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Similarity and the development of rules

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Abstract

Similarity-based and rule-based accounts of cognition are often portrayed as opposing accounts. In this paper we suggest that in learning and development, the *process of comparison* can act as a bridge between similarity-based and rule-based processing. We suggest that comparison involves a process of structural alignment and mapping between two representations. This kind of structure-sensitive comparison process – which may be triggered either by experiential or symbolic juxtapositions – has a twofold significance for cognitive development. First, as a learning mechanism, comparison facilitates the grasp of structural commonalities and the abstraction of rules; and, second, as a mechanism for the application and extension of previously acquired knowledge, comparison processes facilitate the application of abstract knowledge to new instances. © 1998 Elsevier Science B.V.

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> We are **far** cleverer than anybody else, and that we are cries out for explanation.
> (Fodor, 1994).

1. Introduction

Adult humans are formidable thinkers. We routinely carry out feats of abstract reasoning that are beyond the capabilities of other species. And as Rips (1994), notes, ‘much of the deductive work that we carry out from day to day consists of... ‘steps so routine that they seem not to require deduction at all.’ For example, when given two options, we know that if we reject one, we are committed to the other; and this reasoning appears to us so natural that we are not aware of invoking the abstract inference schema of modus tollendo ponens (P or Q, not P; therefore Q). Yet, as

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Fodor (1990) has pointed out, our ability to reason across contexts in a content-independent way is, or should be, deeply puzzling. How do these abstract cognitive abilities develop?

Accounts of the development of abstract thought can be grouped into four broad categories. According to the empiricist tradition, abstract cognition evolves through experiential learning and complex ideas are compounded out of simple ideas. Behaviorism, the heir to empiricism in this century, proposed the mechanisms of association and stimulus generalization to explain learning. However, its refusal to deal with mental representations and its reliance on purely perceptual similarity restricted this account to only the most rudimentary forms of learning. A second approach is Piagetian constructivism, which postulates increasingly complex mental representations learned through the child's own interactions with the experiential world (Piaget, 1951). A third, related approach was Vygotsky's (1962, 1987) theory of the social formation of mind: that abstract cognition develops through interaction with cultural and linguistic systems. The theories of Piaget and Vygotsky offered a richer and more appealing view of cognitive development, but the processes by which learning occurs – assimilation, accommodation, acculturation, internalization – are not closely defined. The inadequacy of learning mechanisms powerful enough to explain the development of abstract cognition was all the more apparent in light of increasingly persuasive evidence of the sophistication and generativity of human cognition and language. Cognitive developmental research such as Gelman's (1990) findings on early number concepts and Spelke's (1988, 1990) and Baillargeon's (1987) research on infants' knowledge of objects was revealing early capabilities far beyond what had been envisioned. This gap lent force to an extremely influential fourth view: that higher-level cognition is guided by innate constraints. The strong nativist approach postulates that the mind comes endowed with abstract principles, though perhaps in nascent form. In strong versions, development is seen as the maturation or unfolding of innate potentialities, with learning playing a distinctly minor role.

The fortunes of similarity as an explanation of development have risen and fallen with these tides. (Although we have laid these out historically, all four views exist in various degrees in current theorizing.) In behaviorist approaches, similarity is a major engine of learning. However, because similarity is conceived of narrowly as stimulus and response generalization, its success in this arena does little to address issues of abstract thought. Perhaps as a reaction to the simplistic reliance on perceptual similarity in behaviorist accounts, similarity has been relegated to a minor role in most current accounts of intellectual development. Similarity is seen as a distraction from the important principles, or at best as a fallback when theory fails. There are exceptions, of course: similarity figures in many information-processing views (e.g. Klahr, 1984; Siegler, 1989; Halford, 1993) and in some moderate forms of nativism that emphasize innate specific processing capacities, rather than innate declarative knowledge. However, our point is that in rejecting similarity processes along with the behaviorist account of learning, our field has thrown the baby out with the bathwater.

Our goal in this paper is to argue for a reconsideration of similarity-based learning as a major force in development. We propose that similarity, viewed as a *process of comparison*, is a key mechanism in experiential learning and in linking experiential learning to cultural learning. We will suggest (1) that the comparison between two representations can be understood as a process of alignment or structure-mapping; (2) that these kinds of alignment processes display the kind of structure-sensitivity that could facilitate rule-learning; and (3) that comparison processes can be invited not only by experiential juxtaposition but also by *symbolic* juxtaposition through the learning of common linguistic labels. Our research suggests that similarity comparisons, guided by cultural and linguistic patterns, can lead the child from concrete comparisons to abstract, rule-like regularities.

A proposal to reconsider similarity-driven mechanisms of abstraction may seem perverse in light of the wealth of philosophical and developmental literature that casts doubt on the explanatory power of similarity. As Quine (1969) puts it, there is little reason to think that ‘the muddy old notion of similarity’ has anything to contribute to the development of abstract capacities. Similarity has been viewed as too context-dependent and too narrowly perceptual (or if not too perceptual, then too unconstrained) to account for abstract, rule-governed capacities such as reasoning and categorization, either in adults (Goodman, 1972) or in children (Keil, 1989). Goodman’s arguments that similarity is uninformative (because any two things can be similar in some respect) or superfluous (once the respects are specified) have been taken as particularly damning to similarity-driven accounts. We will return to Goodman’s challenge later, after we lay out our proposal. For now we merely preview our argument: that similarity becomes both more constrained and more powerful if we shift from considering similarity as a cognitive *state* or *product* to similarity as the *process* of comparison. We will argue that there are natural structural constraints on similarity when similarity is viewed as a process of alignment and mapping (e.g. Gentner, 1983; Markman and Gentner, 1993a,b, 1996; Medin et al., 1993; Gentner and Markman, 1994, 1995, 1997; Goldstone, 1994b).

1.1. A note on terminology

Before going further, we need to clarify the key terms, since both ‘rules’ and ‘similarity’ are used in different ways. Rules can be transformations, as in $S \rightarrow NP + VP$, or simply expressions that specify a particular set of relations; they can be concrete, as in ‘dial 9 for an outside line’ or abstract; and they can be implicit or explicit. Smith et al. (1992) propose several criteria for rule use such as that rule-following should be unaffected by the familiarity or concreteness of the material, that application of a rule should prime subsequent uses and that rules may be mentioned in a verbal protocol. We will adopt Smith et al.’s construal of *rule* as an explicit, abstract schema that contains variables. As in their treatment, we will be liberal in our interpretation of ‘explicit’. We will not require that a schema be explicitly mentioned on each use in order to count as a rule, rather, it must seem readily capable of being stated. (We are aware that this is a loose description, but to count only fully-articulated principles would be unrealistically restrictive.) We will include not only abstract rules of reasoning such as modus ponens but also abstract conceptual representations. This extension is fairly standard, Rips (1989) comments that concepts are in many ways akin to rule-governed explanations, and Murphy and

Medin (1985) argue that concepts are theory-governed, and not arbitrary collections of features. Smith and Sloman (1994) note evidence for rule-based categorization, in that adults often focus on certain criterial features, such as ‘has the correct DNA,’ in judging category membership. Under this construal, there is abundant evidence for abstract rules and concepts in adults.

‘Similarity’ is a another pluralistic term. The most serious ambiguity is between similarity as a *process* of comparative reasoning and similarity as a *product* – e.g. a sense of closeness or representational unity. We will avoid this ambiguity by using process language to talk about the first sense, reserving ‘similarity’ for the product. The second polysemy occurs at the product level. There is a persistent ambiguity in the use of ‘similarity’ to mean sometimes overall similarity (common perceptual and functional characteristics) and sometimes purely perceptual or surface similarity. This is a dangerous ambiguity that obscures important distinctions. For one thing, overall similarity is a good predictor of further commonalities and surface similarity is not. As Goldstone (1994b) has shown, this ambiguity can distort the interpretation of similarity data.

In our research we distinguish three classes of similarity – analogy, literal similarity and mere-appearance (object similarity). These similarity types are not strict categories, but rather continua. In *analogy* – e.g. comparing the atom with the solar system – there is substantial relational overlap with very little object similarity: objects correspond not because of inherent similarity but by virtue of playing like roles in the relational structure. As object-similarity increases, the comparison shifts towards *literal similarity* – e.g. comparing one stellar system with another – which involves both relational and object commonalities. In the opposite direction, *mere-appearance* matches – e.g. comparing a planet with a round ball – share object descriptions but not relations. Mere-appearance matches are the quintessential ‘dumb similarity’ matches; they have virtually no predictive utility. Nonetheless, they are important to consider, because they often occur among children and other novices, and may interfere with learning. Finally, *surface similarity* is another polysemous term. It is used contrastively with some better or deeper form of similarity and typically means either *perceptual similarity* or *mere-appearance (object-based) similarity*. For our purposes, the major interest is in literal (overall) similarity and purely structural similarity (analogy). Though both can yield useful inferences, they have different psychological profiles. Overall similarity comparisons are far easier to notice and map than analogies, especially for novices (Holyoak and Koh, 1987; Keane, 1988; Ross, 1989; Gentner et al., 1993; Ross and Kilbane, 1997). As we will discuss, analogies occur later in learning and development.

Focusing on mapping process, we suggest that there is a continuum between similarity-based and rule-based processes. More fundamentally, we suggest that the process of structural comparison acts as a bridge by which similarity-based processes can give rise to abstract rules. There are two parts to this second claim. The first is that comparison can render domain representations more abstract, in two senses: Carrying out an analogy can lead to a schematic structure in which (a) the domain objects are replaced by variables, while retaining the common relations[1].

