consider two of the terms in the three-relation (see sect. 3.5). Hence, 3-year-olds default to the more familiar judgment (Frye et al. 1996) and make the realist error of concluding that everyone will see the situation as it really is.

Another advantage of complexity, one that may be unique, is that it manifests what the target article labels "omni-directional access" (sect. 2.2.6). When children master a set of relations, there are a number of different, equivalent problems they will be able to solve. Consequently, it becomes possible to predict that seemingly unrelated developments will have a common source. For example, it is well established that children's understanding of false belief is connected to their ability to act deceptively (Wimmer & Perner 1983) although this link could be conceptual, given belief is involved in both. However, theory of mind has now been shown to be related to executive function (for a review, see Zelazo et al. 1997) – that is, the development of children's abilities to control their own actions. Mental state understanding and control of one's own actions do not share an obvious conceptual link, yet their similarity can be explained in a complexity account (Frye, in press; Zelazo et al. 1997).

Despite the similarities, there are some points of disagreement between the complexity proposals of the target article and CCC theory. Both now indicate that a conditional (basically, an *or* that selects between perspectives – the child's and the other person's in false belief) forms the ternary relation that supports the acquisition of theory of mind. However, the relational complexity account fails to recognize the hierarchical dependency that obtains among dimensions in this instance (although it could in principle; see sect. 4.2.5). For example, one cannot tell by looking at the ternary relation, Seen-Object (<condition>, <object-colour>, <percept>), whether one argument controls the others. In contrast, on the CCC account, the task is difficult precisely because it requires a hierarchical rule structure.

Moreover, the relational complexity account does not appear to consider the relation's type when predicting developmental difficulty. All that seems important is the complexity of the relation. CCC theory distinguishes among relational types in addition to structural complexity. Theory of mind involves choosing between perspectives, ignoring a familiar one to judge from the other, which will be simpler than combining perspectives, even though both require ternary relations. Being able to select flexibly between dimensions occurs earlier than the feat of combining them (Frye et al. 1995, Experiment 3). The distinction among relational types makes it possible to explain why theory of mind appears at about 4 years, rather than at the end of preschool when conservation and matrix classification – the classic examples of combining dimensions – occur.

The target article also appears to underestimate other control or performance factors, with the consequence that it neglects the variety of variables that affects the likelihood children will actually use their knowledge to guide action in any particular situation. Success on problems such as the A-not-B task is not simply a matter of unary relations. There is ample evidence that children who can master the relational complexity nonetheless commit the A-not-B error under certain circumstances. For example, Zelazo et al. (1998) found that 24-month-olds perseverated on a multistep, multilocation version of the A-not-B task. Presumably these children understood the relational complexity of the problem: adding steps and locations does not involve adding a new dimension. Yet, they apparently had trouble maintaining attention to the relevant information and inhibiting a tendency to repeat a previously rewarded response. The point is that actual action cannot be explained by logical relations and domain-specific knowledge alone. The relational complexity approach adds a great deal to our understanding of understanding, but it under-emphasizes the importance of the control processes that extend from understanding to action.

Deep thinking in children: The case for knowledge change in analogical development

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Abstract: Halford, Wilson & Phillips argue that cognitive development is driven by increases in processing capacity. We suggest that changes in relational knowledge are as important or more so. We present evidence that 3-year-olds' analogical abilities are sharply improved by teaching them relational labels; over a 30-minute experimental session children gained approximately 2 years in effective performance. These results mandate caution interpreting age-related change as indicating maturational change, and call for a deeper consideration of the role of epistemological change in cognitive development.

In their fascinating and provocative target article, Halford et al. present developmental and comparative evidence for the thesis that cognitive development is driven by increases in processing capacity. We challenge this account as it applies to the development of analogy. In Halford's relational complexity account, children's ability to carry out analogical matches increases maturationally with increasing processing capacity, from unary relations (object matches) through binary relations, ternary relations, and finally quaternary relations. We also have theorized a shift from objects to relations in the development of analogy (Gentner 1988; Gentner & Rattermann 1991; Gentner & Toupin 1986). However, we postulate a change in the depth of the relational structures that can be matched (Gentner 1993; Gentner & Markman 1997), rather than in the dimensionality of the relations. The sequence we propose is, first, object similarity matches (e.g., red ball/apple); then, relations between objects (e.g., ball rolling on table/toy car rolling on floor); and then higher-order relations between relations (e.g., ball's rolling causes glass to fall/car's rolling causes vase to fall). We further suggest that change of knowledge, not change of processing capacity, is the main driver of this evolution (Brown 1989). This knowledge-based claim is supported by the observation that the relational shift occurs at different ages – ranging from infancy to adulthood – in different domains, depending on level of knowledge.

