

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

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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 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. (2007a) 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 1977), 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. (2007b) 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 (1-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 explain (1) 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) 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; Morrison et al. 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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