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REVIEW ARTICLE

Relational Reasoning in Science, Medicine, and Engineering

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Abstract This review brings together the literature that pertains to the role of relational reasoning, or the ability to discern meaningful patterns within any stream of information, in the mental work of scientists, medical doctors, and engineers. Existing studies that measure four forms of relational reasoning—analogy, anomaly, antinomy, and antithesis—are included in this review. These studies are organized into four groups based on their general measurement paradigm: those that use naturalistic observation methods to study relational reasoning in vivo; those that take a historical perspective to describe the construct as it arises in recordo; those that manipulate relevant variables in an in vitro or laboratory setting; and those that formulate computer models and algorithms to simulate relational reasoning in silico. Principal findings from this literature are presented and discussed, as are enduring questions about the nature and consequences of relational reasoning.

Keywords Relational reasoning · Science · Medicine · Engineering · STEM

Relational Reasoning in Science, Medicine, and Engineering

Relational reasoning, the foundational human ability to discern patterns within any stream of information (Alexander and DRLRL 2012, Bassok et al. 2012; Crone et al. 2009; Dumas et al. 2013), is an important cognitive process that supports thinking and learning across the gamut of academic and professional domains (Goswami 2013; Krawzcyk 2012; Richland et al. 2007). Of those myriad contexts where relational reasoning can be identified, this special

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issue is concerned particularly with those extant investigations that have sought to uncover and assess the construct within science, technology, engineering, and mathematics (STEM) education. For example, my fellow contributors have detailed ways in which the power of relational reasoning may be harnessed to improve mathematics instruction (Richland et al., this issue), comprehension of scientific text (Kendeou & O'Brien, this issue), and learning from STEM diagrams (Danielson & Sinatra, this issue). In general, each of these contributions delineates ways in which relational reasoning is vital for STEM students.

For those within the field of educational psychology, and especially for those already familiar with STEM learning broadly or relational reasoning specifically, the studies reviewed by my colleagues have unquestionable merit, in part because effective STEM education that prioritizes complex thinking skills such as relational reasoning tends to produce more and better prepared STEM professionals (Thiry et al. 2011). However, I contend that investigations of the relational reasoning of those STEM professionals, rather than students, can also be informative for educational researchers and psychologists. This is because, for STEM education to be as effective as possible at producing and supporting an effective and thriving scientific community, it should logically have a close correspondence to the enactment of STEM practice in the professional setting. Therefore, investigations into the work of STEM professionals can and should be an integral part of educational and psychological research agendas targeting STEM.

Rather than focusing on all disciplines within STEM, this review will specifically highlight findings from investigations of professionals working within scientific, medical, and engineering disciplines. As a way to elucidate the cognitive processes that support scientific thinking after students' formal schooling has ended. The central contention of this review is that relational reasoning fundamentally supports the mental work of scientific and engineering professionals. Further, the forms of relational reasoning (i.e., analogy, anomaly, antinomy, and antithesis) serve as an effective lens through which to study the mental work of scientists, medical doctors, and engineers.

Also, it should be noted here that a large literature exists, with a rich history, on the general process and philosophy of scientific discovery (e.g., Hesse 1966; Kuhn 2012; Popper 2005; Tweney et al. 1981; Wason 1968). For a review of this general literature, please see Dunbar and Klahr (2012). In contrast to this wide-ranging literature, this review will be more concentrated in nature, focusing specifically on the role of four specific types of relational reasoning (i.e., analogy, anomaly, antinomy, and antithesis) within three STEM domains (i.e., science, medicine, and engineering).

Relational Reasoning and Its Forms

While relational reasoning can be conceptualized as a broad construct encompassing any instance of the discernment of pattern (Alexander and DRLRL 2012; Bassok et al. 2012), for the purposes of measurement or observation, its operationalization must necessarily be more specific in empirical research. Therefore, some researchers in the field (e.g., Alexander et al. 2015) describe relational reasoning as taking multiple forms depending on the type of pattern being recognized or reasoned with. For example, instances of structural similarity between and among concepts have been termed *analogies* (Richland and Simms 2015; Holyoak 2012). For example, a popular analogy utilized in engineering education describes electric circuits as analogically similar to water flowing through pipes, because each system contains a network of interconnected conduits designed to control the flow of a particular resource. Through the careful use of this analogy in instruction, students may successfully map their previous knowledge of water-pipes onto their growing understanding of circuits, enhancing their ability to comprehend electrical systems (Iding 1997).