[1]Whether relations can also turn into variables is debatable; we think this is possible but rare.

(Winston, 1982); and (b) the domain relations are more abstract or general than the original domain relations (i.e. they contain fewer conceptual features). So far, these ideas are not new. Our second major claim is a bit newer and results from our recent empirical work: It is that carrying out a fully concrete mapping – even one in which the objects transparently match their intended correspondents – makes it easier to subsequently carry out an analogical mapping, in which relational structures must be matched with no support (or even with conflict) from the object matches. Putting this together, the comparison process offers a mechanism for moving from highly-similar pairings of concrete representations to gradually less similar pairings. With repeated comparisons, the resulting common system becomes more abstract, until it can be represented as a schema containing variables rather than objects. Such a schema can be applied as a rule.

Our main contention is that the process of comparison constitutes an important bridge between similarity-driven and rule-governed processes. We suggest that the developmental significance of a structurally-sensitive comparison process is two-fold. In the first place, as just described, structural alignment is a central learning mechanism enabling the child to notice and store abstract relational commonalities. Second, structure-mapping acts as a mechanism for the extension and application of knowledge. We will argue that for adults as well as children, structure-mapping processes can provide both a means of deriving abstract knowledge from instances and a means of extending it to new cases.

We also want to be clear about what we are *not* claiming. We do not claim that comparison is the only force in development, or the only kind of learning. We also do not claim that comparison processes are the chief or only source of knowledge representations. On the contrary, we assume that knowledge is initially derived in a number of ways – from direct experience, social interaction, and so forth. Our point is that comparisons among these various representations act to enrich, abstract, or otherwise modify them to create new representations. We will show that such modifications can result in meaningful changes in knowledge.

2. Structure-mapping

We briefly lay out the theoretical framework. We propose that comparison takes place via a structure-mapping process of alignment of conceptual representations. According to this view, the commonalities and differences between two situations are found by determining the maximal structurally-consistent alignment between their representations (Gentner, 1983, 1989; Falkenhainer et al., 1989). A *structurally consistent* alignment is one that obeys *one-to-one mapping* (i.e. an element in one representation corresponds to at most one element in the other representation) and *parallel connectivity* (i.e. if elements correspond across the two representations, then the elements that are linked to them must correspond as well). A central characteristic of analogy and similarity comparisons is *systematicity*: a preference for matching *connected systems of relations* (Gentner, 1983, 1989). A matching system of relations interconnected by higher-order constraining relations makes a better analogical match than an equal number of matching relations that are unconnected to each other. People are not much interested in analogies that merely capture a set of coincidences. The systematicity principle captures a tacit preference for coherence and causal predictive power in analogical processing.

Arriving at a deep structural alignment might seem to require advance knowledge of the point of the comparison. Such a mechanism would be implausible as a developmental learning process. In fact, however, structural alignment can be realized with a process that begins blind and local. The structure-mapping engine (SME) utilizes an alignment process that begins with purely local matches and culminates with one or a few deep, structurally consistent alignments (Falkenhainer et al., 1989; Forbus et al., 1995; see also Keane and Brayshaw, 1988; Holyoak and Thagard, 1989; Hummel and Holyoak, 1997). SME carries out its mapping in three stages. In the first stage, it detects possible matches between all pairs of identical predicates at any level (attribute, function, relation, higher-order relation and so on) in the two representations. At this stage, there are typically many mutually-inconsistent ($1 \rightarrow n$) matches. In the second stage, these local matches are coalesced into structurally-consistent connected clusters (called *kernels*). Finally, in the third stage, these kernels are merged into one or a few maximally structurally-consistent interpretations (i.e. mappings displaying *one-to-one correspondences* and *parallel connectivity*). SME then produces a structural evaluation of the interpretation(s), using a cascade-like algorithm in which evidence is passed down from predicates to their arguments. This method is used because it favors deep systems over shallow systems, even if they have equal numbers of matches (Forbus and Gentner, 1989). Finally, predicates connected to the common structure in the base, but not initially present in the target, are proposed as *candidate inferences* in the target. This means that structural completion can lead to spontaneous unplanned inferences.

Taken as a process model, SME has testable psychological implications. First, as mentioned above, it begins rather blindly with a mass of mutually-inconsistent local matches; the overall interpretation emerges out of the alignment through a preference for systematicity and structural consistency in the common system. Second, although SME often produces one interpretation, it can produce two or three alternative interpretations of an analogy. This, we believe, captures the occasional human experience of alternative possible interpretations. Third, inference projection occurs as a natural outcome of comparison, without special intention. This capacity to produce unanticipated inferences fits with human patterns: inferences often arise unbidden from an analogy and may even surprise the reasoner. Fourth, SME can save the common schema that results from carrying out a comparison. For example, Skorstad et al. (1988) simulated category learning by allowing SME to sequentially compare instances and retain the common system as a category abstraction. This fits the human phenomenon of spontaneous schema abstraction as a natural outcome of the comparison process (Gick and Holyoak, 1983; Catrambone and Holyoak, 1989; Ross et al., 1990).

SME's process of structural alignment also suggests limitations on the human comparison process, that are relevant to children's processing. First, because the alignment process operates simultaneously over objects and relations, we should find that the easiest, most natural form of similarity to process is *literal similarity* (*overall similarity*), in which the object matches and the relational alignment are correlated. In this case the matching information is mutually supporting and there is one dominant interpretation. Pure analogies, in which the matching relations are unsupported by matching objects, should be more difficult to process. This prediction fits the human pattern. Adults normally prefer relational interpretations but will select object matches when under time pressure (Goldstone et al., 1988). Furthermore, children can correctly carry out overall similarity mappings before purely relational mappings (Gentner and Toupin, 1986; Gentner and Rattermann, 1991; Rattermann and Gentner, 1998). Second, the most difficult case for both adults and children should be a *cross-mapping* (Gentner and Toupin, 1986): an analogical match in which similar objects play different relational roles in two analogous scenarios: e.g. *grandmother*: *mother*::*mother*:*daughter*. This prediction is also supported for both adults and children, as discussed below.

3. The career of similarity in development

Developmentally, these assumptions interact with considerations of change of knowledge. When domain theories are weak, as for very young children, the representations typically contain relatively sparse knowledge of relations, but often contain rich knowledge of objects. Gentner and Rattermann (1991) proposed a knowledge-driven account of the 'career of similarity',[2] as follows. Very young infants can notice highly specific, massively overlapping literal similarity comparisons, but at this stage they are limited to strong similarity matches (Foard and Kemler-Nelson, 1984; Smith, 1989). For example, infants show that they can remember a mobile that they have seen before (by later kicking a similar mobile in the same way to make it move) but only if the new one is a very close perceptual match to the original (Rovee-Collier and Fagen, 1981). As infants gain in stable knowledge, they become able to make partial matches. Object matches, such as the similarity between one shoe and another, occur very early. As children's domain knowledge becomes richer and deeper, purely relational matches become possible: e.g. the similarity between a shoe *covering* a foot and a mitten *covering* a hand. There is a domain-specific relational shift with experience (Gentner, 1988). Thus, the career of similarity runs from overall matches to object matches to relational matches to higher-order relational matches (Gentner and Rattermann, 1991; see Halford, 1987, 1993 for a related proposal).

These predicted patterns are illustrated in a study of children's ability to map a plot structure from one set of actors to another (Gentner and Toupin, 1986). Two factors were varied: (1) *object similarity (transparency)*, the degree to which corre-

[2]The claim that the relational shift is driven by increases in domain knowledge has wide support (Gentner, 1977a,b, 1988; Ortony et al., 1978; Gentner and Toupin, 1986; Vosniadou, 1987; Brown and Kane, 1988; Brown, 1989; Chen and Daehler, 1989; Goswami, 1992) although changes in processing capacity have also been argued to be important (Halford, 1987, 1993).

sponding actors resembled one another and (2) *systematicity*, whether children were given an explicit statement of the higher-order relational structure that governed the plot. The story plots were identical across the object-similarity conditions. However, in the systematic condition, two additional statements were given – one at the beginning and one at the end of the story – that provided an overarching causal or moral summary. Both age-groups were affected by object similarity: They were more accurate in retelling the story when *squirrel* mapped onto *chipmunk* than when it mapped onto *moose*. In contrast, the systematicity of the relational structure appeared to influence only the older children: 9-year-olds, but not 6-year-olds, were far more accurate when given a higher-order structure that constrained the plot. In fact, 9-year-olds in the systematic condition were able to transfer the story accurately regardless of the transparency (or degree of object similarity) of the correspondences. Although we cannot be sure, we suspect that the young children's failure to profit from systematic structure stemmed from lack of sufficient knowledge of social and causal regularities, rather than from inherent processing limitations.

These results fit the predictions of the career of similarity account. Children gradually shift from object-dominated to relation-dominated similarity matches as their domain knowledge increases. Other studies of analogical transfer have found a similar early reliance on object matches, (e.g. Holyoak et al., 1984; Daehler and Chen, 1993; Chen et al., 1998; Rattermann and Gentner, 1998).

