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Neurocognitive Process Constraints on Analogy: What Changes to Allow Children to Reason like Adults?

Robert G. Morrison
Loyola University Chicago, rmorrison@luc.edu

Soohyun Cho
University of California - Los Angeles, soohyun@psych.ucla.edu

the appropriate layers and interleaved the appropriate control process at just the right time to ensure that each of the necessary relations was picked out in turn. How else could it be that the model never cycled through the same relation twice, or searched for a nonexistent element and became stuck?

In contrast, structural alignment assumes that inferences involve facts from the base that are connected to matching higher-order relations between base and target (Clement & Gentner 1991). This systematic relational structure and the preference for systematicity thus provide constraints on inferences such that structural accounts can function even with rich natural concepts and without any external direction. In addition, the inferences can easily be incorporated into the representation of the target domain.

The authors of the target article try to head off criticisms of this variety by suggesting that explicit mappings (and presumably inferences) could be carried out by different processes than the more implicit processes that find correspondences between domains. The authors use the example of semantic priming in language to illustrate their point. If their suggestion turns out to be correct, then it is those processes that could form the basis for a new theory of analogy. Therefore, the theory posited by the authors may help us to understand some of the sub-processes that are recruited during analogical processing, but it is not actually a theory of analogical processing itself. Indeed, it is worth noting that semantic priming is not taken to be a theory of language; rather, it is understood to be a sub-process that is used in language.

If there were no computational models of analogical reasoning that encompassed both mapping and inference processes, and if those models had never been applied to both developmental and adult data, then it might be reasonable to divide these processes into separate components and assume that two distinct models are required to account for them. However, models like the Structure-Mapping Engine (SME) (Falkenhainer et al. 1989) and Learning and Inference with Schemas and Analogies (LISA) (Hummel & Holyoak 1997) are designed to account for both analogical mapping and inference, and both models are able to make use of higher-order relations in their domain representations. Furthermore, as the target article notes, SME has been applied to developmental tasks (Gentner et al. 1995). Thus, it seems unparsimonious to assume that analogical reasoning abilities begin with processes that cannot ultimately perform the variety of tasks that are clearly part of the repertoire of older children and adults.

Although a developmental approach to analogy has the potential to offer great value, it must ultimately point the way toward adult analogical competence in order to actually deliver that value. That is, to be a successful developmental account, a theory must begin at a reasonable starting point and demonstrate the path/process through which the system progresses to reach the known end state. The ARP theory does not explain full competence, and cannot, in principle, be extended to do so without it becoming a part of a larger theory.

Neurocognitive process constraints on analogy: What changes to allow children to reason like adults?

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Robert G. Morrison[a] and Soohyun Cho[b]

[a]*Department of Psychology, Northwestern University, Evanston, IL 60208-2710;* [b]*Department of Psychology, University of California, Los Angeles, Los Angeles, CA 90095-1563.*

morrison@northwestern.edu
http://www.morrisonlab.org
soohyun@psych.ucla.edu
http://shcho.bol.ucla.edu

Abstract: Analogy employs a neurocognitive working-memory (WM) system to activate and bind relational representations, integrate multiple relations, and suppress distracting information. Analogy experiments exploring these processes have used a variety of methodologies including dual tasks, neuropsychology, and functional neuroimaging, as well as experiments with children and older adults. Collectively, these experiments provide a rich set of results useful in evaluating any model of analogy and its development.

Analogy involves a structured comparison, or *mapping*, between one situation (*source*) and another (*target*). For instance, a reasoner may be given a problem such as:

bird:nest::bear: ?

and be asked which word, CAVE or HONEY, completes the analogy. To choose CAVE, the participant would need to realize that birds *live in* nests as bears *live in* caves while not being distracted by the fact that bears *eat* honey. Using several priming tasks, Spellman et al. (2001) investigated whether analogy might just be a consequence of the organization of concepts in semantic memory. They found that unlike traditional semantic priming, "analogical" priming was not automatic and instead required the participant to direct attention to relations between word pairs. This suggested that controlled retrieval of a bound relation into working memory (WM) may be a necessary process for analogical reasoning. Subsequent experiments demonstrated that WM was indeed important for analogical mapping (e.g., Morrison et al. 2001), as well as relational binding (see Morrison 2005), a finding confirmed using functional magnetic resonance imaging (fMRI; Bunge et al. 2005).