The study of analogical reasoning has a long history within the educational psychology literature (e.g., Sternberg 1977; Holyoak and Thagard 1995; White and Alexander 1984), and the ability to reason with analogies has been empirically linked to student success in many domains outside of STEM, especially reading and language learning (Ehri et al. 2009; Goswami and Bryant 1992). Within STEM, analogical reasoning ability has been implicated within mathematics (Richland and McDonough 2010), chemistry (Trey and Khan 2008), physics (Mason and Sorzio 1996), and engineering (Christensen and Schunn 2007), among other domains. In general, analogical reasoning has been the most studied of the forms of relational reasoning within the educational and psychological research literatures, although a second form has also received sustained scholarly interest.

An *anomaly* is any occurrence or observation that deviates from an expected pattern (Chinn and Brewer 1993; Trickett et al. 2009). In this way, anomalous reasoning requires the understanding of a relational pattern that represents the norm in a given context, as well as the discernment of a discrepancy from that norm (Klahr and Dunbar 1988; Kulkarni and Simon 1988). For example, if computer scientists are to be effective at debugging lines of code, they must understand how the commands within that code relate to one another, and then identify instances where the code deviates from those intended relations. Interestingly, anomalous reasoning has received the most scholarly attention from those within the literature on STEM thinking and learning (e.g., Darden 2006), connecting the construct to success in STEM domains such as engineering (Dumas and Schmidt 2015) and meteorology (Trickett et al. 2009). However, empirical links to early reading skills have also been drawn by educational psychologists interested in anomalies more generally (Otero 2009).

The third form of relational reasoning, *antinomies* are defined by the presence of a relation of mutual incompatibility among concepts (Cole and Wertsch 1996; Gardner 1995; Sorensen 2003). Perhaps nowhere is the importance of antinomous reasoning more evident than in medical decision-making, where the practice of differential diagnosis requires the "ruling out" of particular diagnoses given the symptoms a particular patient is presenting (Dumas et al. 2014). Within this context, the known relations among a patient's symptoms make a given diagnosis incompatible, allowing the reasoner to consider more likely diagnoses. Although the term "antinomy" is comparatively rare in the educational psychology literature, this form of relational reasoning can be theoretically identified in a variety of studies of categorical reasoning within and outside of STEM domains (e.g., Chi and Roscoe 2002; Chi and Slotta 1993).

Finally, *antitheses* arise when a relation of opposition between two concepts is identified by a reasoner (Bianchi et al. 2011; Kuhn and Udell 2007; Sinatra and Broughton 2011). Reasoning with antithetical relations has been widely studied within the educational and psychological literatures, being connected to academic success from preschool through higher-education (Baker et al. 2010; Broughton et al. 2010; Kendeou and O'Brien 2015). For example, if a molecular biologist observes that introducing a certain gene into one kind of bacterium results in a sharp increase in the bacteria population, but introducing the same gene into a different kind of bacteria has the opposite effect (i.e., decrease in population), they are engaged in antithetical reasoning. In this way, the biologist has found that the relation between the gene and the first type of bacteria and the relation between the gene and the second type of bacteria are themselves antithetically related—forming a higher-order relation of opposition.

It should be noted that the forms of relational reasoning presented here are not intended to be an exhaustive list. Instead, they represent a meaningful set of relational forms that may arise within the educational and professional context—forms that previous research has suggested may warrant further investigation (Dumas et al. 2013). Moreover, this conceptualization of relational reasoning and its forms may provide a useful framework in which to bring investigations of reasoning processes that seem different on the surface (e.g., anomalies and analogies) together based on their underlying mechanisms (i.e., the discernment of higher-order patterns). Therefore, where possible, this review will highlight research programs that uncover ways in which these forms of relational reasoning operate together or separately to support thinking and reasoning within STEM domains.