4. Learning

We can now be more specific about our central claim that comparison promotes learning, and, more specifically, that children's comparison processes can lead to the development of abstract rules. Structure-mapping suggests three[3] ways in which the alignment and mapping process brings about learning. First, by *highlighting common systems* of features and relations, thereby promoting the noticing and extraction of subtle and possibly important commonalities (especially common relational systems), and facilitating schema-abstraction. Second, by *projecting inferences* from the base to the target (Clement and Gentner, 1991; Gentner et al., 1997; Gentner and Wolff, 1998; Markman, 1998). Third, by *inviting re-representation* to improve the match, thereby promoting representational uniformity. Crucial to our position is the claim that comparison acts to promote *systems of interrelated knowledge*.[4] If the comparison process resulted in isolated feature matches, it would hardly qualify as a candidate for abstracting causal laws and other principled regularities. One way to observe the effects of structure in comparison is to use cross-mappings, which put structural commonalities in conflict with object matches (Gentner and Toupin, 1986;

[3]A fourth way in which analogy can promote learning is by inviting the re-structuring of one domain in terms of the other (Gentner et al., 1997). This mechanism is beyond the scope of this paper.

[4]This may seem to contradict our earlier assertion that young children often focus on object matches. However comparison can promote relational commonalities only relative to the learner's existing knowledge base.

Ross, 1987; Markman and Gentner, 1993b; Goldstone and Medin, 1994). For example, Markman and Gentner (1993b) showed people two scenes. In one, a women was shown *giving* food to a squirrel; in the other, the women was shown *receiving* food from a man. One group of participants rated how similar the two scenes were to each other, while another group simply rated the two scenes' aesthetic value (to control for time spent looking at the pictures). All participants were then asked to say which thing in the second picture the *woman* should map to. Participants who first rated the similarity of the scenes made significantly more relational mappings (i.e. woman to squirrel) (69%) than those who did not (42%). It appears that the very act of carrying out a similarity comparison can induce a structural alignment, increasing people's likelihood of making matches on the basis of shared relations instead of simple object similarities.

More specifically, there is evidence that which information is selected by a comparison is determined by *systematicity*: the presence of higher-order connections between lower-order relations. For example, Clement and Gentner (1991) showed people analogous scenarios and asked them to say which of two lower-order assertions shared by base and target was most important to the match. People chose the assertion that was connected to matching causal antecedents: that is, their choice was based not only on the goodness of the local match, but on whether it was connected to a larger matching-system. A second study showed that inferences from one scenario to the other were also governed by systematicity; people made the inference that completed a causal system. (See also Bowdle and Gentner, 1998). We now consider highlighting, re-representation and inference projection, showing developmental evidence that these processes operate to promote learning.

4.1. *Highlighting common systems*

We suggested above that comparison acts to promote common systems. If such highlighting of common structural systems occurs in development, then comparison could act to orient children towards *systems of interconnected knowledge* – e.g. systems linked by higher-order causal, mathematical or perceptual relations. Kotovsky and Gentner (Gentner et al., 1995; Kotovsky and Gentner, 1996) investigated the possibility that comparison processes might promote children's learning about higher-order perceptual relations such as *symmetry* or *monotonic increase*. We focused on perceptual relations for four reasons: (a) the materials – objects in simple configurations – are familiar to children; (b) prior work indicates a relational shift in children's sensitivity to perceptual relational structure (Chipman and Mendelson, 1979; Smith, 1984) and, most importantly; (c) perceptual patterns permit independent manipulation of different levels of relational commonality (Chipman, 1977; Smith, 1984, 1989, 1993; Halford, 1987, 1992), in contrast to rich causal situations, in which object similarity and relational similarity are typically correlated; and (d) we wished to extend the evidence for systematicity beyond causal relations.

We asked when and how children become able to perceive cross-dimensional relational matches. The task was a triads-similarity task: The child was shown a standard geometric pattern (e.g. oOo) and two choice alternatives and was asked to

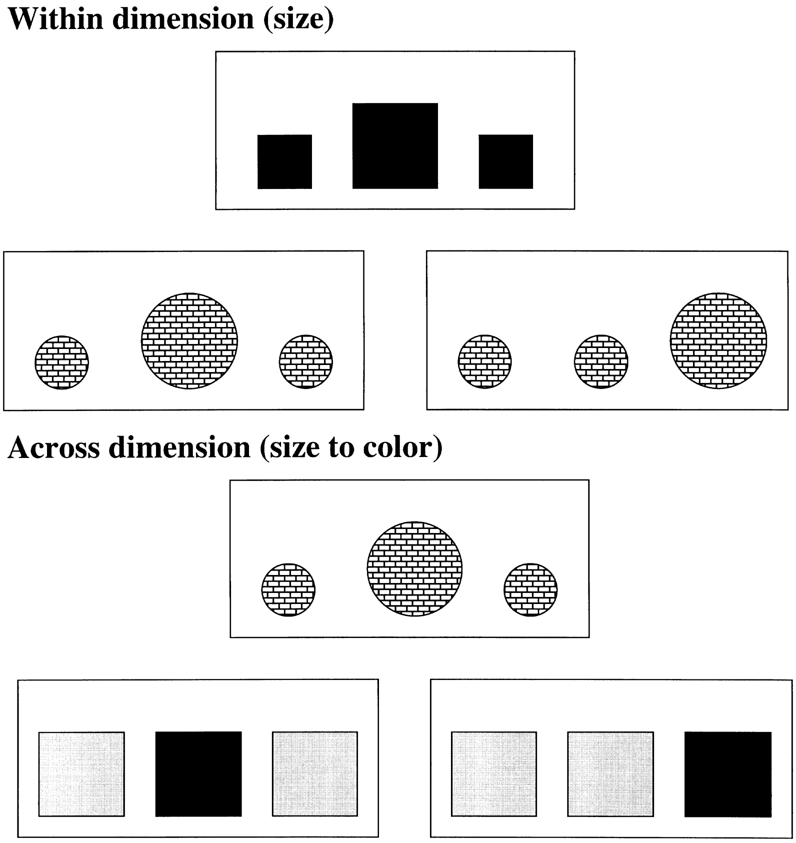

Fig. 1. Results of Kotovsky and Gentner's (Kotovsky and Gentner, 1996) progressive alignment study. Given mixed triads, 4-year-olds were at chance (47%) on cross-dimension triads, even when they chose relationally on the within-dimension triads. However, when given the within-dimension triads first – inviting easy alignment – those 4-year-olds who chose relationally on within-dimension triads also chose relationally on cross-dimension triads. Those who scored above median on within-dimension triads chose 80% relationally on the cross-dimension triads.

say with which alternative the standard 'goes best'.[5] Each triad had a relational choice that shared a higher-order relation with the standard – either *symmetry* or *monotonicity*. The other alternative was a foil. It was composed of the same elements as the relational choice, rearranged to remove the higher-order pattern (see Fig. 1). Since the relational choice and the foil were made up of the same objects, this task is a pure test of children's appreciation of relational similarity. The key manipulation

[5]We avoided the term 'most similar' as we feared it might lead children to seek concrete matches (See Goldstone, 1994b). We oriented them towards similarity by giving them pre-training with clear similarity choices. During the task, although no feedback was given, the children showed that they construed the task as a similarity task by choosing correctly on filler triads designed to be easy similarity matches as well as on most of the within-dimension triads.

was whether the higher-order relation occurred over the *same* dimension or over *different* dimensions (as shown in Fig. 1). The logic was, first, to verify that the cross-dimensional task is difficult for young children and, second, to ask whether the comparison task itself can *improve* children's subsequent ability to detect the higher-order commonalities.

Study 1 was a baseline study that varied the degree of concrete support for the higher-order relational match. The results showed that although 6- and 8-year-olds were able to recognize higher-order relational matches across different dimensions (e.g. size vs. saturation), 4-year-olds chose relationally only in the same-dimension condition; they were at chance on cross-dimensional matches. That is, they could match *little-big-little* with *little-big-little* (with different objects), but not with *light-dark-light*.[6] To test whether the comparison process could help the 4-year-olds learn to detect common higher-order structure along different dimensions, Study 2 utilized a *progressive alignment* technique in which children were given the same-dimension matches before the cross-dimensional matches. The rationale is that within-dimension comparisons, being strong overall matches, should be very easy for children to notice and align. By hypothesis, each time a pair of these concrete relational structures is aligned, their common structure is promoted. If so, then concentrated repeated experience on within-dimension pairs should help the child to notice the pattern of symmetry or monotonicity.

The manipulation in Study 2 was fairly minimal. Children received the same triads as in Study 1. The only difference was that this time the trials were blocked so that within-dimension matches preceded cross-dimensional matches (see Fig. 1). This small change in presentation had a large effect. The 4-year-olds in this study who scored above the median on the same-dimension triads showed significantly more relational responding on the cross-dimensional triads (80%) than those who scored at or below the median. In contrast, children in Study 1 (in which cross- and within-dimension triads were mixed) showed no such difference: They were at chance on the cross-dimensional triads regardless how they did on the within-dimension triads. It appears that receiving the 'easy' within-dimension triads did indeed help children to notice the higher-order patterns of symmetry and monotonicity. In a control study, we showed that alignment experience on both dimensions – size and saturation – was required in order to gain cross-dimensional insight.

In a further study, we used a more intensive training task (Study 4 in Kotovsky and Gentner, 1996). After a pre-test on the cross-dimensional triads, 4-year-olds received training with feedback on the same-dimension triads to a criterion of seven out of eight correct (relational) answers (roughly two runs-through). Then they were tested on the eight cross-dimensional triads, without feedback. Children chose relationally on 74% of the post-test items, significantly better than their pre-test performance of 41%. These findings again confirmed that experience with concrete similarity comparisons can improve children's ability to detect cross-dimensional similarity.

