Cognitive Control as an Underpinning of Relational Abstraction and Reasoning from Diagrams

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Diagrams are powerful opportunities for grappling with and learning abstract relationships, for example learning the relations between elements in an ecosystem rather than simply memorizing the objects within the system. Further, what is crucial from any diagrammatic learning opportunity is the ability to use this relational knowledge in a new context or with new materials, beyond simply understanding the initial presentation. This is cognitively effortful, however, and individual differences in how reasoners benefit from such relational learning opportunities are not well understood. We describe a computational simulation that examines how cognitive control of attention enables relational learning from visual stimuli such as diagrams. Specifically, we propose that cognitive control is critical for both abstracting relational representations from that visual stimuli, and to the ability to use these representations in subsequent problem solving.

This study draws on extant behavioral longitudinal data from children who viewed and solved geometric analogy problems repeatedly over six months [1]. As shown in Figure 1, each set of stimuli were geometric diagrams that contained a key set of relationships. The study measured children's ability to notice and draw analogical inferences based on the key relationships within these representations, which is a key to successful diagrammatic reasoning. Problems used common relations such as above/below (see Figure 1). The complexity of the problems were varied by changing the number of relations needed to characterize the A:B transition. During testing, children were presented with A:B :: C:D problems in which they had to draw the D term to make a valid analogy. Importantly, children's performance could be categorized into three distinct learning trajectories: analogical reasoners throughout, non-analogical reasoners throughout, and transitional - those who start non-analogical and grew to be analogical.

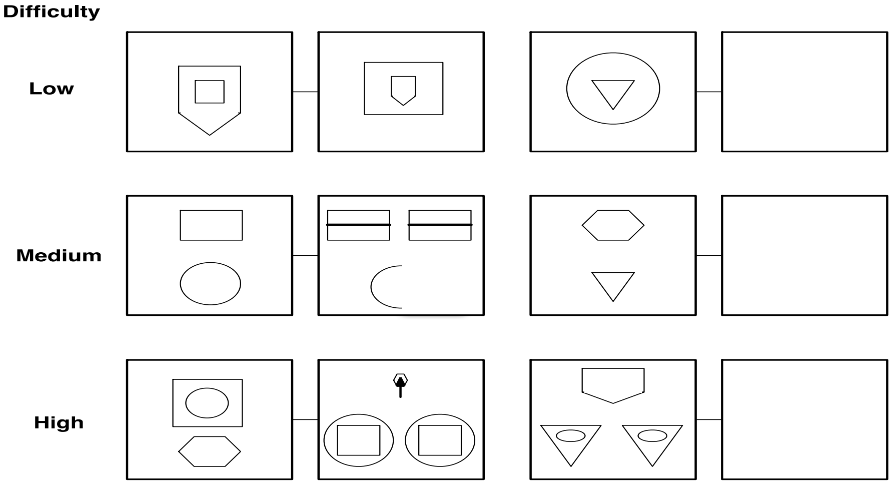

Figure 1. Analogy problems varying in complexity based on those in Hosenfeld et al., (1997)[1].

Developments in children's analogical reasoning are traditionally attributed either to increased working memory resources due to maturation [2,3] or accretion of a knowledge base relevant to the particular task [4].

Both principles have some empirical support, so in order to develop a comprehensive framework for how both knowledge accretion and individual differences in cognitive skills could affect learning from diagrams, we test a theory for their integration using computational simulations in a symbolic connectionist model of analogical thinking, DORA/LISA (Discovery Of Relations by Analogy)[5]. Specifically, we use a version of the model, DORA, which can build representations from relational inputs to simulate children's ability to better recognize spatial relations over repeated training on the analogical diagrams. Then we use LISA to simulate children's reasoning based on these spatial relations. Importantly, we manipulate working memory in both models (via changes in lateral inhibition) to simulate individual differences across groups of children.

Varying the base level of lateral inhibition in DORA affected the ability to learn relational representations, which, in conjunction with lateral inhibition levels used in LISA during reasoning, simulated accuracy rates and error types seen in the three different learning trajectories. These simulations suggest prior knowledge and cognitive control may not only impact reasoning ability, but may also shape the ability to benefit from relational learning opportunities.

1. Model Description

LISA [6]is a symbolic-connectionist model of analogy and relational reasoning. DORA [5] is a model, based on LISA, that learns structured (i.e., symbolic) representations of properties and relations from unstructured inputs. That is, DORA provides an account of how the structured relational representations LISA uses in the service of relational reasoning can be learned from examples.

DORA accounts for over 20 phenomena from the literature on children's and adults' relation learning and relational reasoning including the discovery of relational representations that support analogical thinking (i.e., learning structured representations from unstructured examples), the relational shift, children and adult's learning of dimensions and relational representations, the role of comparison and progressive alignment in relation learning, and the shape bias observed in early childhood categorization [5,7]. In addition, since DORA is based on the LISA architecture, as DORA learns adult-like representations of relations and properties, DORA can also simulate the 30+ phenomena phenomenon accounted for by LISA.

2. Simulations

We hypothesized that differences between the three groups of children from Hosenfeld and colleagues' (1997) [1] experiment were at least partially a product of differences in working memory. We simulated these differences in LISA/DORA by varying levels of lateral inhibition. In LISA, inhibition is critical to the selection of information for processing in working memory. Specifically, inhibition determines LISA's intrinsically limited working-memory capacity[6], controls its ability to select items for placement into working memory and also regulates its ability to control the spreading of activation in the recipient. We have previously used this approach to simulate patterns of analogy performance in a variety of populations with lesser working memory functions including older adults [8] and also patients with damage to prefrontal cortex [9] as well as young children [10].