Organization of Review

In their now classic review of studies of scientific discovery, Klahr and Simon (1999) offered four major approaches to the study of scientific thinking: (a) direct observation of working scientific professionals, (b) historical accounts of scientific discoveries, (c) laboratory-based investigations of cognitive processes related to science, and (d) simulation of those cognitive processes using computer models. In this review, I utilize the same four categories to organize the available research. Moreover, in the literature related to scientific thinking and reasoning, direct observation of scientific work has come to be known as in vivo research, while laboratory-based studies, which allow researchers a degree of control over the reasoning context, have come to be known as in vitro research (Dunbar and Blanchette 2001). Here, I follow suit by offering the Latin term, in recordo, for historical accounts of scientific discoveries, because the available record of published work, laboratory notes, or written correspondence form the basis of measurement in such research (Holmes 1987; Johnson-Laird 2005). I also use the term, in silico, often used in computer science (Mesirov 2010), to describe computational modeling approaches to understanding relational reasoning. These Latin terms are designated *measurement paradigms* and form the basis for the organization of this review. This review also expands on earlier work (e.g., Klahr and Simon 1999; Dunbar and Klahr 2012) by broadening the scope to include the domains of engineering and medicine, not only science, while simultaneously focusing in on research findings that are specifically pertinent to relational reasoning. After describing the literature representing each of the four measurement paradigms, principal findings that can be drawn from the body of research as a whole are presented and discussed. Finally, some enduring questions that remain unanswered within the relational reasoning literature are posed. It should be noted that because the literature in which relational reasoning is evident within science and engineering domains—even if the term relational reasoning is not explicitly used by the authors—is very large that the literature will be reviewed selectively here, with an eye toward particular bodies of work that exemplify these particular measurement paradigms.

Measurement Paradigms

In Vivo

Evidence suggests that relational reasoning is a foundational cognitive ability associated with complex problem-solving across the gamut of STEM domains and disciplines (Holyoak 2012; Bassok et al. 2012). Therefore, relational reasoning must often be unfolding within the minds of scientific, medical, or engineering professionals who work in a variety of settings, be they laboratories, hospitals, or businesses. The issue, then, for those who study relational reasoning, is how best to tap that reasoning process in order to collect data for analysis. For some of these researchers (e.g., Chan and Schunn 2015; Dunbar 1993, 1995; Dumas et al. 2014), going out into the field, to the very places where such professionals work, in order to conduct naturalistic observations of scientists and engineers as they reason, is a powerful data collection strategy. Such naturalistic methods are termed in vivo, because they seek to capture reasoning as it unfolds in life, without any manipulation on the part of the researchers.

Although in vivo methods have been used generally within the scholarly and scientific literature for some time (Pridham and Hansen 1980), Dunbar (1993, 1995, 1999, 2001) is typically credited with first applying the method within the psychological literature to understand the relational reasoning of scientists. Specifically, Dunbar observed the reasoning processes of molecular biologists within their own laboratory groups as they reasoned about their and others' experimental findings and planned new studies to conduct. Within these data, Dunbar observed the molecular biologists collaboratively responding to anomalies, in times resulting in major conceptual shifts within the group. Moreover, Dunbar focused on the analogies mapped by the molecular biologists and argued that those analogies varied depending on the goals of the reasoner. Specifically, if the analogy was meant to address an issue with a particular experiment or piece of equipment that analogy was usually based on superficial features. However, if the analogy was meant to explicate or formulate a hypothesis, the analogy was usually based upon deep relational knowledge. Indeed, one advantage of in vivo methods for investigating relational reasoning is that professional scientists have deeper relational knowledge of the processes they are investigating, or the materials with which they are working, than would typical participants in a psychological laboratory-based study. In this way, more and richer relational mappings may be apparent in vivo than in other measurement paradigms.

Since Dunbar's studies, in vivo methods have been employed to tap relational reasoning in a variety of domains including engineering design (Chan and Schunn 2015), meteorology (Trickett et al. 2009), and medicine (Dumas et al. 2014), among others. For example, Chan and Schunn (2015) captured the analogical reasoning processes of a design team as they attempted to create a novel application of thermal printing technology. This study investigated the hypothesis, seemingly supported by the previous work (Chan et al. 2011; Dahl and Moreau 2002) that far analogies—those analogies that are mapped between two superficially dissimilar ideas—are most effective at supporting the generation of original concepts and designs. In contrast to this hypothesis, their analysis showed that far analogies were actually associated with smaller, incremental conceptual moves than other thought processes in which the design team engaged. This surprising finding concerning analogical reasoning may point to other forms of relational reasoning as more critically related to design originality in engineering. For example, in their study of graduate-level engineering design students, Dumas and Schmidt

(2015) found that antinomous thinking was the most strongly related form of relational reasoning to design originality.