[6] Research by Smith and Sera (1992) indicates that *big* and *dark* both have positive polarity for young children.

4.2. Symbolic juxtaposition

It appears that experiential juxtaposition can make common relational structure more salient. We next asked whether the use of relational language could also promote such alignment and abstraction. As discussed above, such a demonstration would help explain how a child's internal learning processes can connect to cultural systems. There is precedent for supposing that words can act to guide children's attention, in the studies showing that noun labels can call attention to object categories, overriding competing associations (e.g. Markman and Hutchinson, 1984; Waxman and Gelman, 1986; Markman, 1989; Waxman and Markow, 1995). It seems reasonable that such semantic orienting effects should occur for relational terms as well as for object terms, although possibly at a later age (Gentner, 1982; Gentner and Boroditsky, 1998). Thus we conjectured that providing labels for the higher-order relations might increase the salience of the common relational structure.

We taught 4-year-olds labels for the relations of monotonic change ('more-and-more') and symmetry ('even'). On the symmetry-training trials, children were told that the 'picky penguin' (Waxman and Gelman, 1986) only liked 'even' patterns. Then they sorted the 12 individual patterns used in the same-dimension symmetry triads according to whether they were *even*. If they made an error, the correct answer was explained. The same method was used for monotonic-increase. After going through each sequence once, the children were given the cross-dimensional triads task with no feedback. Those 4-year-olds who scored above the median on the labeling task were significantly more likely to show relational responding on the cross-dimensional trials than those below the median. Learning to use relational labels appeared to increase children's attention to common relational structure.

4.3. Comparison and re-representation

Why should repeated within-dimension alignments facilitate subsequent cross-dimensional alignment? We have suggested that highlighting the higher-order structure was important, but this is not enough. In addition, some degree of re-representation seems to be required. Consider a typical 4-year-old in Study 4 (Kotovsky and Gentner, 1996) (the training study). At first she sees no likeness between *little-medium-big* and *light-shaded-dark*. Yet after experiencing training only on within-dimension triads, she is able to see the cross-dimensional match. We suggest that initially she represented the relations in dimension-specific fashion, so that difference in magnitude was conflated with the dimension of difference. In other words, her representations were expressed in terms of first-order relations such as *bigger* (x,y) and *darker* (a,b). These relations cannot be matched. We suggest that the within-dimension comparisons made the higher-order pattern of monotonicity more salient in her representations, so that it constituted a partial match in the subsequent cross-dimensional trials. As noted above, a partial match invites re-representation to improve the match. The relations were re-represented to separate the common pattern of magnitude change from the (non-common) specific dimension of change, resulting in partially matching relations, represented roughly as *greater* (*size*(x), *size*(y)) and *greater* (*shading*(a), *shading*(b)). Although this may seem like a trivial distinction, it allows for noticing that the *same* relation of magnitude change is occurring across different dimensions. The (unlike) dimensional values can then be put into correspondence by virtue of their like relational roles. In this way, the child can see that a higher-order commonality holds across different dimensions. Separating a higher-level constancy from the specific dimension over which it occurs is a critical learning step. (See Gentner et al., 1995 for a more detailed discussion and simulation.) The emerging appreciation can be seen in the comments of one 8-year-old in Study 1. On her first six trials, she responded correctly to three within-dimension trials and incorrectly to all three cross-dimension trials, on which she showed her frustration with comments like 'it can't be the size, because those two are the same size. It can't be color.' Finally, on her seventh trial, she exclaimed 'even though the smaller ones come first and the big one's in the middle, it's exactly the same – but different!' She went on to choose correctly for the remainder of the study.

We suggested earlier that children's initial representations are often highly conservative. Their knowledge is described as 'concrete', 'situated' or 'contextually embedded'. What we are suggesting here is that comparison processes can facilitate seeing that the same relational patterns may apply across different concrete situations. In this way comparison promotes the abstraction or disembedding of relations from their initial rich contexts. This research further suggests that this abstraction process can be promoted by learning relational labels. So the capacity to see consistent mappings between structures across different dimensions is promoted both by direct comparisons and by learning common language that invites later comparison – 'symbolic juxtaposition'. This proposal is consistent with research suggesting that dimensional structure develops gradually (Smith and Kemler, 1977; Smith, 1989) and that verbal cross-dimensional matches developmentally precede perceptual cross-dimensional matches (Smith and Sera, 1992).

Our notion of re-representation is in the same spirit as Karmiloff-Smith's (1992) *representational redescription*. Both address the change from concrete, situated representations to more abstract representations. However, in our account, re-representation occurs on a smaller scale. Whereas representational redescription involves metalevel insight and occurs only after considerable mastery has been attained, we envision re-representation as more like local tinkering (Burstein, 1983; Kass, 1989); and we assume that it can occur at any time during the course of learning. Many of the earliest early alignments and re-representations may be too simple to be noticed, but they nonetheless facilitate later juxtapositions.

4.4. *Comparison and category abstraction*

Comparison processes can contribute to children's learning of the deep commonalties that characterize a category. Such learning is important because although there is considerable evidence that even very young children believe that words name like kinds (Markman, 1989; Waxman and Markow, 1995), their initial sense of likeness may rely heavily on perceptual similarity, especially shape similarity (Landau et al., 1988; Baldwin, 1992; Imai et al., 1994). In the first set of studies, following the basic Markman (1989) word versus no-word choice task, Imai et al. showed 3- and 5-year-old children a standard – e.g. a drum – along with three alternatives, e.g. a bucket (same shape), a flute (same category) and drumsticks (thematically related). When asked to choose the picture that had the same name as the standard (e.g. a *blicket* in dinosaur language), the children, especially the 3-year-olds, were highly likely to choose the same-shape item: 68% shape versus 10% taxonomic responses for 3-year-olds and 56% shape versus 28% taxonomic responses for 5-year-olds (chance, 33%). In fact, both age groups were significantly *more* likely to make shape choices in the word condition than in the no-word condition, in which they were simply asked to 'choose the one that goes with' the standard. However, there was a *shape-to-taxonomic* shift: 5-year-olds made significantly more taxonomic responses in the word condition (28%) than did 3-year-olds (10%).

This shape-to-taxonomic shift presumably reflects children's generally deepening conceptual knowledge. However, perhaps language itself, in combination with the learning mechanisms we have discussed, contributes to the shift. We hypothesize that learning common terms for same-shape items in basic-level categories might prompt comparisons among these items; this in turn would promote the discovery of deeper commonalities. Evidence for this conjecture comes from a further study by Gentner and Imai (1995) in which a fourth alternative (e.g. a tambourine) was added that shared *both* shape and taxonomic category with the standard. Children were allowed to make two choices. For their first choice, 3-year-olds in the word condition appeared to choose solely on the basis of shape: their responses were evenly split between the two shape alternatives, even though one shared taxonomic category with the standard and the other did not. So far, the results simply replicate the shape bias in word extension. When children were asked to choose a second *blicket*, however, with their first choice placed next to the standard to allow comparison, there was a dramatic change. Children who had chosen the same-shape/same-category alternative (the tambourine) chose the remaining categorical alternative (the flute) twice as often as the remaining shape alternative (the bucket) (60% vs. 33%). This contrasts strikingly with the behavior of children in the previous study (Imai et al.), who, given the same three alternatives (bucket, flute, drumsticks) overwhelmingly chose the shape alternative. Children who compared the drum and tambourine as blickets could perfectly well have settled for the conclusion that same-shape defined the meaning of *blicket*, but they did not. In fact, they were *six times* as likely to choose the alternative that shared category but not shape (the flute) (given the same three alternatives) as children who had seen the drum only as a *blicket* in the previous Imai et al. study. We suggest that comparing the two *blickets*– the drum and the tambourine – made commonalities such as 'playing music' more salient.[7]

One concern is that the results could reflect subject self-selection effects: the children who choose the same-shape same-category item on the first round may be just those who possess superior category knowledge. This seems unlikely given the magnitude of the difference. However, Gentner and Namy (unpublished data)

[7]This categorical bootstrapping effect of comparison occurred only in the word condition, not in the no-word condition.

have recently completed a study that clearly shows that juxtaposition of the two perceptually-similar exemplars, given a common label, can invite the child to notice further, more abstract commonalities. The materials, shown in Fig. 2, were designed so that each of two standards was perceptually similar to the same alternative, and conceptually similar to the other. When 4-year-olds were given the naming task with *either* standard – e.g. the apple or the pear – and asked to 'find another dax', they tended to prefer the shape-similar item (the balloon) or to choose randomly. However, when a third group of children was given both standards at once and told 'these are both daxes. Can you see why they're both daxes?', the children showed a significant shift towards the category choice (the banana). These results show that comparisons among similar exemplars – even if initially prompted by common perceptual features – can and do serve to highlight deeper commonalities. Similarity processing is not a dead-end computation of a single product, as a behaviorist view might suggest, but a generative process.