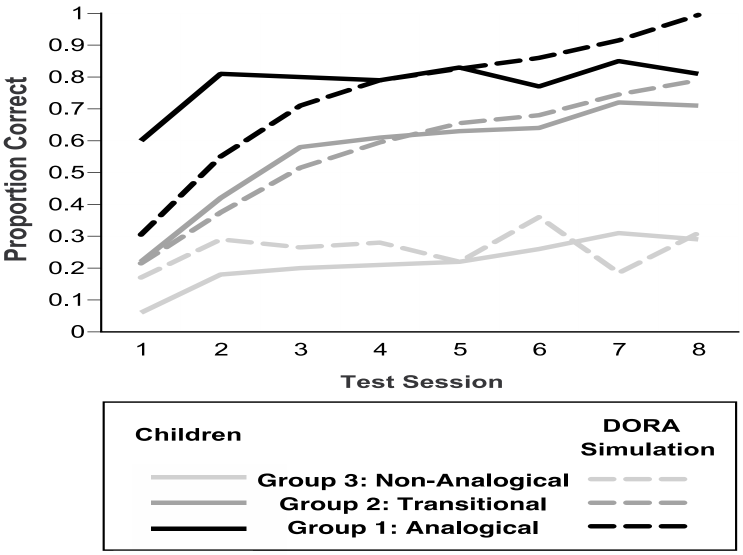

Figure 2. Results from Hosenfeld et al., (1997b) and LISA simulations. Simulation results were the result of training in DORA followed by reasoning in LISA. Groups were created solely by changing DORA/LISA's working-memory capacity (i.e., adjusting lateral inhibition).

We defined three groups for the purposes of the simulation: (1) non-analogical, (2) transitional, and (3) analogical. We ran 100 simulations for each group. During each simulation we chose an inhibition level from a normal distribution with a mean of .4 for the non-analogical group, .6 for the transitional group, and .8 for the analogical group (each distribution had a SD = .2). For each simulation we ran 800 learning trials and checked the quality of the representations DORA had learned during the last 100 trials after each 100 trials. Quality was calculated as the mean of connection weights to relevant features (i.e., those defining a specific transformation or role of a transformation) divided by the mean of all other connection weights + 1. A higher quality denoted stronger connections to the semantics defining a specific transformation relative to all other connections (i.e., a more pristine representation of the transformation).

As can be observed in Figure 2, the patterns of change observed in DORA/LISA's performance on the testing trials closely followed those of the children in Hosenfeld and colleagues (1997) [1]. Just like the non-analogical children, LISA/DORA with a low inhibition level performed poorly throughout. Like the transitional children, LISA/DORA with a medium inhibition level started slow but improved slowly. Like the analogical children, LISA/DORA with a high inhibition level performed well virtually from the start and maintained this throughout.

Though we cannot present these data for space reasons, it is also important to note that LISA made the same types of errors, in similar proportions, as children made in the empirical study. For instance, DORA, just like children, tended to make errors by inferring a D tern solution with the correct transformations applied to the wrong objects, or simply copying all or part of the B term.

3. Summary

In summary, this simulation suggests that when children learn from diagrams, their learning will vary based on individual differences in their level of internal inhibitory control over the noise abstracted from diagrams as inputs. Their cognitive control differences would impact how likely the reasoners were to notice and reason about the relationships visible in the diagrams over time, versus simply attending to the surface appearance markers of the diagrams.

Author Note

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References

1. Hosenfeld, B., van der Maas, H.L.J., & van den Boom, D. (1997). Indicators of discontinuous change in the development of analogical reasoning. *Journal of Experimental Child Psychology, 64,* 367-395.
2. Halford, G. (2005). Development of Thinking. (pp. 529-558). In K.J. Holyoak, R. G. Morrison (Eds). *Cambridge Handbook of Thinking and Reasoning,* New York: Cambridge University Press
3. Rattermann, M. J., & Gentner, D. (1998). More evidence for a relational shift in the development of analogy: Children's performance on a causal-mapping task. *Cognitive Development, 13,* 453-478.
4. Richland, L.E., Morrison, R.G., & Holyoak, K.J. (2006). Children’s development of analogical reasoning: Insights from scene analogy problems. *Journal of Exp Child Psychology, 94,* 249–273.
7. Doumas, L. A. A., & Hummel, J. E. (2007). A Computational Account of the Development of the Generalization of Shape Information. *Proceedings of the 25th Annual Conference of the Cognitive Science Society*.
5. Doumas, L.A.A., Hummel, J.E., & Sandhofer, C.M. (2008). A theory of the discovery and predication of relational concepts. *Psychological Review,115,* 1-43.

Goswami, U. (2001). Analogical reasoning in children. In D. Gentner, K. J. Holyoak & B. N. Kokinov (Eds.), *The analogical mind: Perspectives from cognitive science* (pp. 437-470). Cambridge, MA: MIT Press.

6. Hummel, J. E., & Holyoak, K. J. (2003). A symbolic-connectionist theory of relational inference and generalization. *Psychological Review, 110,* 220-264.
10. Morrison, R.G., Doumas, L.L., Richland, L. E. (2011). A computational account of children's analogical reasoning: Balancing inhibitory control in working memory and relational representation. *Developmental Science, 14*(3), 516–529.
9. Morrison, R.G. et al. (2004). A neurocomputational model of analogical reasoning and its breakdown in frontotemporal lobar degeneration. *Journal of Cognitive Neuroscience, 16,* 260-271.
8. Viskontas, I.V., Morrison, R.G., Holyoak, K.J., Hummel, J.E., & Knowlton, B.J., (2004) Relational integration, inhibition and analogical reasoning in older adults. *Psychology and Aging, 19,* 581-591.