In terms of reasoning with anomalies, Trickett and colleagues (2009) used an in vivo methodology to determine how professional meteorologists and physicists responded to unexpected findings in their data. Importantly, physics is an example of basic science, in which scientists hold the goal of building knowledge about particular natural phenomena, whereas meteorology is an applied science, in which knowledge of phenomena is leveraged to solve human problems (i.e., predict the weather). Interestingly, these researchers found that scientists' responses to anomalies differed depending on whether they were working in an applied or basic field. Specifically, while the meteorologists appeared to mentally manipulate their maps and charts in order to reason with an anomaly, the physicists used conceptual simulations of their mathematical models to identify the cause of a discrepancy. Moreover, when Trickett and colleagues added a sample of novice meteorologists to their study, they found the novices, unlike any of the experts previously examined, used direct visual comparisons of their data in order to address an anomaly. These findings from an in vivo study speak to important differences in strategies for relational reasoning among basic and applied scientists as well as expert and novice scientists.

Such differences in expert and novice scientific professionals were also identified by Dumas and colleagues (2014) within a team of clinical neurologists. This team was composed of one expert attending physician and nine comparatively novice medical residents. Using in vivo methods, these researchers sought to identify how each of the forms of relational reasoning were used by the neurologists in order to make diagnostic and treatment decisions about patients. As far as I know, this study remains the only published work to use in vivo methods explicitly to capture the four forms of relational reasoning (i.e., analogy, anomaly, antinomy, and antithesis) within scientists, medical doctors, or engineers. As such, this study had a number of findings related to the purpose of this review. For example, Dumas and colleagues observed that anomalies arose in clusters, one after the other, and the probability of any member of the medical team pointing out an anomaly rose significantly after another member of the team pointed one out. Moreover, the residents, rather than the attending, were significantly more likely to point out anomalies in patient cases. In contrast, the attending physician was significantly more likely to verbalize analogies and antinomies than were the residents. These researchers hypothesized that perhaps the greater expertise of the attending gave him access to relational structures, in terms of analogies and antinomies, among patient cases that the residents did not see. Moreover, analogies and antinomies may have been utilized, on the part of the attending physician, as instructional tools to guide the residents' thinking. Indeed, such relations have been shown in other work to be effective instructional techniques (e.g., Richland and McDonough 2010).

Based on the studies reviewed here, in vivo methods are a powerful way for researchers to capture relational reasoning as it unfolds in the scientific context. Moreover, in vivo methods, more than other techniques, are effective at capturing the collaborative process of relational reasoning in a group. However, one caveat of this measurement paradigm is that data can be time-consuming and expensive to collect, and collaborations with researchers outside of educational psychology and within the domain being studied are often necessary in order to gain access to participants. Further, when a researcher collects in vivo data from a group of STEM professionals, there is no guarantee that those scientists or engineers will be especially effective reasoners at that particular time. It would be exceedingly lucky, for example, to audio record a group of scientists on the same day they make a major breakthrough, or a group of engineers on the day an invention is created. Typically, the thought processes that lead to especially eminent scientific, medical, or engineering innovations are analyzed through a different method, one that take a retrospective or historical view of the reasoning process.

In Recordo

In contrast to in vivo investigations of relational reasoning in scientific and engineering domains, those researchers who have examined thinking and reasoning in recordo do not have access to the reasoning process as it unfolds. In contrast, in recordo investigations use as their data source available written documentation of the reasoning process. These may include published papers, laboratory notes, or archived letters written by reasoners (Klahr and Simon 1999; Kurz-Milcke et al. 2004; Thagard and Croft 1999). Moreover, retrospective interviews with scientists or engineers, in which participants' recollection of their reasoning process is ascertained and described, are also sometimes incorporated (e.g., Wertheimer 1945). It should be noted that the related Latin term in historico has also been used in the literature to describe such research (i.e., Dunbar and Fugelsang 2005).