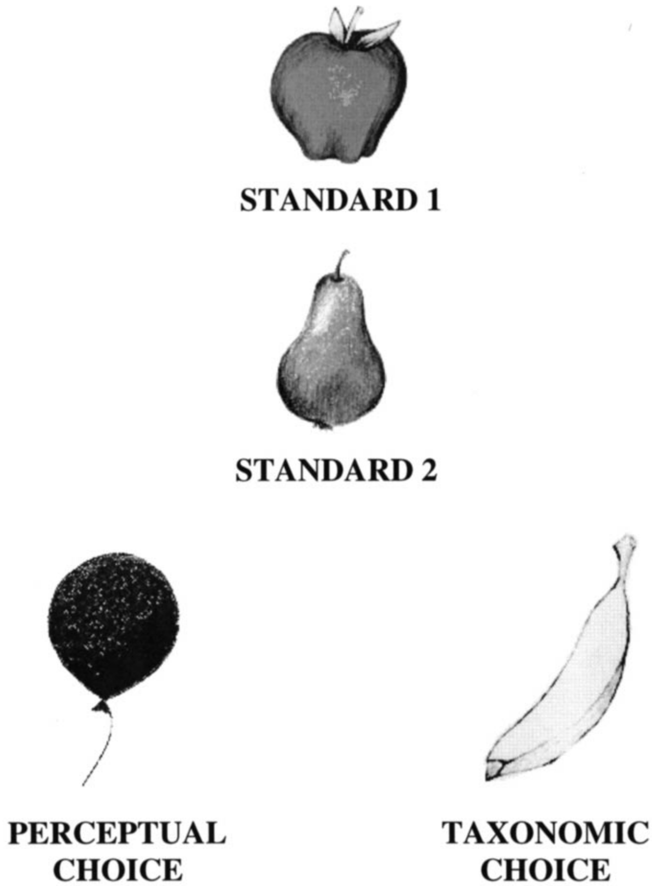

Fig. 2. Sample materials used in the naming task (Gentner and Namy, unpublished).

4.5. Comparison and inference projection

A third way in which structural comparison can lead to learning is by the projection of inferences. Rattermann and Gentner (1990; and unpublished data) investigated children's ability to align two situations and to project a simple inference from one to the other. As in the prior study, the logic was, first, to investigate when this mapping ability naturally develops and, second, to investigate possible contributors to this development by asking whether the skill could be acquired earlier. Whereas the previous studies focused chiefly on progressive alignment, the Rattermann and Gentner studies focused on the effects of learning relational language. The task was a mapping task inspired by DeLoache's (1989, 1995) model-room search task. The child had to infer where a sticker was hidden in one space by mapping a corresponding location from an analogous space. As in Kotovsky and Gentner's studies, simple perceptual configurations were used so that an unambiguous higher-order relation – in this case, monotonic increase in size – was available (See Gentner and Rattermann, 1991; Rattermann et al., 1994).

Children aged 3, 4 and 5 years saw two triads of objects, the child's set and the experimenter's set, both arranged in monotonically-increasing order according to size. The child watched as the experimenter hid a sticker under an object in the experimenter's triad; she was told that she could find her sticker by looking 'in the same place' in her triad. The correct response was always based on relational similarity; the child was meant to choose the object of the same relative size and relative position, which were always correlated. In the high-similarity condition, the child's triad was identical to the experimenter's – e.g. E:1*2*3 → C:1*2*3. This is predicted to be an easy mapping, because object similarity and relational alignment converge on the same result: 2 → 2. In the cross-mapped condition, the object similarity matches were inconsistent with the best relational alignment – e.g. E:1*2*3 → C:2*3*4. This should be much harder; if the experimenter chooses her middle object (object 2), then to choose correctly (object 3), the child must resist the competing identity match (object 2). The child was always shown the correct answer, but was allowed to keep the sticker only if he had pointed to the correct object.

In Study 1, a developmental baseline was obtained by varying the match condition and the degree of object similarity between the two triads (see Fig. 3). As predicted, children were more accurate with literal similarity than with cross-mapped arrays. Also as predicted, there was an interaction between match type and object similarity. In literal similarity trials, for which the object matches agreed with the correct relational alignment, performance was better for rich objects than for sparse objects. For cross-mappings, in which the object matches conflicted with the correct relational alignment, the reverse was true: performance was better for sparse objects than for rich objects. Indeed, 3- and 4-year-olds performed at chance (33%) on the rich cross-mapped trials despite being shown the correct response on every trial.

Having thus established a challenging relational task, Rattermann and Gentner then investigated whether teaching children to apply relational language could help them perform the mapping. Children again received the cross-mapping task, but this time they were taught to use the labels *Daddy*, *Mommy* and *Baby* for both their own triad and for the experimenter's. (These family labels are often used spontaneously by preschool children to mark monotonic change (Smith, 1989).) The reasoning was that applying these labels would invite the child to map this monotonic pattern from families to the arrays in our study. Having this common higher-order relation of *monotonicity* should make it easier to align the two sets. The results of the labeling manipulation were striking. The 3-year-olds' performance in the cross-mapping task was far better on both the sparse and the rich stimuli (89% and 79% relational responding, respectively) than the baseline performance of same-age children in

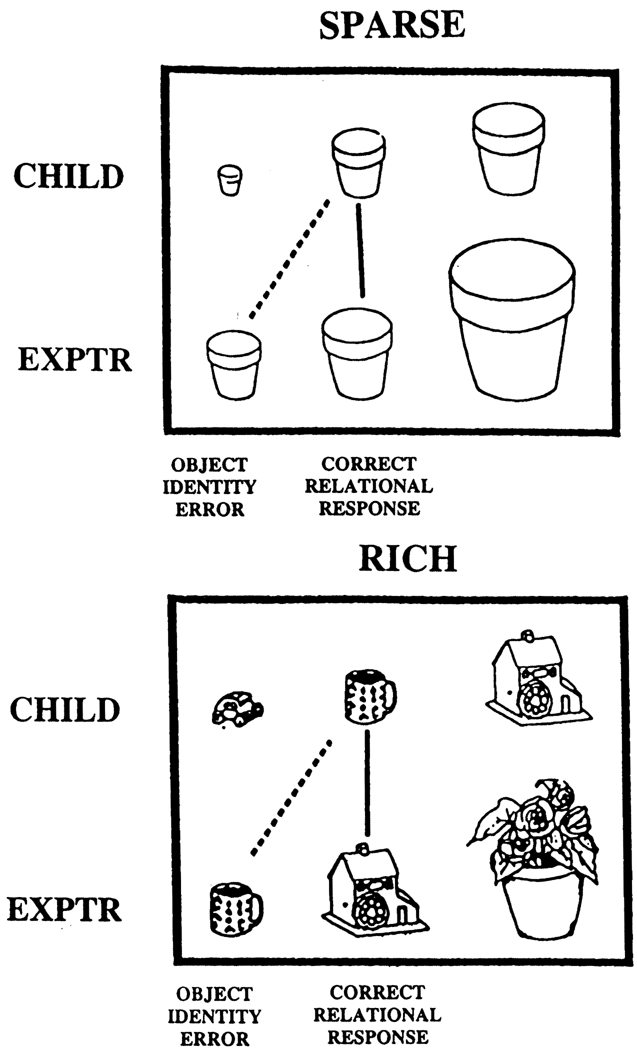

Fig. 3. Materials used in Rattermann and Gentner's mapping task.

Experiment 1 (54% and 32%, respectively). In fact, the 3-year-olds' performance with 'Daddy-Mommy-Baby' labels was comparable with that of 5-year-olds in the baseline study.

That a brief intervention could improve performance so strongly is evidence for a substantial role of knowledge change, as opposed to purely maturational change, in analogical development (Gentner, 1978a,b; Vosniadou, 1987; Brown, 1989; Goswami, 1992). Moreover, the gains are not specific to the initial materials; the children are able to transfer this learning to new triads even with no further use of the labels by the experimenters. Finally, in a recent follow-up, children were found to have preserved this learning over substantial periods. Children were brought back 4 weeks later and asked to play the game again (without the labels). Children initially taught relational labels performed far better (65%) than those in the no-label (31%, chance).

Our account of this improvement, as noted above, is that the relational labels invited higher-order representation (Gentner and Rattermann, 1991). Just as object labels appear to facilitate noticing object-level similarities, so relational labels may facilitate the noticing and matching of relational structures.[8] It appears that the use of relational labels can invite children's attention to common relational systems, thereby allowing even very young children to carry out a relational alignment. We speculate that the relational shift in children's similarity mapping may be promoted in part by the learning of relational language.

5. Comparison as a mechanism for the application and extension of knowledge

So far our case for comparison has focused on its role as a mechanism for new learning and progressive abstraction. However, structure-mapping processes can also function to apply available knowledge to new cases. Consider the phenomenon of property induction from categories. Although category-based induction and similarity-based inference are commonly said to involve different processes – the former consisting in the extrapolation of knowledge on the basis of category structure and the latter consisting in the projection of knowledge from one specific instance to another – we think it worth exploring some connections.

6. Inductive inference

Carey's (1985) studies of inductive inferences in biology revealed striking differences between adults and children. When asked questions of the form 'species X has property p. Do you think species Y has property P?' adults differentiated across both properties and ontological categories, e.g. they assumed that *breathing* was a reasonable inference about animals, whereas *having bones* was specific to vertebrates. In

[8]However, the present effects are not due to linguistic labels per se, but to learning labels that convey *relations*. A further control study showed that children taught *object* labels – such as 'Jiggy-Zimbo-Gimli' – did not improve in their performance.

contrast, regardless of the property, 4-year-olds ascribed it to other creatures on the basis of their overall similarity to humans. Carey suggested that young children may use humans – as their most central or typical biological creatures – to reason about less familiar species. Lacking knowledge, young children rely on a kind of analogizing, whereas adults and older children can use category-level conceptual knowledge.

