MIND, BRAIN, AND EDUCATION

Analogical Reasoning in the Classroom: Insights From Cognitive Science

Michael S. Vendetti[1], Bryan J. Matlen[2], Lindsey E. Richland[3], and Silvia A. Bunge[1]

ABSTRACT— Applying knowledge from one context to another is a notoriously difficult problem, both for children and adults, but lies at the heart of educational endeavors. Analogical reasoning is a cognitive underpinning of the ability to notice and draw similarities across contexts. Reasoning by analogy is especially challenging for students, who must transfer in the context-rich and often high-pressure settings of classrooms. In this brief article, we explore how best to facilitate children's analogical reasoning, with the aim of providing practical suggestions for classroom instruction. We first discuss what is known about the development and neurological underpinnings of analogical reasoning, and then review research directly relevant to supporting analogical reasoning in classroom contexts. We conclude with concrete suggestions for educators that may foster their students' spontaneous analogical reasoning and thereby enhance scholastic achievement.

A key challenge for students is learning to recognize and learn from opportunities to apply previously learned information to new situations. For example, when teaching students about the atom in school, one approach could be to present an analogy between the solar system and the atom (see Figure 1a). In this example, the solar system represents a domain that is already familiar to students (the source), and the atom represents the domain that students are learning about (the target).

[1]Department of Psychology, University of California, Berkeley
[2]WestEd Program in Science, Technology, Engineering, and Mathematics
[3]Department of Comparative Human Development, University of Chicago

Address correspondence to Michael S. Vendetti, University of California at Berkeley, Berkeley, CA; e-mail: m.vendetti@berkeley.edu

Appreciating and learning from this analogy requires the student to look past surface-level differences between the source and target and instead notice the underlying, shared relational structure between domains—in this case, the fact that the planets orbit the sun in an analogous fashion as the electrons orbit the atom's nucleus (Gentner, 1983).

This ability, termed analogical reasoning, is critical for success in education. Nevertheless, research from cognitive science has consistently found that spontaneous transfer across analogical contexts is rare in laboratory settings (Gick & Holyoak, 1980, 1983). How do humans develop the capacity to reason by analogy? And how can educators support the analogical reasoning process? In this brief article, we explore ways of supporting students' analogical reasoning with the aim of providing teachers with research-based strategies for supporting analogical thinking. We begin by defining what it means to reason by analogy, and then examine the neurocognitive development of analogical reasoning to provide educators with insight into their students' thinking and reasoning development. Finally, we review findings from cognitive science that bear directly on ways that educators can support students' ability to generate and appreciate analogies in the service of learning.

Analogical Reasoning as Relational Comparison

What does it mean to reason analogically? Several steps are presumed to take place in analogical reasoning, including paying attention to relevant information, extracting relationships within and across items, and making the appropriate mappings across domains to either generate inferences and/or derive their common principles (Holyoak, 2012). The key component underlying each of these steps is *attending to shared relationships that are common to both domains* (Gentner, 1983, 2010). When comparing the atom to the solar system, one must attend to the key common relationships that guide both domains—for example, the larger object in both domains causes the smaller object to rotate around it—and place entities into correspondence

