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REVIEW ARTICLE

Building from In Vivo Research to the Future of Research on Relational Thinking and Learning

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Abstract This concluding commentary takes the perspective of research on practicing scientists and engineers to consider what open areas and future directions on relational thinking and learning should be considered beyond the impressive research presented in the special issue. Areas for more work include (a) a need to examine educational applications of relational thinking in divergent reasoning, rather than primarily in convergent reasoning; (b) considerations of when to *not* focus on relational reasoning in learning; (c) more research on the distributed nature of relational reasoning across students in a class, and to embedded physical, social, and historical contexts; (d) treatment of the hot components of relational reasoning including motivational and emotional processes; and (e) more attention to how relational reasoning is changed by the details of modalities rather than treating all contents as abstract symbols.

Keywords STEM learning · Relational thinking · Analogy · Science · Design

Introduction

This special issue presents a thorough exploration of recent work on relational thinking and also involves proposals of new understandings of phenomena and new possible interventions using a framework of relational reasoning. As the introduction to the special issue foreshadows (Alexander 2016), the special issue is impressive in its consideration of the range of objects that are often compared in relational ways in instruction: abstract concepts to space (Resnick et al. 2016), texts to graphics (Danielson and Sinatra 2016), a current proposal to past ideas (Dumas 2016; Kendeou et al. 2016), and concurrent ideas on a topic (Dumas 2016; Richland et al. 2016). While analogical thinking (and to some extent metaphor) has a long history of research in many

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domains (Dumas 2016; Goel 1997; Holyoak and Thagard 1995), this broader conceptualization of relational thinking (i.e., including anomaly, antimony, and antithesis) is particularly novel and powerful (Alexander et al. 2016).

Since the introduction to the special issue (Alexander 2016) was particularly thorough in summarizing what was included in the special issue, my commentary on the set of papers will not summarize what was included. Instead, I will focus my comments on what was not included, pushing for new conceptualizations and research that extends the current work in various directions. I make these remarks as a researcher who has spent over two decades formally studying the moment-by-moment actual work of scientists and engineers on real projects over extended periods; some of this in vivo work is reviewed by Dumas (2016). This research often involves systematic coding and quantitative analysis of conversations obtained from video, including particularly high-functioning product design teams at innovative firms (Chan and Schunn 2015a; Christensen and Schunn 2007, 2009), large numbers of student engineering teams varying in effectiveness (Jang and Schunn 2014), and various kinds of basic and applied scientists (Chan et al. 2012; Paletz et al. 2011, 2013a, b, 2016; Trickett et al. 2009). This prior work has also included analysis of computer logs of choices and text of engineers and scientists designing and reasoning (Chan et al. 2015; Chan and Schunn 2015b; Schunn and Anderson 1999). While much of this work can be considered basic cognitive science research, it has many educational implications that I have systematically explored. In particular, the in vivo research in which my colleagues and I have engaged has informed the design of innovative curricula for middle-school and high-school science classrooms. For example, these curricula ground the learning of students in more realistic activities of actual scientists and engineers to produce large improvements in student learning outcomes (Apedoe et al. 2008; Ellefson et al. 2008; Mehalik et al. 2008; Peffer et al. 2015; Reynolds et al. 2009; Schuchardt and Schunn 2016; Silk et al. 2009). It is from this understanding of STEM reasoning and its applications to student learning that the following themes emerged.

Broad Functions of Relational Reasoning—Converging and Diverging Functions

Research on relational reasoning in psychology and education has occasionally been connected to computational modeling work (Dumas 2016). Within the broader computational literature, there has been work on understanding both the diverging and converging search sides of STEM problem-solving (Dumas 2016; Schunn et al. 2012). That is, both scientists and engineers need to consider new ideas (divergent search) as well as evaluate which ideas are most productive or refine ideas to make them more productive/accurate (convergent search). Although relational reasoning plays a central role in both psychological and computational accounts of divergent and convergent search, it is worth noting however that this special issue, particularly in its educational applications, has focused almost exclusively on convergent search: which relationships or inferences do students correctly encode from co-presented ideas, concepts, and representations? This focus may reflect the long-standing bias introduced by the influential philosopher of science Karl Popper who argued that only evaluation of hypothesis was a topic worthy of systematic analysis, denying that the discovery of new hypotheses can be understood in rational terms (Simon 1977).

Although the task at hand in many situations for students is to evaluate/refine presented ideas, that is not the only task at hand, especially vis-à-vis relational reasoning:

1) When students are reading texts on their own, they must make choices in which prior concepts and instances/examples to which to relate the current talk, text, or image (Forbus et al. 1995);
2) Most students are tasked on occasion to engage in problem-based learning, which involves a phase of generating possible solutions (Kolodner et al. 2003); and
3) Learning to be an effective problem-solver involves not only refining existing problem-solving strategies in terms of making them more accurate, faster, and more appropriately applied but also discovering new strategies (Lemaire and Siegler 1995; Schunn et al. 2005).

