-relational shift hypothesis predicts that young children initially use perceptual similarity to generalize from exemplars to targets; with age and experience, older children use perceptual and relational similarity on both types of problems. In contrast, our cue validity hypothesis predicts that relational matching *increases* with age and experience on offspring problems (where relational similarity is most reliable) and relational matching *decreases* with age and experience on prey problems (where perceptual similarity is most reliable). We tested these two competing predictions in Experiment 1, where we examined age differences in generalization, and in Experiment 2, where we examined trial-to-trial differences in generalization as children gained information about the accuracy of their choices.

Experiment 1

Method

Participants

Participants comprised 31 undergraduates (mean age = 20.8 years), 32 5-year-olds (mean age = 5.4 years; 11 girls and 21 boys), 32 4-year-olds (mean age = 4.5 years; 12 girls and 20 boys), and 32 3-year-olds (mean age = 3.6 years; 19 girls and 13 boys). One undergraduate was eliminated due to failure to complete the task.

Stimuli and procedure

A computer presented participants with illustrations of juvenile and adult insects (see Figures 2 and 3 for stimuli layout), with scripts presented by prerecorded audio to prevent experimenter bias. Perceptual similarities among stimuli presented in a single trial were varied within subjects and counterbalanced from trial to trial using the same Latin-square design in both conditions. Juvenile insects had six segments, colored either dark or light. Adult insects had six segments (antennae, head, thorax, wings, legs and abdomen), each of which could take five possible forms. The relative similarity of the adults ($Sim[XX,TT]/Sim[XX,TT] + Sim[YY,TT]$; adult similarity) was never equal to the relative similarity of the juveniles ($Sim[a,t]/Sim[a,t] + Sim[b,t]$; juvenile similarity). That is, if juvenile-*a* were 100% similar to juvenile-*t*, then adult insects-*XX* were 0% similar to adult insects-*TT*. Thus, on any given trial, we could determine whether participants used juvenile or adult insect similarity to solve the problems.

Individuals received either offspring or prey problems, as described previously and displayed in Figures 2 and 3. For every question, juvenile-*a* appeared first with accompanying auditory stimuli ('Look at this one!'); next, adults-*XX* appeared, forming a triad with juvenile-*a* (offspring condition: 'These two bugs gave birth to this one here'/prey condition: 'These two bugs want to eat this one here'). Juvenile-*b* next appeared ('Look at this one!'), followed by adults-*YY* to complete the second third of the triad (offspring condition: 'These two bugs gave birth to this one here'/prey condition: 'These two bugs want to eat this one here'). Finally adults-*TT* (offspring condition: 'These two bugs gave birth to . . .'/prey condition: 'These two bugs want to eat . . .') and juvenile-*t* ('this one here') completed the triad. On each of eight trials, participants were asked three questions about juvenile-*t*: the target – whether the target was the same kind as juvenile-*a* or *b* (categorization), whether it would look like juvenile-*a* or *b* in the future (projection), and whether it had a property (*golgi*) inside its blood similar to juvenile-*a* or *b* (induction). Participants were instructed to answer by pointing to the left or right side of the computer screen.

Results

We first examined the proportion of relational matches for each of the three questions independently. Across all conditions, trials, and age groups, the proportion of relational matches did not differ by question (*p*s > .10); therefore, we collapsed the three items into one summary measure of relational matching. Subsequent analyses were performed on proportion of relational matches over four trials, and post-hoc comparisons were performed using Fisher's PLSD unless otherwise indicated. Results are depicted in Figure 4 and Table 1.

To determine whether there was a developmental trend in our findings, we first performed a 2 (condition: offspring, prey) × 4 (age: 3-, 4-, 5-year-olds and adults) repeated-measures ANOVA on proportion of relational matches. As expected, there was a main effect of condition, indicating that relational matching was more frequent when juveniles were in the role of offspring rather than prey, $F(1, 119) = 71.16$, $p < .0001$. Further, the overall proportion of relational matches *decreased* with age, $F(3, 119) = 5.10$, $p < .01$. Finally, age and condition produced interactive effects on relational matching, $F(3, 119) = 14.83$, $p < .0001$. To examine this interaction further, we analyzed relational matching in each condition separately.