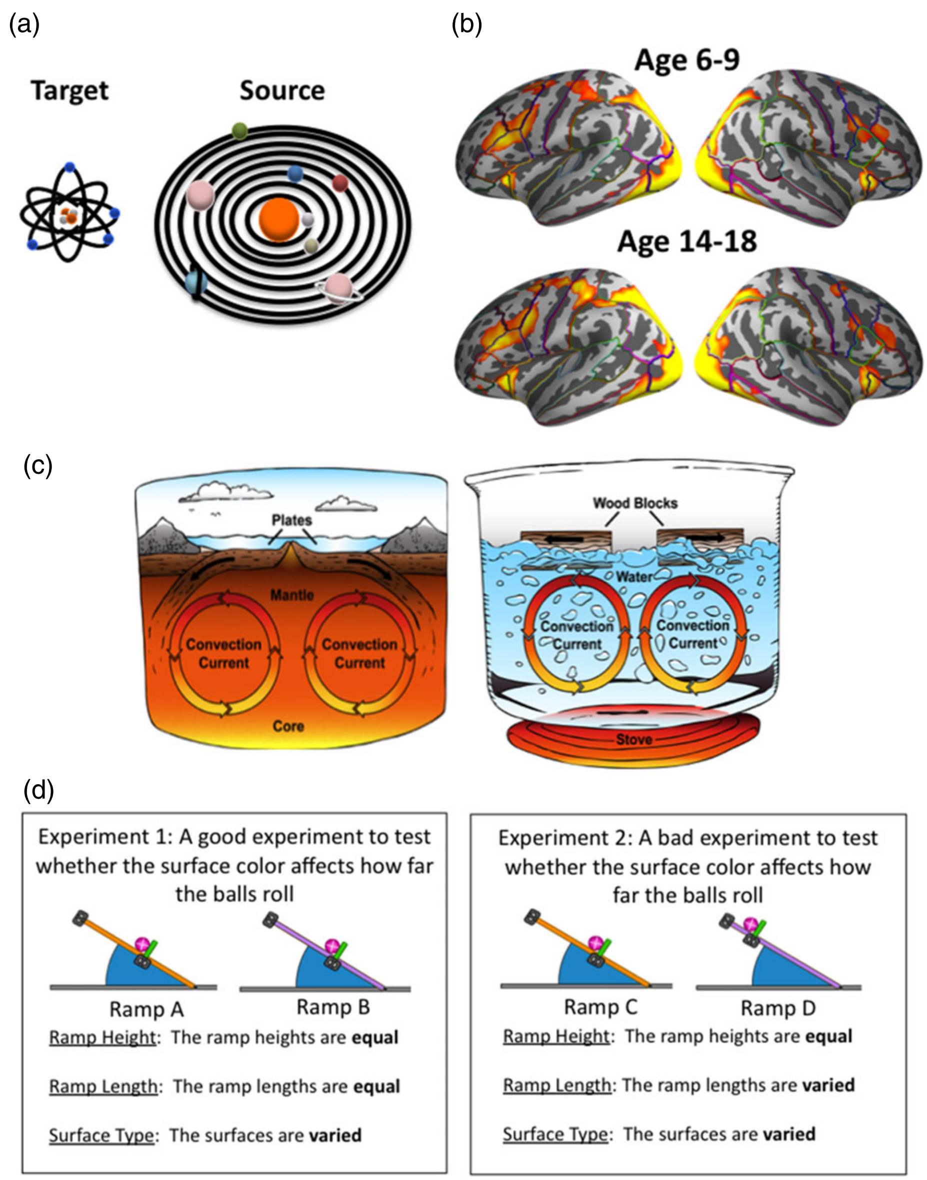

Fig. 1. (a) Example analogy between models of the solar system and the atom. In this example, the atom is the target because this is the domain that children are going to be learning more about. The solar system would be the source, and this would provide information that would be transferred to the atom once an analogical comparison had been made. (b) Brain activation patterns demonstrating greater activation while solving analogies versus looking at a fixation cross, for correct trials only. Average activation for 6- to 9-year-olds ($N = 34$) and 14- to 18-year-olds ($N = 29$), with the left and right hemispheres shown to the left and right, respectively. A remarkably similar network of regions are involved while solving analogies across these two age ranges, even though the older participants performed the task more accurately. This image is based on analyses by Dr. Kirstie Whitaker of data from an NIH-supported project led by S. Bunge and E. Ferrer, titled "Neurodevelopment of Reasoning Ability." (c) A visual analogy comparing the Earth's convection (the target domain) to a boiling pot of water (the source domain). The visual analogy is designed to direct attention to relationally corresponding parts. For instance, the Earth's Core and the Stove are both physically aligned at the bottom of the images to emphasize their common relational roles (i.e., they both act as the heat source). Similarly, the convection currents are made to be perceptually similar (in both color and shape) to emphasize their common relational roles. (d) Correct (left) and incorrect (right) examples of controlled experiments that are designed to test whether the color of the ramp's surface affects how far a ball will roll. The design of the experiments differ in only one way: the ramp lengths are set to be equal in the correct example, but they are set to be varied in the incorrect example. Side-by-side comparison helps students to recognize the key difference connected to the common structure: namely, that two variables are set as varied in the incorrect example and only one variable is set to be varied in the correct example (the variable that is the target of the experiment).