A key prediction in Halford et al.'s account is that children under 4–5 years cannot process ternary relations nor integrate two binary relations. Halford et al. consider one challenge to this claim, namely, Goswami's (1995) studies suggesting that 3-year-olds can map ternary relations in analogies. Their reanalysis shows that in Goswami's task the correct relational response was often the best object-similarity match (based on closest absolute size), compromising her evidence for relational processing. However, our studies using similar methods pose a stronger challenge (Gentner & Rattermann 1991). We placed object similarity in direct competition with relational similarity (using Gentner and Toupin's cross-mapping technique), so that the relational match was never supported by object similarity. We showed 3-, 4- and 5-year-olds two triads of objects, each arranged in monotonically decreasing size (e.g., 4 3 2 → 3 2 1) in a fanlike pattern. The child watched the experimenter place a sticker under an object in her set and then searched in his own set for a sticker hidden under the corresponding object. Because of the cross-mapping, matches based on object similarity (e.g., 3 → 3) competed against matches based on relational similarity (e.g., 3 → 2). The child received feedback on the correct answer, which was always based on relational similarity.

The results show a strong developmental change, from 43% correct in 3-year-olds to 82% correct in 5-year-olds. So far this pattern is consistent with either a maturational or a knowledge-based account. However, further results suggest that the difference between the 3-year-olds and the 5-year-olds lay in their knowledge of the relevant relations: specifically, the higher-order relation of

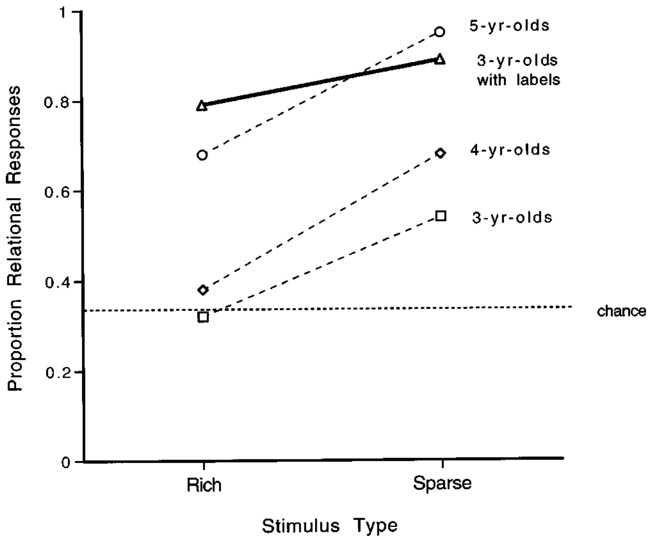

Figure 1 (Gentner). Proportion correct relational responses for different ages on a cross-mapped analogy task with relational lables (solid line) and without them (dashed lines).

monotonic change that governs the two lower-order relative size relations.

According to the knowledge-based account, increasing children's relational knowledge can lead to improved analogical performance. To test this, we taught a group of 3-year-olds to use the relational labels "Daddy/Mommy/Baby," which convey the relation of monotonic change. When the labels were used on each trial, 3-year-olds were 84% correct, performing comparably to the 5-year-olds in the original task (see Fig. 1). (Similar results were obtained with the relational labels "big/little/tiny.") The beneficial effects of learning relational labels were not dependent on direct modeling. After experience with the "Daddy/Mommy/Baby" labels, 3-year-olds maintained much of their gain (57%) when given new stimuli on which no labels were used. Indeed, 3-year-olds who returned four to eight weeks after the initial session produced significantly more correct relational responses (62%) than a control group without label experience (28%; Rattermann & Gentner, in preparation).