WM is also important for suppressing distracting information, such as irrelevant semantic associates or featural similarities likely to enter WM during analogical retrieval and mapping. Waltz et al. (2000) demonstrated that adults performing a semantically rich scene-analogy task shifted from preferring analogical to featural mappings under WM dual-tasks. Using the same task, Morrison et al. (2004) found that frontal patients with damage to WM areas showed a similar pattern. Morrison et al. also developed an A:B::C:D or D′ verbal analogy task that required participants to choose between D (analogically correct choice) and D′ (foil), which were both semantically related to the C term of the analogy. When the foil was more semantically associated to the C term than was the correct choice, frontal patients performed near chance. In contrast, semantic dementia patients who exhibited profound decrements in relational knowledge performed poorly on all of the verbal analogies regardless of the degree of semantic association between C:D and C:D′. Using the same task, Cho et al. (2007b) found that individuals who scored higher on the Raven's Progressive Matrices (RPM) showed greater fMRI activation increase in neural areas, including the prefrontal and visual cortices, on trials in which reasoners had to reject foils that were highly associated with the C term. This finding suggests that there are neural regions whose level of activation for interference resolution during analogical reasoning relates to individual differences in fluid intellectual capacity.

Many real-world analogies, as well as reasoning tasks developed for psychometric purposes such as the RPM and People Pieces Analogy task (PPA; Sternberg 1977b), require integration of multiple relations to map more relationally complex analogies. Numerous fMRI studies (e.g., Christoff et al. 2001; Kroger et al. 2002) have shown increasing levels of activation in anterior prefrontal cortex for more relationally complex RPM problems, a finding consistent with a neuropsychological study with frontal patients (Waltz et al. 1999). Using an adaptation of the PPA task, Viskontas et al. (2004) found that older adults showed decrements in both relational integration and relational distraction. Using this same task, Cho et al. (2007a) found that executive resources are shared between relational integration and interference resolution during analogical reasoning. In an fMRI follow-up study, Cho et al. (2007c) found partially overlapping but distinct regions within inferior frontal gyri (IFG) showing sensitivity to each component process of analogical reasoning. Separate regions that showed exclusive sensitivity to each component process were also identified within IFG. In addition, the degree of activation increase in the right ventral IFG during trials in which participants had to integrate three relations (compared to one) was greater for individuals whose performance accuracy was higher.

Although the above studies do not directly deal with the development of analogy during childhood, they do clearly demonstrate several component processes involved in analogical reasoning that are dependent on prefrontal cortex, an area of the brain that actively develops throughout childhood (Diamond 2002). In an effort to explore these processes directly in children, Richland et al. (2006) developed a scene-analogy task manipulating both relational complexity and featural distraction. Even 3-year-olds could solve simple (one-relation, no-distraction) problems, but they had difficulty if the problem required integration of multiple relations or ignoring a featurally similar object. Similarly, Wright et al. (2007) performed an fMRI study with children using another semantically rich visual analogy task, and found that brain activation in areas associated with relational integration was the best predictor of analogy performance. Wright et al. also found that these areas, which are not associated with semantic retrieval (Bunge et al. 2005), become more and more engaged over the same time period in which children dramatically improve in their ability to solve more relationally complex problems (Richland et al. 2006).

We are highly sympathetic with the target article's efforts to computationally model the development of analogy, and we certainly don't dispute the importance of relational knowledge in development. However, we believe that a successful model of development must (1) explain how knowledge representation and process constraints interact to produce the changes in analogy observed in children, including increases in ability to perform relational integration and resist featural distraction; and (2) explain how an architecture consistent with the demands of adult analogical reasoning develops. Unfortunately, the connectionist model described in the target article does not meet these requirements. In contrast, Morrison and collaborators have used LISA (Learning and Inference with Schemas and Analogies; Hummel & Holyoak 1997; 2003), a neurally plausible model of analogical reasoning, to successfully simulate many of the developmental and neuropsychological results discussed in this commentary (e.g., Morrison et al. 2004; 2006; Viskontas et al. 2004).