On offspring problems, where juvenile insects were in the role of offspring, relational matching *increased* with age, $F(3, 62) = 2.92$, $p < .05$. Post-hoc analysis indicated that adults and 5-year-olds were more likely than 3-year-olds to generalize using relational matches (*p*s < .05). Further, one-group *t*-tests indicated that all age groups were more likely to generalize to relational matches than expected by chance (*p*s < .05).

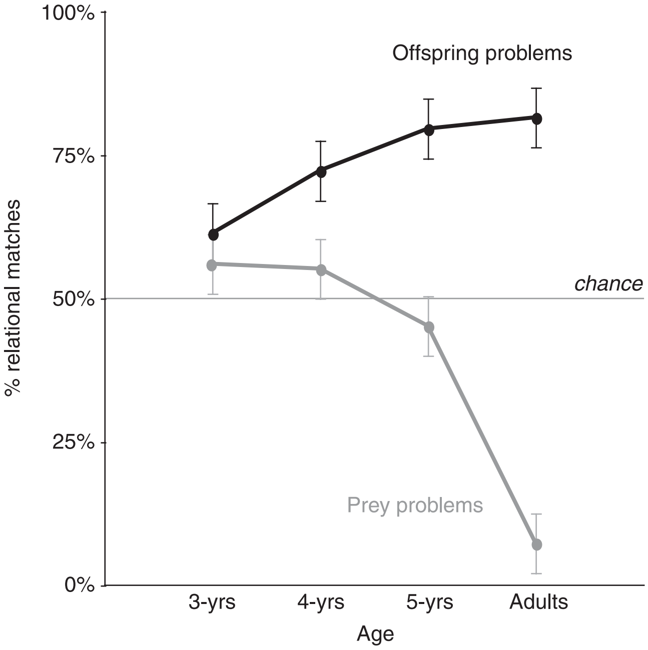


Figure 4 *Developmental trend in relational matches. In offspring problems, relational matches increased with age,* F*(3, 62) = 2.92,* p *< .05; in prey problems, relational matches decreased with age* F*(3, 63) = 16.58,* p *= .0001).*

Table 1 *Relational matching by problem type and age*

	Mean	Standard deviation
Offspring problems		
Adults	81.42%	22.32
5-year-olds	79.47%	23.28
4-year-olds	72.13%	18.04
3-year-olds	61.25%	20.84
Prey problems		
Adults	7.23%	17.85
5-year-olds	45.02%	23.48
4-year-olds	55.08%	26.99
3-year-olds	55.92%	20.76

On prey problems, where juvenile insects were in the role of prey, relational matching *decreased* with age, $F(3, 63) = 16.58$, $p < .0001$, with children more likely to generalize over relational matches than adults (*p*s < .0001). Further, only adults were less likely than expected by chance to generalize to relational matches, $t(15) = 9.59$, $p < .0001$.

Experiment 2

In Experiment 1, we found increases and decreases in relational matching, depending on whether the juvenile insects played the offspring or prey role in the relation. We hypothesized that this pattern would emerge over development as children learned that the parent–offspring relation predicts category membership, whereas the predator–prey relation does not. To test this hypothesis more directly, we provided feedback to 3-year-olds according to this rule, and observed its impact on generalization patterns of 3-year-olds, whose answers in Experiment 1 did not differ by problem type (offspring vs. prey). If the overall developmental trend in Experiment 1 reflected the learning history of children, we reasoned that a similar trend would emerge as young children learned about the predictive accuracy of the two different relations for generalization. Furthermore, we could compare the results of Experiment 2 to prior analogy tasks (e.g. Gentner & Rattermann, 1991), which typically provide children with feedback as well. Finally, as a follow-up to this learning study, we tested the same children's generalization at a later date to examine the durability of the experimentally induced developmental change.

Method

Participants

Participants comprised 16 3-year-olds (mean age = 3.79 years; eight girls and eight boys).

Stimuli and procedure

Children participated in a feedback phase when they received feedback on their responses and a retention phase, two days later, when they were retested without feedback. As a point of comparison, data from 3-year-olds in Experiment 1 were included as pretest data in Experiment 2.