Why would these labels be so effective that the benefits persist four to eight weeks later? Our explanation is that the "Daddy/Mommy/Baby" labels act to invite a higher-order relational structure. With this structure, the relational mapping is sufficiently deep and internally constraining that it can compete successfully with the local object match. (Markman & Gentner [1993] found a similar relation between relational depth and object similarity in adults.) These striking changes in performance are a testament to the importance of learned relational structure in children's analogical mapping, and by extension in the development of relational reasoning in general. These findings challenge Halford's account of development, first, because they show that 3-year-olds can carry out mappings based on what in his account are ternary relations; and, second, because they establish that striking changes of performance – equivalent to that of a 2-year-age gain – can occur even over the course of one experimental session, based on the acquisition of relational knowledge.

Halford has suggested that 3-year-olds succeed in our cross-mapping task not by representing the relationship of monotonic change across the three objects (a ternary relation that should be beyond their capacity), but rather by chunking the three objects into two sets – *the chosen object* and *the other two objects* – thus permitting a simple binary relation (Halford et al. 1995). For example, the child would process a Mommy → Mommy match by encoding two chunks: [Mommy] vs. [Daddy and Baby]. But this encoding seems implausible. First, it would require the children to repeatedly rechunk the stimulus set, as the chosen object changes on each trial. Second, in middle-object examples like the above, a split chunk would be required. Third, it is hard to see how such a binary encoding would result from the use of the triadic relationship "Daddy/Mommy/Baby."

Halford and his colleagues acknowledge that knowledge accretion plays a role in development, but in their theory the major impetus is maturational change in processing capacity. Clearly, neurological change influences children's developing abilities. But as the above results demonstrate, one needs to be cautious about interpreting age-related change as resulting from capacity change. We believe that our evidence calls for deeper consideration of the role of epistemological change in cognitive development.

Is relational complexity a useful metric for cognitive development?

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Abstract: This commentary focusses on the evidence used by Halford et al. to support their postulated links between relational complexity and age differences in children's understanding of concepts. None of their developmental claims is consistent with recent cognitive-developmental research. Relational complexity must be an important variable in cognition, but it does not provide a satisfactory metric for explaining cognitive development.

Halford et al. have presented an elegant theory of how relational complexity can be modelled. Their view has impressive support from neural net applications. Their "core argument," however, concerns the applicability of their theory to human cognition (sect. 1). This core argument must stand or fall on the basis of empirical evidence. My comments will focus on the postulated links between relational complexity and age differences in children's understanding of concepts. The key issue is whether relational complexity is a useful metric for *explaining* cognitive development. I will show that, although Halford et al. point out that a capacity approach does not imply insurmountable barriers to performance, and although they make a number of caveats (which limit the testability of their theory), a survey of current research in developmental psychology does not fit neatly into their theoretical framework.

Halford et al.'s first claim is that in infancy representation is limited to objects in the immediate spatio-temporal frame. "There is no evidence that semantically interpretable relations are represented, however, or that inferences go beyond the perceptible properties of objects" (sect. 6.2.1). This is not the case. Recent infancy research has shown that some forms of relational reasoning are present in the first year. For example, Baillargeon has shown that 4- to 5-month-old infants are surprised by "impossible" physical events in situations where surprise must be based on inferences about cause-effect relations that occur outside the immediate spatio-temporal frame (e.g., Baillargeon 1994; Baillargeon & Graber 1987; Baillargeon et al. 1990). Infants can even impose an "intentional stance" onto simple perceptual events, making assumptions of agency on the basis of causal analyses of impoverished physical situations such as computer displays of moving circles (e.g., Gergely et al. 1995; see Goswami, 1998, for a review). Baillargeon's conclusion that the infants in her experiments are engaging in a knowledge-based, conceptual analysis of the physical world is increasingly accepted in developmental psychology.

Halford et al.'s second claim is that the disappearance of well-documented phenomena in infancy such as the A-not-B search error can be explained by their theory. They suggest that the A-not-B error should be understood in terms of "an inability to treat hiding place as a variable" (sect. 6.2.2). They argue that perseverative searching at location A occurs because infants treat hiding place as a constant. Yet similar perseverative errors are made when