that share common relational roles (e.g., the sun and the nucleus are similar because they are both the *larger* object). This relational mapping process is critical for analogical reasoning. However, novices in a domain often notice and map correspondences based on perceptual features of the analogs instead of the underlying relationships (Chi, Feltovich, & Glaser, 1981). For instance, one could attend to visual similarities between the analogs, noting similarities between the sun and the electrons (e.g., both are depicted as round objects suspended in space), which could lead to misconceptions or conceptual misalignments. As we will outline below, a key challenge in analogical reasoning is learning to attend to the deeper structural relationships between domains in the face of these irrelevant perceptual similarities.

Development of Analogical Reasoning

When do children begin to make analogical comparisons, and how does this ability develop? Though the rudiments of analogy are in place at an early age, children's reasoning is not adult-like until late adolescence, meaning that they will need additional support to notice and successfully use analogical thinking in learning contexts (e.g., Gentner & Ratterman, 1991; Halford, 1992; Richland, Morrison, & Holyoak, 2006). Children's reasoning is more fragile than adults' in two primary ways. First, children exhibit more difficulty ignoring irrelevant perceptual distractors than adults, though this improves with age. For instance, work by Richland et al. (2006) demonstrated that, although children as young as 3 could notice and use analogical relationships among items between two visual scenes, they were far more likely to make an incorrect match when distracting information was included in the scenes. Richland et al. demonstrated that it was not until around 9 to 11 years of age that children could reliably make the correct relational match in the face of distracting information. This research suggests that elementary school children may need structured guidance when attempting to make relational comparisons between domains so that they draw the intended conclusion from the analogy.

The second way that children's reasoning is challenged is by their generally more limited knowledge about the world. With more knowledge about specific topics, people of all ages tend to shift from attending to perceptual information to noticing and using relational information, leading to what has been described as a *relational shift* (Gentner & Ratterman, 1991). Thus, a learner who better understands the nature of gravity and the orbiting patterns of the solar system would be better able to identify and represent the nature of the electron orbits in an atom.

Thus, there seem to be both environmental (instructional) and internal (neurological) reasons that children's analogical reasoning improves over childhood. To understand better the ways that instruction can support learning, it is useful to understand better the timing and nature of change in the neural mechanisms underlying children's analogical reasoning growth.

Given the observed changes in analogical reasoning over elementary school, one possibility is that younger children rely on different underlying neural mechanisms when attempting to solve analogies. Another possibility is that younger children recruit the same network of brain regions as older children when solving analogies, but do not yet engage the network in an efficient manner. This distinction is helpful for understanding whether young children already have the necessary "hardware" to engage in analogical reasoning, or whether significant brain maturation must first take place.

Research to date on analogical reasoning across typical development has demonstrated that children engage the same set of brain regions as adults during analogical reasoning by the age of 6 (and perhaps earlier, although this is not yet known; see Figure 1b; Wendelken, O'Hare, Whitaker, Ferrer, & Bunge, 2011; Wright, Matlen, Baym, Ferrer, & Bunge, 2008). Thus, by the time children enter into early elementary school, they already engage the appropriate neural network for processing analogies. However, two key developmental differences have been observed. First, as children get older, they exhibit reduced activation of key brain regions when making easier relational comparisons (Wendelken et al., 2011). Second, older children and adolescents show stronger functional connectivity—that is, temporal coupling—among brain regions that are centrally involved in reasoning, but decreased connectivity among other brain regions (Wendelken, Ferrer, Whitaker, & Bunge, 2014). These results indicate that the reasoning network continues to be refined throughou adolescence.

Thus, although the brain network used for analogical reasoning is in place by the time children enter elementary school, it is still being refined as children mature and garner experience reasoning with analogies. This means that not only will children benefit from learning content through analogical reasoning, but they are also training their analogical reasoning system through use. Encouraging basic relational thinking (identifying similarities and differences between objects or finding patterns in sets of objects) in preschool and kindergarten or early elementary may build a strong foundation for analogical reasoning in elementary school and beyond. Indeed, children have been shown to already differ widely in reasoning skills by age 6 (e.g., Green, Briones-Chiongbian, Barrow, Ferrer, & Bunge, 2015), which may be due largely to differences in their early academic preparation.