Results like this have led to the statement that children's induction is comparison-based and adults' is category-based. However, adults continue to use comparison along with their category-based processes. Indeed, most models of adult category-based induction include a similarity component. For example, the similarity-coverage model of Osherson et al. (1990) postulates three underlying components – *similarity*, *category coverage* and *category generation* – that give rise to a large set of empirical phenomena in category-based induction. An example of the positive effects of similarity between the premise and conclusion categories is that people consider (1) a stronger argument than (2)

(1)	Foxes have property P.
	Deer have property P.
	Therefore weasels have property P.
(2)	Elephants have property P.
	Deer have property P.
	Therefore weasels have property P.

However, other findings suggest that adults generate and make use of categories in this task. For example, adults show effects of *premise diversity* – the more diverse the premises, the stronger the argument: e.g. *hippo*, *hamster* $\rightarrow$ *mammal* is stronger than *hippo*, *rhino* $\rightarrow$ *mammal* – and of *monotonicity* – i.e. that adding premises strengthens a conclusion.

To study the development of these effects, Lopez et al. (1992) gave children inductive inference problems similar to those of Osherson et al. As in Carey's studies, they found a developmental pattern of early reliance on similarity, with category-based reasoning entering later. Both kindergarteners and second-graders showed effects that follow from the similarity component – namely, similarity of premise to conclusion, typicality of premise and homogeneity of the premise items. However, only second-graders showed effects that follow from category coverage – namely, premise diversity and monotonicity. Adults showed all these effects plus others that also require *generating* an inclusive category. As in the Osherson et al. studies, adults seemed to use both comparison-based and category-based processes. We return to the characterization of adult processes below.

6.1. Symbolic juxtaposition in inductive inference

Language may play a facilitating effect in category induction, as in the phenomena discussed earlier. S. Gelman and her colleagues (Gelman and Markman, 1986, 1987; Gelman, 1989; Davidson and Gelman, 1990) have shown that common category labels can invite young children to make inductions. For example, Gelman and Markman (1986) found that the use of a familiar common category label (e.g. 'bird') increased 4-year-olds' propensity to import knowledge from one creature to another. This finding is consistent with Gelman's suggestion that words signal conceptual essences for the child, and with the idea that 'a word can function as a promissory note, signaling subtle commonalities that the child does not yet perceive' (Gentner and Rattermann, 1991).

Davidson and Gelman (1990) investigated interactions of category labeling with perceptual similarity in children's induction. Children of 4–5 years of age were shown a novel animal (e.g. a gnu-like animal, called a 'zav') and taught that it has an unfamiliar property (e.g. 'has four stomachs'). They were then asked whether the property would be present in another animal. The design neatly separated effects of perceptual similarity from those of a common label. Children saw four test items in a 2×2 design (similar/non-similar $\times$ same-label/different-label). In two studies, children drew more inferences to perceptually similar (about 75%) than to perceptually dissimilar pictures (about 45%). There was no effect of common labels, whether the labels were novel (Experiment 1) or familiar (Experiment 2). However, in the third study, the correlation between similarity and common label was improved by omitting one of the 'conflict' pictures in each set (reducing the design to 3 cells). In this case, having a common label did help children (65% for same label vs. 47% for different label). When there was a contradiction between labels and appearances, young children based their inferences on appearances. However, when a genuine – though imperfect – alignment was available, a common label could then be anchored and extended. This pattern of findings is consistent with our earlier findings: Common labels invite comparison, but perceptual similarity is crucial for achieving an initial alignment. Furthermore, as in progressive alignment, once an 'easy' alignment is made, children can notice further, more abstract commonalities. As Gelman and Markman (1986) and Davidson and Gelman (1990) suggest, children notice that the members of a named category have many observable features in common and eventually extend this belief to unobservable properties as well.

6.2. Analogical inference projection

It is instructive to compare children's spontaneous use of analogy in inductive problems from the same domain, biology (Inagaki and Hatano, 1987, 1991; Inagaki, 1989, 1990). Inagaki and Hatano (1987) asked 5–6-year-old children questions such as 'what would happen if a rabbit were continually given more water?' The children often made explicit analogies to humans: e.g. 'we can't keep it [the rabbit] forever in the same size. Because, like me, if I were a rabbit, I would be 5 years old and become bigger and bigger'. Inagaki and Hatano noted several interesting features of children's use of humans to reason about other creatures. First, the personification responses were likely to be reasonable (100% of the explicit personification responses for rabbit were correct, as opposed to 71.5% of the non-personification responses). Second, children were more likely to use the analogy to humans the more similar the target entity was to humans. Both explicit and implicit personification responses occurred far more often for rabbit and tulip than for stone. This is consistent with the findings, noted above, that high similarity facilitates the process of alignment and mapping of inferences. Third, when asked questions for which the analogy with humans would yield incorrect responses (in a second study), children were far less likely to use the analogy.

According to the analogical reasoning account, the person analogy has a special status in early biological reasoning not because of category centrality but because humans, as the most familiar species, provide the richest and most systematic base domain to reason with. Inagaki (1990) provided strong evidence for this analogy account by testing children who had a rich knowledge base about another species, namely, goldfish. On the analogy account, they should be able to use this knowledge as a source of analogical reasoning about other animals. Inagaki (1990) compared 5-year-olds who were raising goldfish with those who were not. Not surprisingly, the goldfish-raisers showed superior factual and conceptual knowledge about goldfish. More importantly for our purposes, when asked questions about unfamiliar aquatic animals such as frogs, children who had raised goldfish were more likely to draw analogies from goldfish than were other children. Interestingly, the goldfish-raisers not only used the *goldfish* analogy more often for frogs than the non-raisers, but they also tended to use the *person* analogy for frogs – and even for goldfish – more often than did the non-raisers (15 vs. 8 explicit person analogies for frogs, respectively; and 18 vs. 12 for goldfish). Inagaki suggests that the goldfish-raisers had derived some understanding of the underlying commonalities between goldfish and humans, and that this helped them see commonalities between humans and frogs. This is consistent with our proposal of progressive alignment and schema abstraction. An alignment and mapping between two species should promote further alignments with other species.

6.3. Induction in adults: weak methods versus strong methods

The evidence from Lopez et al.'s research and other developmental work suggests early similarity-based induction, with a developmental gain in the use of categories in induction. However, as noted above, adults continue to use direct analogies. Striking instances of similarity effects have been documented in adults, including some that seem to flaunt the rules of inductive logic. For example, Osherson et al. (1990) showed that an argument from *robins* → *birds* is judged stronger than one from *robins* → *ostriches.* According to inductive logic, however, it is the latter argument that is stronger, since its conclusion is contained in the conclusion of the former. This phenomenon has been termed the 'inclusion fallacy'. Intuitively, it seems to stem from the greater alignability of robin with bird than with ostrich. Sloman (1993) found an equally-surprising effect in deductive reasoning. People tend to project properties from a superordinate to a subordinate category on the basis of their similarity (the 'inclusion-similarity phenomenon'). For example, the inference 'all birds have an ulnar artery. Therefore, all robins have an ulnar artery' received a higher rating than 'all birds have an ulnar artery. Therefore, all penguins have an ulnar artery'. Even more strangely, the argument from *animals* → *mammals* was rated stronger than the argument from *animals* → *reptiles*. These findings cannot be predicted by a category-based model, since the second category is perfectly included within the first in both cases. Such cases are convincing evidence for at least some direct comparison-based reasoning in adults, even in standard categorical reasoning tasks. Indeed, Sloman (1993) has proposed a model of induction that uses direct featural overlap between the premise and conclusion categories (a measure rela-ted to instance similarity), rather than invoking category membership to draw inferences.

The issue of categories versus similarity in induction can be thought of in terms of Newell and Simon's (1972) distinction between weak and strong methods of reasoning. *Weak methods* are general strategies that can operate without special knowledge of a domain: methods such as means-ends analysis or modus ponens. *Strong methods* are those that make intensive use of specific represented knowledge, such as the facts that raccoons are nocturnal and squirrels diurnal. Weak methods are extremely valuable because of their generality; they provide an avenue wherever knowledge is insufficient. Perhaps because of their abstract character, they tend to be learned late; they qualify as sophisticated knowledge. The fact remains, though, that strong methods are often better when the appropriate knowledge is present. Although Newell and Simon did not discuss analogy explicitly, close analogies clearly qualify as a strong method because they rely on specific knowledge of the base (although the mapping *process* is domain-general).

For example, it seems intuitively clear that an inference from *elk* to *deer* can proceed without recourse to the mammal category.[9] (It could be argued that such an inference would implicitly rely on a common category of 'hoofed, antlered North American ungulates', but then the notion of 'common category' becomes extremely slippery.) Following this line, we speculate that some of the developmental gains in inductive accuracy may come about not through a shift from comparison to category application, but through increasingly sophisticated analogizing. The distinction here is between relatively blind analogy – in which overall similarity provides the metric for attribution of properties – and informed analogy – in which similarity with respect to specific causal or functional systems determines the common system and the projected inference.