Stimuli and procedure were identical to that of Experiment 1 except that feedback was provided following every response. For correct responses, the experimenter said, 'That's right. That one is the same kind as that one', and pointed at the target and appropriate exemplar. For incorrect responses, the experimenter said, 'Actually, that's not right. That one is the same kind as that one', and pointed at the correct target and appropriate exemplar. Participants were not told why the exemplar/target match was correct. In the retention phase, two days following the feedback phase, the experimenter returned and tested the same 16 3-year-old children on the same conditions that they previously viewed in the feedback phase. This testing was done without feedback.

Results

To determine if a similar developmental trajectory occurred when 3-year-olds were provided with feedback on their answers, we first performed a 2 (condition: offspring, prey) × 2 (test phase: pretest, feedback/retention) ANOVA on proportion of relational matches (Figure 5). As in Experiment 1, relational matching was more frequent when juveniles were in the role of offspring rather than prey, *F*(1, 44) = 18.48, *p* < .0001. More importantly, problem and test phase produced interactive effects on relational matching, indicating that young children learned the predictive accuracy of the two different relations for generalizing category judgments, *F*(1, 44) = 11.63, *p* < .001. To test this interpretation, we examined performance in the feedback/retention phase separately.

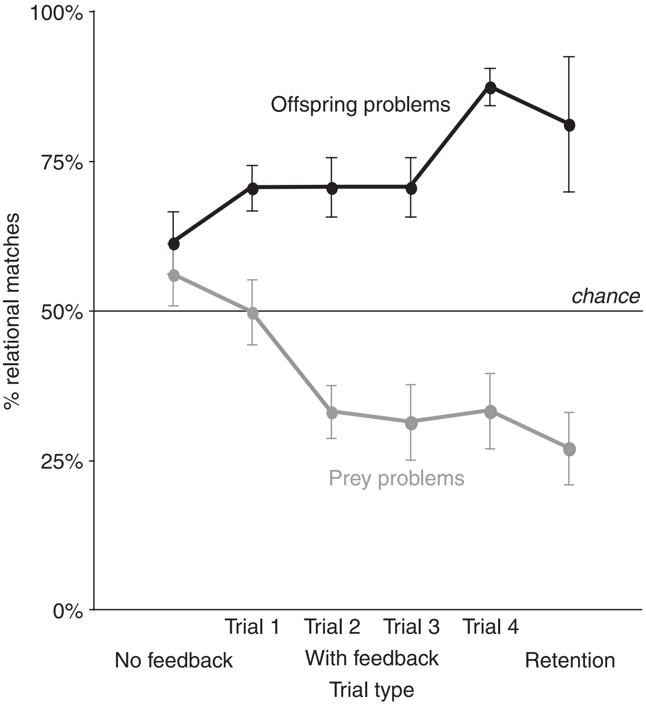


Figure 5 *Trial-to-trial changes in 3-year-olds' relational matching.*

Like older children and adults in Experiment 1, 3-year-olds' relational matching in the feedback phase differed by problem type, *F*(1, 14) = 12.13, *p* < .01, with relational matching occurring more frequently on offspring (*M* = 74%) than on prey problems (*M* = 36%). Most of the differences between 3-year-olds' relational matching in Experiments 1 and 2 occurred as a result of learning after the first trial of feedback. After this point, relational matching did not increase, *F*(3, 42) = 0.48, *p* = *ns*. Further, 3-year-olds' relational matching remained flexible in the retention phase, when they again chose relational matching much more for offspring than prey problems, *F*(1, 14) = 28.16, *p* < .0001.

Discussion

The purpose of this paper was to examine the generality of the 'perceptual-to-relational shift' across relations that differed in their reliability as predictors of category membership. For the parent–offspring relation, where identity of adults predicted category membership of juveniles, we replicated the previously observed perceptual-to-relational shift. In contrast, for the predator–prey relation, where identity of adults did not predict category membership of juveniles, we found that relational matches *decreased* with age. Further, when 3-year-olds were provided with feedback on their judgments, a similar trend emerged from trial to trial, i.e. *increasing* relational matches for problems involving a parent–offspring relation and *decreasing* relational matches for problems involving a predator–prey relation.