Supporting Analogical Reasoning

As suggested above, even young children can reason by analogy, but their skills improve considerably during elementary school and beyond. In particular, children are highly susceptible to irrelevant distractions—often noticing perceptual features instead of the relationships that are at the core of the analogy (Ratterman & Gentner, 1998; Richland et al., 2006). How, then, can educators best support their students' attention to shared relationships? We review several strategies that have been shown to (1) help children notice the utility of analogies, and (2) help them attend to the key relationships rather than irrelevant perceptual information.

Noticing the usefulness of applying information from one example context to another is a real challenge for children and adults. Often a teacher will assume that the similarities between problems or contexts are obvious, but they may not be to a novice in the domain. One consistent and effective strategy is to explicitly and very directly prompt students to engage in a comparison of analogical examples. For instance, Gick and Holyoak (1983) found that telling college students to compare two examples before solving a final problem increased their likelihood of noticing similarities between the examples that revealed a solution strategy to a final problem from approximately 50% to 80%.

Similar findings have been obtained in a variety of domains (Alfieri, Nokes-Malach, & Schunn, 2011), including comparing algebraic worked example solutions (Rittle-Johnson & Star, 2007), business negotiation strategies (Gentner, Loewenstein, & Thompson, 2003), biology education (Gadgil, Nokes-Malach, & Chi, 2012; Kurtz & Gentner, 2013), and geoscience education (Jee et al., 2013). The explicit practice of prompting comparison making is thought to highlight the critical analogical relationships, thereby supporting students' ability to abstract and recognize analogous cases. Supporting the comparison process is therefore critical for successful analogical reasoning in the classroom. Below, we outline a number of research-based strategies that can support students in making effective comparisons.

In general, the research to date suggests that the more guidance a student receives during the process of comparison, the more likely it is that they will attend to the relationships in the analogy. This guidance can take the form of question prompts that explicitly structure the comparison process (Catrambone & Holyoak, 1989) or of visual aids (Richland & McDonough, 2010). For instance, Matlen, Vosniadou, Jee, and Ptouchkina (2011) found that elementary-age students were more likely to learn and retain elementary geoscience concepts when the text passages describing the concepts were accompanied by visual representations of both the source and target than of just the target domain (see Figure 1c). Presenting both the source and target visually when describing the geoscience concepts prompted students to engage in relational comparisons between the two domains, reduced cognitive effort of having to remember information about each domain, and likely clarified which comparisons were important when trying to understand the new concepts. Similarly, studies have suggested that analogical reasoning is enhanced when images of the source and target are displayed simultaneously versus sequentially (Christie & Gentner, 2010; Rittle-Johnson & Star, 2007). Moreover, recent work suggests that arranging images such that relationally corresponding parts are directly aligned can optimize the speed and accuracy with which analogies are processed (Matlen, Gentner, & Franconeri, 2014; see Figure 1c).

These sorts of visual supports can be further enhanced by providing explicit visual cues that draw attention to relational similarity. For instance, Richland and McDonough (2010) provided undergraduates with examples of permutation and combination problems that incorporated visual cueing, such as gesturing back and forth between problems and allowing the examples to remain in full view, versus comparisons that did not incorporate visual cueing. Students who studied the problems with visual cueing were more likely to succeed on difficult transfer problems. Despite the intuitive appeal of providing visual cues during instruction, studies have found that American teachers are less likely to provide such cues when compared to East Asian counterparts (Richland, Zur, & Holyoak, 2007), suggesting there is an opportunity for teachers to increase their use of analogical supports.

A similarly effective strategy is to use children's natural tendency to attend to perceptual features as way of highlighting key analogical relationships. For instance, visualizations that are designed to make relationally similar parts more perceptually similar can "lure" children into processing the relevant relationships (see Figure 1c). As an illustration of this point, Gentner, Loewenstein, and Hung (2007) found that preschoolers were more likely to learn novel part names when they compared examples that shared many versus few perceptual features. Similar findings have been obtained across other analogical reasoning tasks (Kotovsky & Gentner, 1996; Namy & Gentner, 2002). These findings suggest that, although perceptual similarities often distract children, they can also be used to scaffold learning by drawing children's attention to the key relationships that comprise the analogy.