More work needs to be conducted to understand what prompts relational reasoning in students' divergent search and how to best support students use of relational reasoning in divergent search.

Relational Reasoning Is Sometimes Counterproductive

From the work reviewed in the special issue, it is clear that students often benefit from connecting new understandings to old understandings and sometimes benefit from having to adapt old understandings given the relations to the new evidence. However, a focus on prior instances is not always productive (Kendeou et al. 2016). Some analogies are misleading, carrying forward inferential errors as well as useful inferences (e.g., the analogy of electricity flow to water flow). More generally, analogies (and antimonies, anomalies, and antimonies by extension) can be thought of as a kind of model, and all models are necessarily (partially incorrect) approximations. It is not just a matter of having enough knowledge of a source domain to transfer that content (Kendeou et al. 2016; Richland et al. 2016). It is also a matter of trade-offs between the amount of useful new information that the analogy conveys against the incorrect information the analogy also conveys and the learner's ability to debug the incorrect information through additional information and reasoning. Similar points can be made about anomalies: sometimes they challenge student misconceptions in very useful ways, but sometimes they introduce new red herrings.

There is also plenty of research showing that considering prior instances can be hurtful for engineering design (Jansson and Smith 1991; Purcell and Gero 1996), even in experts (Linsey et al. 2010) because activating some ideas may limit overall ideation rates or prevents more novel ideas from being considered (Chan et al. 2011). Which analogies are used (e.g., near vs. far analogies) can matter (Chan et al. 2015; Chan and Schunn 2015a, b), as well how these analogies are labeled (Linsey et al. 2010). In sum, framing all learning as necessarily relational may lead to counterproductive instructional moves and learning activities. More research needs to be conducted to understand not only *which* relations should be emphasized but also *when* relations should be emphasized.

Mental Work Is Rarely Solo Work—All the World Is a Stage

The study of relational thinking is firmly grounded in the cognitive research tradition, which generally emphasizes mental activity inside individual minds. However, in vivo research on scientists and engineers has long revealed that they work in teams and that critical reasoning is done in a distributed fashion across team members, with the nature of that distribution affecting the reasoning outcomes (Dunbar 1995; Paletz and Schunn 2010). This point can be more generally framed within the distributed cognition theoretical framework (Hutchins 1995).

In this issue, several cases of distributed cognition were considered. In particular, Richland et al. (2016) explicitly considered the distributed cognition between students and teachers. Almost all of the papers consider the distributed cognition between students and external supports (e.g., texts, graphics, images, or PowerPoint slides used by the teacher while making analogies or showing different solutions). However, there is also distributed cognition across students in whole class discusses and small group work. The space of relations to be considered is greatly expanded as the set of co-reasoners increases. For example, a new idea can be considered an analogy by one student, an antimony by another student, and an anomaly by a third all in the same group context, simultaneously serving different cognition functions. How do these different interpretations of a new piece of information vis-à-vis old information influence what learners can take away from the new information? It could be that different interpretations seed the group with diverse items that collectively can be minded through discussion to uncover a good understanding (i.e., the diversity of interpretations may be useful). However, unless the differences of interpretation are surfaced, false agreement about the aptness of a new piece of information may cement misconceptions rather than resolve them.

There is also the relation of students' problems and solutions to the larger world, in particular extended physical contexts (their neighborhood, city, region, country), social contexts (family, socioeconomic situation, extracurricular activities), and recent historical events in these physical and social contexts. These relationships influence which ideas and behaviors are commonly occurring in the students' lives and what values are attached to these ideas and behaviors, which in turn influence uptake of these ideas and behaviors. Consider the use of a line of reasoning used in a recent US Supreme Court decision as an analogy in a social studies classroom conversation. Some of the class might be in favor of the decision and some might be against (as would often happen in close decisions), and their stance on the overall decision would likely color their willingness to consider the analogy as useful or not—this point is taken up in greater detail in the next section.

Reasoning Is Not Divorced from Motivation and Emotion

Another consequence of the cognitive foundation of relational reasoning and learning work is the neglect of emotion and motivation despite its clear important role in learning (Alexander 2003, 2016). Motivational goals (Elliot 2006; Harackiewicz et al. 2000) can influence not only how students engage with problem materials (e.g., with performance or mastery learning goals) but also which kinds of learning materials are most useful for them. For example, students with mastery goals are more likely to benefit from discovery learning materials, whereas students with performance goals are more likely to benefit from direct instruction (Belenky and Nokes-Malach 2012, 2013). To date, interactions of motivational learning goals with relational reasoning interventions have not been considered, even though they are likely. For example, it is likely that mastery-oriented students are more likely to follow through the inferences of analogies and be bothered by anomalies.