Consistent with these claims, there is evidence that adults' property induction is

[9]The persistent non-monotonicity effect found in both the Osherson et al. studies and the Lopez et al. studies – in which inference strength goes *down* with the addition of premises, contrary to the monotonicity prediction that increasing the number of premises should increase inductive strength – may reflect structural alignment of the premise categories. For example, *crow*, *peacock* → *bird* is stronger than *crow*, *peacock*, *rabbit* → *bird*. In the first case, the premises are strongly alignable, yielding a rich 'premise schema' which can project inferences to the conclusion category. The addition of a difficult-to-align premise (rabbit) may force a retreat from alignment-based reasoning to category-based reasoning – from strong reasoning to weak reasoning, in the Newell and Simon sense. Osherson et al. speculate that the effect arises from coverage effects; by enlarging the size of the inferred covering category, the similarity to the premise and conclusion categories is diluted. However, Sloman's (1993) example that *crocodile* → *alligator* is stronger than *crocodile*, *king snake* → *alligator* cannot be explained in this way (but could be explained by premise alignment, because *crocodile* has a richer match with *alligator* than does the premise schema that results from aligning *crocodile* and *king snake*).

guided by structural similarity, not merely by featural overlap. Lassaline (1996) found that argument strength did not depend on the overall similarity between premise and conclusion, but on whether there was a causally-connected inference that could be carried over as a candidate inference (as in Clement and Gentner, 1991). Further evidence that people are sensitive to connected *systems* of relations in induction comes from a study by Heit and Rubinstein (1994), who demonstrated that people make stronger inferences when the kind of property to be inferred (anatomical or behavioral) matches the kind of similarity between the animals (anatomical or behavioral). For instance, people make stronger behavioral inferences from tuna to whales (because both swim) than from bears to whales, but stronger anatomical inferences from, whales to bears (because both are mammals). If we assume that anatomy and behavior are represented by different systems of relations, then these findings are consistent with the finding that adults are strongly influenced by causal systematicity in drawing inferences from an analogy (Clement and Gentner, 1991; Bowdle and Gentner, 1998; Markman, 1998).

Overall, the findings on inductive reasoning in children and adults offer no compelling evidence for the idea that comparison is merely a stand-in or fall-back strategy when theory fails. Inagaki (1990) found that children who raised goldfish were more likely than those who did not to draw analogies from people to goldfish, despite the fact that they demonstrably knew *more* about goldfish. Thus the interpretation that analogy is used only in default of deeper knowledge is not tenable. Indeed, deeper knowledge of the target domain – goldfish – made children better able to notice and use commonalities that license cross-species analogies. This pattern fits the claim that alignment and mapping are instrumental in theory development. However, we *could* say that overall similarity is a stand-in for structural similarity, when the child has inadequate relational knowledge. The results suggest a knowledge-driven shift from analogies based on perceptual similarity to (a) analogies based on causal and relational similarity, and (b) derived abstractions.

7. The problem of selection of prior instances: why experiential learning is not sufficient

We have presented a case that comparison can be illuminating. But as Smith et al. point out, the benefits of comparison are crucially dependent on *which* instances are compared. Analogies will play a beneficial role in learning and reasoning only to the extent that the pairs that are compared are legitimately structurally similar. At first glance, the data are not encouraging. There is abundant evidence that memory retrieval is highly responsive to surface similarity between the current item and the prior stored item (e.g. the similarity of objects and characters) and relatively insensitive to relational similarity (Holyoak and Koh, 1987; Reed, 1987; Ross, 1987, 1989; Keane, 1988; Gentner et al., 1993; Reeves and Weisberg, 1994). This is true even when, once both items are present, people judge the match’s quality and inferential soundness on the basis of structural similarity, ignoring surface similarity. For example, Gentner and Schumacher gave subjects a continuous reminding task in which they saw about 100 proverbs and for each one wrote out any previous proverbs that they were reminded of. Subjects were reminded of prior identity pairs (not surprisingly) and of prior mere-appearance pairs sharing a single nominal concept – e.g. ‘a hair from here, a hair from there, will make a beard’ and ‘it is not the beard that makes the philosopher’. They were far less often reminded of prior relational matches – e.g. ‘remove the dirt from your own eye before you wipe the speck from mine’ and ‘he who laughs at a crooked man should walk very straight’. Yet, in a subsequent rating task, they rated the analogy pairs (whether or not they had recalled them) as both more sound and more similar than the surface matches. Strangely, the very matches that come to mind most easily are often judged by the same subjects to be least useful in reasoning (See also Gentner et al., 1993).

If memory retrieval is strongly driven by surface similarity, then spontaneous comparisons are problematic as a route to insight. Comparisons among merely surface-similar instances would not only fail to promote rule-abstraction, they would lead to false generalizations. However, there are some rays of hope. First, people are not at the mercy of their memories, as noted above, subjects tend to reject surface remindings as inferentially worthless. Second, the study above is a bit oversimplified in its total separation of surface similarity from structural similarity. In real life, the two are highly correlated. This consideration leads to the *kind world* hypothesis: most things that look alike are alike relationally as well (Gentner, 1989; Medin and Ortony, 1989) – what looks like a tiger generally is a tiger. Of course, children will sometimes try improper similarity matches, our point is that there are vast numbers of useful overall similarity matches to be had. However, this is still not enough. Even given a kind world, purely experiential juxtapositions are not sufficient to explain the observed sophistication of adult thought. A further crucial factor, as discussed throughout, is the guiding effects of language and culture. We return to this point below.

8. Summary and discussion

We have argued that there is a continuum between similarity-based and rule-based processes and, further, that the process of structural comparison acts as a bridge by which similarity-based processes can give rise to abstract rules. This view of gradual abstraction of initially-conservative, context-specific representations is consistent with the proposal that abstractions can arise from comparison across highly specific instances (Elio and Anderson, 1981; Gick and Holyoak, 1983; Cheng and Holyoak, 1985; Forbus and Gentner, 1986; Medin and Ross, 1989). There is a graceful learning continuum from a fully-concrete mapping, in which the objects transparently match their intended correspondents, to an analogical mapping in which a relational structure is imported to a new domain with no support (or even with conflict) from the object matches, to a fully-abstract mapping in which the base domain contains variables and the target contains objects. At this point the mapping could be described as unification or rule application.

Our case for comparison as a bridge to abstraction has three broad themes. First, comparison provides learning mechanisms that promote learning. The mechanisms of highlighting, inference projection and re-representation have been attested empirically. More directly, we provided evidence that comparison can foster children's learning in diverse tasks, including detecting abstract cross-dimensional relational matches, mapping between two arrays, and category learning. Second, we gave evidence that even among adults there is a mix of comparison-based and rule-based processing, as would be expected if rules are typically formed by gradual abstraction from instances. For example, in category-based induction,[10] young children rely almost exclusively on comparison, while adults appear to use both comparison and category-level knowledge (though see Sloman (1996) for counter-arguments to the latter point). Third, we argued that even after abstract knowledge is present, alignment processes are needed to extend this knowledge to new cases.

The research discussed here is consistent with our claim that children's early representations are conservative and context-specific, relying on massive overlap of perceptual features, and that children gradually develop relationally-articulated representations that enable them to appreciate partial similarity and analogy. We considered two related ways of fostering relational insight: first, the progressive alignment of a series of cases so as to reveal common relational structure and, second, the use of relational language to invite the perception of common relations. The first of these represents alignment through experiential juxtaposition, the second, alignment through symbolic juxtaposition.

9. Arguments against similarity

Defenders of comparison processes must deal with Goodman's (1972) influential arguments against similarity. He argues that the claim that two things are similar is uninformative until we specify in *what respect* they are similar, and that when we do so the similarity statement reduces to whatever specific respect categorizes the items compared. So, for instance, to say that the numbers 8 and 10 have something in common is ambiguous, because there are many properties these numbers can share, but the more specific claim that 8 and 10 are similar because both are divisible by 2 is just to say that they are both even numbers. Thus similarity is either vague or superfluous.

However, as Kripke (1982) has pointed out, Goodman's arguments against similarity were inspired by Wittgenstein's discussion of rule-following but left part of Wittgenstein's discussion behind. Wittgenstein (1953) argues that 'what counts as the same or similar' cannot be established independently of our rule-governed activities, for anything can be similar to anything else in some respect. For example, if someone is given the series '2,4,6,8...' and is asked to 'go on in the same way', it is

[10]Content effects in deductive reasoning provide another example in which adults often use analogies to prior knowledge in cases where purely formal methods could apply (as in Cheng and Holyoak's (1985) discussion of the Wason card task).

indeterminate what is to count as the correct continuation (Wittgenstein, 1953). Following the rule cannot consist simply in being guided by our sense of similarity, for anything can count as 'going on in the same way' under some interpretation of the relevant similarities underlying the sequence '2,4,6,8...'. What is needed is just a grasp of the rule governing this number sequence – e.g. '+2'.