Analogical comparisons can be used not only to highlight similarities between a source and a target, but also the differences (Day, Goldstone, & Hills, 2010; Markman & Gentner, 1993, 1996; Sagi, Gentner, & Lovett, 2012). For instance, consider a comparison of two worked out examples of the same algebraic equation: in one case, the solution has been worked out correctly, and in the other, incorrectly. By comparing the correct and incorrect solutions, students can identify the solution steps that differentiated effective from ineffective algebraic problem solving. Such analogical contrasts are most effective when they are similar except for a single, key difference that distinguishes the examples

(Gentner, Simms, & Flusberg, 2009; Jee et al., 2013; Matlen, 2013; Ming, 2009; Smith et al., 2014). For example, when learning how to design controlled experiments, comparing correct and incorrect examples that vary in only one attribute (e.g., the ramp length in Figure 1d) can support students' ability to identify principles that characterize controlled experimentation (Matlen, 2013). When the difference is connected to the common structure, students can more readily perceive the relevant contrast. In the experimental design example in Figure 1d, the difference is connected to the number of variables that are set as "equal" or "varied."

While analogical contrasts can be a useful way to support analogical learning, some differences between analogies may unintentionally encourage inferences that support misconceptions. For instance, in the convection analogy presented in Figure 1c, the substance where convection occurs in the boiling pot of water is a liquid. Thus, the analogy could lead a student to the reasonable but incorrect inference that the substance where convection occurs in the Earth is also a liquid (a commonly held misconception in children; Gobert, 2005). In cases where educators can anticipate undesirable mappings, it is important to clarify the limits of the analogy. Explicitly indicating where analogies "break down" (Glynn, 1991) can further direct students to attend to the relevant mappings, and protect against common or anticipated misconceptions.

A final way to support analogical reasoning is to use relational language. Using relational language can take the form of stating the key principle in abstract terms (Gick & Holyoak, 1983), or simply using relational words during the comparison (Gentner et al., 2009). For instance, Loewenstein and Gentner (2005) found that children were more likely to succeed on a difficult spatial mapping task when the experimenters used relational words when describing the problem (e.g., verbally labeling the "top," "middle," and "bottom" components of a structure). In addition, providing the common principle that connects two examples can support the analogical mapping (Cummins, 1992; Gerjets, Scheiter, & Schuh, 2008). There is some evidence that stating the analogical principle *after* students have made the comparison is more effective than stating the principle in advance (Alfieri et al., 2011; Schwartz & Bransford, 1998). In summary, relational language can support encoding of analogical relationships and support the transfer of the relationships to future tasks.

Conclusions

We have argued that, despite the protracted developmental course of analogical reasoning, children exhibit the capacity to reason by analogy at early ages. The key challenge for educators is providing appropriate supports to structure the process of analogical reasoning (Richland & Simms, 2015; Richland, Stigler, & Holyoak, 2012). Prompting students to compare analogous examples is a robust and effective strategy for supporting analogical learning and transfer. However, students benefit from support in making analogical comparisons. The comparison process can be enhanced by:

1. Providing students with opportunities to make comparisons between newly learned concepts and previously learned ones.
2. Presenting source and target analogies simultaneously so that the student may visualize ways in which they are related.
3. Providing additional cues, such as gestures, that move between the two contexts being compared in order to highlight analogical mappings.
4. Highlight both the similarities and differences between sources and targets. If the difference can potentially lead to an incorrect inference, indicate explicitly where the analogy "breaks down."
5. Using relational language to facilitate attention to shared relationships.

Engaging in a comparison of several analogies can afford powerful cognitive benefits on learning and transfer. The strategies provided above can further support the comparison process and scaffold children's developing ability to reason by analogy. Being able to gather information by making analogical comparisons, along with understanding when certain inferences may not transfer between examples, is an important part of critical thinking that can be applied in a diverse range of educational disciplines. The fact that the neural structures for analogical reasoning are already in place by age 6, if not earlier, highlights the point that young children do not have a structural impediment to relational thinking. We propose that providing children with systematically guided experiences in using analogies will support the development of a strong reasoning system and promote a deep understanding of concepts across a broad range of disciplines.

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