Historically, analogy has generally been examined in purely cognitive rather than emotional terms. However, as noted by Thagard (2008), analogies themselves can be emotional in that there are valences associated with components of the analogy that influence inference and agreement. Further, even when analogies are not themselves emotional, my research has shown that analogies have emotional antecedents and consequences. For example, (some types of) analogies are more likely to spring from moments of interpersonal conflict in the team or high levels of uncertainty, and analogies can resolve uncertainty (Chan et al. 2012) and produce new forms of interpersonal conflict (Paletz et al. 2013a). Further, in scientists and engineers, anomalies can be a large source of frustration and debate, acting as a motivator for extended research on a topic and hence new discoveries. But there are many different possible responses to anomalies (Chinn and Brewer 1992), some more productive for learning than others. Further, not all students are willing to engage in public debate, and this resistance to public disagreement can limit how much they learn in a science class (Bathgate et al. 2015). Little is known how this resistance to publicly disagree shapes classroom learning from analogies and other relational thinking in particular, although it seems likely to matter given the importance of distributed reasoning and needed depth of reasoning required to benefit from relational reasoning.

Mental Life Is Multimodal—Symbols Are Often Not Like Analogs

A third common characteristic of the cognitive foundations of research on relational reasoning is the focus on framing reasoning primarily in terms of symbol processing, sometimes referred to as the physical symbol systems hypothesis (Newell 1994). Yet there are different conceptualizations of intelligent behavior, including the subsymbolic framework of connectionist theories (Rumelhart et al. 1988), perception-action Gibsonian theories (Gibson 1979), and embodied cognition and dynamic systems theories (Barsalou et al. 2003; Thelen and Smith 1996). While many of the papers in this special issue mention the affordances of external representations, most of this special issue makes no distinctions in kind of relational processing across modalities (e.g., Do students think differently about the mapping between space and time when the mapping is verbally given, shown with a cartoon, presented along with a physical ruler that is shown, or presented along with a physical ruler that is held and manipulated by the students during mapping?).

Regardless of the theoretical framework being applied, it is a simple empirical observation that scientists and engineers spend much of their lives dealing with complex visual-spatial representations, figuring out both what information they contain and the ways in which the presented information is misleading (Schunn and Trafton 2012; Trickett et al. 2009). Further, decades of research in neuroscience have revealed that human brains have multiple complex brain systems devoted to processing visual-spatial information, and each of these brain systems has different computational properties (Harrison and Schunn 2002; Previc 1998). For example, there is a system for identifying objects quickly that treats objects in approximate/relational 2-D ways to support better identification, whereas there is another system for supporting perceptual-motor coordination that treats objects in very precise 3-D ways (Biederman 1987; Kosslyn et al. 2001; Previc 1998).

Since scientists, engineers, and students must use these long-standing neural systems even when working with very recently developed (in evolutionary terms) complex visual-spatial representations, the computational affordances of these different systems are important to understand (Schunn et al. 2007). Novice reasoners are likely more bound by their physical inputs. For example, novices being given visual information in terms of 3-D topography will be more likely to internally represent the information using their 3-D spatial representation, producing both the representational advantages and disadvantages of that system, whereas experts quickly re-represent the information internally in a format that better meets the needs of the task (Schunn et al. 2007). Teachers and textbook writers likely place little emphasis on visual details of example images like whether it is a cartoon approximation or a 3-D highly detailed image even though these differences can matter for students.

Student use of analogies for creative tasks/divergent thinking is likely also constrained by the physical environment. Even for expert creative engineers, physical artifacts were found to dramatically reduce use of long-distance analogies in ways that sketches did not (Christensen and Schunn 2007). Physical prototyping is a highly recommended practice in design, and clearly interacting with these physical prototypes has cognitive advantages for both experts and students (e.g., in reducing memory load), so the issue is not whether to use physical prototypes but rather when to use physical prototypes (e.g., putting them away during brainstorming).

Conclusions

Much has been learned about how relational reasoning and learning functions, and this special issue contains groundbreaking work in this tradition, in many cases setting forth a productive research agenda for the coming years. However, STEM reasoning and learning is very complex and it is useful to consider what has been left off the table in this set of papers vis-à-vis relational reasoning. Grounded in careful investigations of the moment-by-moment work of engineers and scientists, this commentary notes five directions that may be important to consider to maximally optimize how relational reasoning is used to drive student learning.

Compliance with Ethical Standards

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Conflict of Interest The author declares that he has no conflict of interest.

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