So far Wittgenstein's argument is that *similarities without rules are empty*, just as Goodman later argued. However, Wittgenstein goes on to apply the same reasoning to rule-following. He argues that following a rule cannot consist simply in being guided by a representation of the rule (e.g. '+2'). Such a representation *by itself* does not determine unequivocally how to continue the number series, for it can be interpreted and applied in various ways (e.g. as '$x + 2$ if $x < 1000$, otherwise $x + 4$'). Wittgenstein emphasizes that rules are not self-interpreting: a rule does not contain within itself what counts as a correct application to each new case. One might address this concern by postulating further rules that fix the application of the rule, but this would lead to a regress, for these rules would also stand in need of interpretation. Wittgenstein's point is that, in order to be cognitively useful, rules have to be supplemented with standards of similarity for their application. As some commentators have emphasized (Baker and Hacker, 1984; Williams, 1994), the upshot of Wittgenstein's discussion is that our capacity to follow a rule is crucially dependent on our grasp of 'normative similarities', i.e. to similarities that have been disciplined by norms in rule-governed practices. Gagné (1970) notes that 'one could perhaps think of a whole range of situations of potential applicability of a learned rule that displayed decreasing degrees of similarity to the situation in which the rule had originally been learned' – an idea that mirrors our notion of progressive abstraction. Wittgenstein's arguments underscore the strong interdependence of rules and similarity. Goodman exploited the first strand of Wittgenstein's arguments, thereby posing a challenge to similarity theorists. However, the second part of Wittgenstein's argument, although often overlooked, is equally important. In short, we could summarize Wittgenstein's rule-following discussion by rephrasing the Kantian dictum about concepts and intuitions: *similarities without rules are empty*, *rules without similarities are blind*.

10. Separate systems for similarity and rules?

Some cognitive researchers have proposed that similarity-based and rule-based processes are both important in human cognition, but that they function as different cognitive systems (Smolensky, 1988; Sloman, 1996). Smolensky (1988) has argued that reasoning involves two different mechanisms: a conscious rule interpreter that processes knowledge algorithmically and an intuitive processor that operates at the subconceptual level. A more specific proposal is Sloman's (1996) proposal of two independent but interacting systems of reasoning, one associative and similarity-based, the other symbolic and rule-based. In Sloman's account, the associative system encodes and processes the covariation of features in the environment and makes estimates based on statistical regularities. In contrast, the rule-based system operates on structured symbolic representations and reasons on the basis of underlying causal or mechanical structure. As evidence for the existence of two independent systems of reasoning, Sloman cites strong dissociations between rules and similarity seen in fallacies like the inclusion fallacy or the conjunction fallacy, where similarity and rules lead to contradictory conclusions (Tversky and Kahneman, 1983; Smith and Osherson, 1989; Shafir et al., 1990). For instance, in the celebrated ‘Linda the bank teller’ example of the conjunction fallacy (Tversky and Kahneman, 1983) participants judged that Linda (who, as a student, ‘was deeply concerned with issues of discrimination and social justice’) was more likely to be ‘a bank teller and active in the feminist movement’ (B and F) than ‘a bank teller’ (B). One explanation of this phenomenon is that participants were swayed by the greater similarity of the description of Linda to a ‘feminist bank teller’ than to the typical bank teller (Smith and Osherson, 1989). Even people who know that B and F cannot be more probable than B experience the lure of the conjunctive solution. Sloman argues that this strong inclination to draw contradictory inferences is due to a conflict between the rule-based and the similarity-associative reasoning systems.

Contradictory responses could be generated *within* a single comparison-based reasoning system, however, in at least three ways. First the retrieval process may produce more than one alternative for a given contextual probe. Second, once two comparands are present in working memory, the local-to-global alignment process discussed above often produces contradictory responses over time, since early responses will be dominated by local object matches and later responses by the relational alignment (Falkenhainer et al., 1989; Ratcliff and McKoon, 1989; Goldstone, 1994a; Goldstone and Medin, 1994). A third way is that the same comparison can give rise to two alternative interpretations, even under the same correspondences. For example, the statement that a given battle ‘is the mother of battles’ could mean that it is the biggest (as a parent is larger than her offspring) or that it will engender a host of others (which may be larger than the parent).

Although we find much to agree with in Sloman’s two-system proposal, we think it incorrect to relegate comparison processes to an associative subsymbolic system. First, the accumulated evidence that the comparison process is structure-sensitive (Gentner and Clement, 1988; Gentner and Markman, 1993, 1994, 1997; Markman and Gentner, 1993a, 1996; Medin et al., 1993; Goldstone and Medin, 1994) suggests that similarity cannot be captured by merely associative processes. To capture similarity processing requires representations that include structural dependencies among their parts – the same kind of structural specificity that is necessary for the representation of rules.[11] Second, the evidence reviewed here shows that the process of structural alignment can promote the noticing of structural regularities (Gick and Holyoak, 1983; Markman and Gentner, 1993a; Gentner and Imai, 1995; Kotovsky and Gentner, 1996) and that rule-based reasoning is bootstrapped by comparisons between symbolically-structured representations. Thus we argue that similarity – or,

[11]Gentner and Markman (1993) have laid out a set of benchmark phenomena that computational models, including connectionist models, must demonstrate in order to be said to have captured the phenomena of structural similarity and analogy.

more accurately, the comparison process – must have full citizenship in the same symbolic cognitive system that contains rules.[12]

11. Implications for cognitive development: is onward always upward?

Our assessment of the developmental evidence suggests that the abstractness and content-independence characteristic of abstract cognition (Smith et al., 1992; Rips, 1994) are the result of considerable experience. On the ‘career of similarity’ view, similarity comparisons are initially conservative – heavily perceptual and context-bound – and become increasingly abstract and structurally-articulated with domain experience and with enculturation. This framework also emphasizes the possibility of cognitive pluralism. Adult cognition includes knowledge-intensive reasoning processes – e.g. strong similarity-based inferences – as well as general-purpose weak reasoning methods such as *modus ponens*. As Quine (1969) puts it, people ‘retain different similarity standards... for use in different contexts’. According to our framework, rule-governed processes are based on structural similarity, but they may coexist, in adult cognition, with processes governed by other forms of similarity.

As discussed above, there is a danger in overrating the cognitive centrality of weak methods. General, abstract processes such as deductive inference or category-based reasoning tend to strike us as particularly elegant forms of cognition. However, recent evidence from cross-cultural research suggests that we should be cautious about assuming that particular weak methods are either central or universal in cognition. For example, Lopez et al. (1997) found that inductive reasoning among the Itzaj-Mayans resembled that of American subjects in making heavy use of similarity and typicality, but differed in its lack of reliance on premise diversity. When premise variability was high, Mayans often drew on their ecological knowledge concerning relations among the creatures, whereas Americans tended to compute a more abstract category. One way of construing these results is that the Mayans, who possess far more detailed knowledge of their ecology than do the American subjects, could and did rely on strong methods, such as strong representational alignment and detailed causal knowledge of interactions. These results suggest that which weak methods are developed and how they are used may be culturally influenced to some degree.

11.1. The role of language

Children delight in experiential comparisons. From the circular reaction in infancy, to sand-castles built and rebuilt, to crib talk, children love to present themselves with examples and variations. Yet learning via experiential juxtaposition

[12]However, we concede that some kinds of similarity may indeed be part of an associative system. For example, a kind of associative similarity may arise from caching the results of repeated similarity computations. (We probably do not need to recompute the alignment between *horse* and *zebra* when we encounter them anew, for example.)

alone would be hopelessly unsatisfactory. As the history of science makes clear, if each of us learned from the world alone we would lack such intellectual amenities as rational numbers, a zero, Newton's laws and other tools of thought. For these reasons, we've emphasized the role of culture and language in learning: specifically, in inviting comparisons. Common language can invite symbolic juxtaposition and serve as a signal that there are important commonalities to be discovered. In this way, language and other cultural systems influence which comparisons get made. Language thus augments direct experiential learning in two ways. First, by giving two things the same name, we invite children to compare them, even if they do not occur together in experience. Second, learning words for relations may increase the likelihood that the learner will encode relations in the same way across different situations. Such representational uniformity would promote cross-situation remindings. Thus when relational concepts become part of our mental store, they may facilitate implicit application of the cultural theories they embody to new experience.

Vygotsky (1962) argued that with the advent of language children augment their repertoire of pre-linguistic cognitive capabilities – reactive attention, associative learning and sensorimotor intelligence – with post-linguistic capabilities of focused attention, deliberate memory and symbolic thought (see also Bruner et al., 1966; Dennett, 1993). We would amplify this proposal by noting that symbolic representations permit structural comparison processes. Once language is present, the child may continue to use her associative system, but also possesses a symbolic system that permits structural representations and structured comparison processes. There is recent intriguing evidence of new cognitive capabilities at around the time that language emerges. Mandler and McDonough (1993) and Mandler (1996) find that 14-month-olds and probably 11-month-olds, but not 7–9-month-olds, will imitate actions across basic level categories. Xu and Carey (1996) found evidence that 12-month-olds, but not 10-month-olds, individuate objects on the basis of object kind and, further, that this ability may be correlated with knowledge of the names of the objects.

11.2. Conclusions

Although similarity is often treated rather slightingly in current theories of cognitive development, we suggest that similarity – even mundane within-dimension similarity – can act as a positive force in learning and development. We propose that simply carrying out similarity and analogy comparisons plays a fundamental role in the development of abstract structural representations. Comparisons – even overall similarity comparisons – can lead the child to focus on relational commonalities that would otherwise pass unnoticed. These structures may then be mapped from well-understood situations to less-understood situations.

We have argued that the capacity to perceive structural similarity is crucial for the development of an abstract symbolic system. Our point is not that structural similarity can replace rules, nor that rules are inevitably acquired via progressive abstraction. (After all, sometimes we are simply told the rule.) What we do suggest is that comparison is very often the critical path in the development of rules, especially early in development when higher-order knowledge is sparse and requires the support of concrete commonalities. Furthermore, we argue that at any age, structural alignment provides the necessary bridge in applying rules and abstract knowledge to ongoing experience. Comparison is fundamental to the development and use of rules in cognition.

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