We believe that the development of analogical reasoning is best conceptualized as an equilibrium between children's relational knowledge and their current processing ability. As children mature, their prefrontal cortices more efficiently implement WM and thereby can process more complex analogies. However, more efficient relational representations can impose fewer processing demands at any given age, which is why a child who becomes an expert in a given domain can show rapid progress even though the child's WM system has not improved (Morrison et al. 2007). This framework can account for the observed changes in children's analogical reasoning, as well as subsequent changes in analogy during normal and abnormal human aging. It can also be simulated in symbolic-connectionist models of relational learning and reasoning (e.g., Doumas et al. 2008; Hummel & Holyoak 1997; 2003).

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Relational priming plays a supporting but not leading role in adult analogy-making

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Alexander A. Petrov

Department of Psychology, Ohio State University, Columbus, OH 43210.

apetrov@alexpetrov.com

http://alexpetrov.com

Abstract: Leech et al.'s analysis adds to an emerging consensus of the role of priming in analogy-making. However, their model cannot scale up to adult-level performance because not all relations can be cast as functions. One-size-fits-all accounts cannot capture the richness of analogy. Proportional analogies and transitive inferences can be made by nonstructural mechanisms. Therefore, these tasks do not generalize to tasks that require structure mapping.

Leech et al. argue forcefully that adult-level models of analogy-making must make contact with the developmental constraint. This argument cuts both ways: Developmental models must also make contact with adult-level capability. We argue that although relational priming does play a role in adult analogical reasoning, it does not play the leading role that Leech et al. suggest.

Relational priming. The role of priming in analogical reasoning is well documented empirically (e.g., Kokinov 1990; Schunn & Dunbar 1996). It also features prominently in several models, including Associative Memory-Based Reasoning (AMBR) (Kokinov 1994; Kokinov & Petrov 2001) and Copycat (French 1995; Hofstadter 1984; Mitchell 1993). All of these models implement priming as residual activation. The present proposal thus adds to an emerging consensus of the importance of priming and of its underlying mechanism.

Not all relations can be cast as functions. Leech et al. claim that "for the purposes of analogy it may be sufficient to conceptualize relations as transformations between items" (sect. 2.2, para. 2). The main idea is to cast each binary relation $R(a,b)$ as an equivalent univariate function[1] $b = F_R(a)$. The model uses hand-coded representations, *rep*, such that $rep(F_R(a)) = rep(a) + F_R(a)) = rep(a) + rep(R)$. The authors argue this is beneficial because "relations do not have to be represented explicitly, avoiding the difficulties of learning explicit structured representations" (sect. 5.1.1, para. 1). However, this benefit comes at the cost of rendering the model incapable of scaling up to adult-level performance.

The problem is that a relation can be cast as a function only if it is deterministic: that is, if for each a there is precisely one b that satisfies $R(a,b)$ (Halford et al. 1998). Many important relations violate this condition. Consider the transitive inference task: *taller*(*Ann*,*Beth*), *taller*(*Beth*,*Chris*) → *taller*(*Ann*,*Chris*). Now, if the relation *taller*(*a*,*b*) is cast as a function $b = shrink(a)$, the query $shrink(Ann) = ?$ becomes ambiguous. There are techniques for supporting nondeterministic functions in connectionist networks (e.g., Hinton & Sejnowski 1986) that can be incorporated into the model. However, the priming account faces a deeper challenge: Why should *Chris* be produced as the answer to the above query after the system has been primed with $Beth = shrink(Ann)$?

Many relationships in the world are indeed near-deterministic transformations such as *bread* → *cut bread*. It is an important developmental constraint that young children find such regular, familiar relations easier to deal with (e.g., Goswami & Brown 1989). These strong environmental regularities shape coarse-coded distributed representations that can support generalization and inference (Cer & O'Reilly 2006; Hinton 1990; Rogers & McClelland 2004; St. John & McClelland 1990). The target article demonstrates the utility of relational priming in these cases. However, there are also relationships such as *left of* that are quite accidental and changeable. To process them, the brain relies on sparse conjunctive representations (McClelland