These experiments do not provide support for a universal perceptual-to-relational shift. Children in our study did not use perceptual similarity overall and then abruptly shift to using relational similarity overall – neither as they aged nor as they acquired feedback. In our view, these findings raise questions about theories of relational development that posit the primacy of perceptual similarity in situations where children recognize relations and percepts to conflict. If perceptual similarity were the default mode of generalization, we should have seen a high rate of perceptual matching among 3- and 4-year-olds regardless of condition. In fact, their overall rate of perceptual matching was lower than adults, and even the youngest children were more likely than not to make relational matches in the offspring condition (cf. Goswami, 1992). Moreover, if relational similarity were the preferred developmental endpoint, we should have seen older children and adults making relational matches more often in both the offspring and prey conditions. However, we instead observed adults and older children making perceptual matches more often in the prey condition, but not in the offspring condition. These results highlight the susceptibility of young children to irrelevant similarities overall, but argue against the primacy of mechanisms that focus attention on just irrelevant perceptual similarities (Keil, 1995; Keil & Batterman, 1984; Gentner, 1988; Rattermann & Gentner, 1998).

Far from requiring that we assume a context-general perceptual-to-relational shift, our pattern of results can be understood instead from the assumption that relational matches are just one possible developmental endpoint that typically ends with high rates of overall accuracy. In this account, children in Experiments 1 and 2 learned to maximize accuracy by using the relevant similarity for each type of problem. This account differs from the perceptual-to-relational shift account in accurately predicting that young children's initial rate of perceptual matching would be even lower than adults' when solving prey problems. Also consistent with this account, feedback led to 3-year-olds in Experiment 2 quickly learning to generalize over perceptual and relational similarities as the context required. This fast learning was also quite durable, with 3-year-olds retaining their new knowledge about relevant similarities when tested at a later date. Thus, our learning study in Experiment 2 replicated both the perceptual-to-relational shift and the relational-to-perceptual shift observed in Experiment 1.

One possible objection to our account is that the relational shift we found was not as dramatic as might be expected. We suggest that the relational shift that occurred over time in Experiment 1 was not pronounced because children came to our task knowing the value of the parent–offspring relation. Origin relationships are generally important to young children, and they have a certain amount of expertise in these, particularly in contrast to predatory relationships. Indeed, previous work on analogy (Gentner & Rattermann, 1998; Goswami, 1995; Goswami & Pauen, 2005) demonstrated that the 'Father, Mother, Baby' triad provided a good analogy for 3- to 5-year old children to solve a variety of problems. Further research into acquisition of cue knowledge would be highly valuable, particularly using other relations.

Our explanation of the perceptual-to-relational shift as a function of sensitivity to cue validity points to an integration of statistical and symbolic approaches (which seem necessary for analogical reasoning) in understanding the development of generalization. Within this account, it is entirely possible (as in the present studies) for children to fail to generalize over relations that they represent merely because they fail to realize that the relation is a reliable predictor of the property, name, or category that they are asked to induce. Computational approaches to such developmental phenomena might be profitably modeled by cognitive architectures such as DORA (Doumas & Hummell, 2005; Doumas, Hummel & Sandhofer, submitted), which is able to discover new relations on the basis of observation alone. In our view, an architecture that is capable of discovering relations from distributional information is, at least in principle, also capable of tracking which relations are and are not reliable for making analogical inferences, and thus to accommodate the relational-to-perceptual shift that we observed in Experiments 1 and 2, as well as the perceptual-to-relational shift commonly highlighted in the developmental literature.

In conclusion, we think that what makes humans so smart is not just the ability to shift from generalizing over common features to generalizing over common roles. Instead, the flexibility of cognition that makes human cognition so adaptive – that allows us to classify dolphins as perceptually similar to swordfish but biologically similar to bears, or to draw analogies when they are warranted and to ignore them when they are not – is an increased sensitivity to different types of similarities (concrete as well as abstract) as reliable predictors of novel properties. This adaptive flexibility is not always evident in young children, but often these failures may reflect an insufficient base of knowledge about which type of information to use rather than any inherent bias toward perceptual over relational similarity.

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Received: 3 May 2007
Accepted: 18 December 2007