As has been pointed out (e.g., Burton 1970), such retrospective sources can at times be unreliable sources of information about the thinking process as it actually occurred. However, despite the apparent limitations of retrospective methods for tapping the reasoning processes of scientists and engineers, in recordo investigations have as a major strength the ability to target those individuals who are already known to have made a breakthrough discovery in science or engineered a meaningful innovation. In this way, in recordo studies provide windows into the reasoning of some of the most eminent reasoners within STEM domains.

For example, Wertheimer's (1945) classic publication *Productive Thinking* drew on his long correspondence with Albert Einstein to describe the thinking process that led to the Theory of Relativity. Perhaps no scientist of the twentieth century is more respected than Einstein, giving Wertheimer's work uncontested value, despite its retrospective vantage point. As such, Wertheimer incorporated Einstein's published work, written letters, as well as in-person interviews he had conducted with Einstein almost 20 years previous, as sources of data. This investigation effectively launched modern psychological efforts to understand reasoning from a historical point-of-view and therefore stands as a critical example of in recordo methodology in psychology. However, Wertheimer's goals in explicating Einstein's thinking were not only germane to basic psychological science, but also to the application of psychology to education. In fact, in writing *Productive Thinking* Wertheimer (1945) originally included a footnote requesting written correspondence from educators who could find inspiration for their teaching in his account of Einstein's thought process (Miller 1975). Presumably, Wertheimer included this request because of a belief that studying the thinking of preeminent scientists like Einstein may help to inform educational practice, and therefore indirectly support the intellectual development of future innovators. Unfortunately, Wertheimer passed away before *Productive Thinking* was published, and therefore any collaboration he may have built with educators based on that work remained unaccomplished.

Wertheimer, as may be expected given his theoretical stance toward the investigation of human thought, kept his description of Einstein's reasoning at the gestalt level. Therefore, he presented the "drama" of Einstein's discovery in a sequence of "acts," but did not attempt to parse Einstein's thinking into componential processes or identify the effects of separable cognitive constructs, including relational reasoning. However, a modern reading of *Productive Thinking* allows for the identification of various forms of relational reasoning within Einstein's thought process as Wertheimer reports it. For example, by the late 1800s, Michelson and Morley's (1887) major anomalous finding concerning the motion of light was weighing on the minds of physicists. Some in the field attempted to fit this finding into the existing physical theories of the time, but Einstein suspected that the nature of the universe was incompatible or antinomous, with those existing theories. Then, he constructed a number of analogies—some concerning the motion of trains, objects moving within them, and observers alongside the tracks—to illustrate what previous theories could not explain about light. Further, Einstein saw the oppositional relation, or antithesis, between the change in an object's size when it is in motion close to the speed of light and the change in time that object experiences. Specifically, while the physicist Lorentz had previously found that, as it moves close to the speed of light, an object's size contracts along the dimension of its movement, Einstein reasoned that the object's experience of time must dilate. Because the object's size and its experience of time both affect its speed, this antithetical relation helps to explain the original anomalous findings. In this way, Wertheimer's writing can be used to infer that Einstein almost certainly reasoned relationally while working on his Theory of Relativity.

Another major work of in recordo research in relational reasoning was Johnson-Laird's (2005) analysis of the reasoning of the Wright brothers as they worked to invent the airplane. In this writing, Johnson-Laird had a more explicit focus on relational reasoning, as he pointed out several critical analogies between the bicycle and the airplane that the Wrights (who were bicycle mechanics) utilized in order to solve problems related to flight. For example, Johnson-Laird noted that other engineers and scientists were contemporaneously working on engineering airplanes; however, these competitors of the Wright brothers took their inspiration from carriages or trains, not bicycles. Therefore, they attempted to design airplanes that were fully stable around their mid-point (i.e., would not turn by banking) and that could be balanced even when not moving. However, the Wright brothers saw that, unlike a car or train, an airplane would need to be like a bicycle in that it should be unstable around the mid-point (i.e., it needs to bank in order to turn) and, also like a bicycle, would require forward motion in order to be balanced. In this way, in the minds of the Wright brothers, the airplane was a flying bicycle. Using the terminology of this review, the Wrights saw the antinomy between a car-like construction and the principles of flight, and the analogy between bicycles and flying machines. Based on Johnson-Laird's analysis, it is likely that the Wright brothers also reasoned antithetically when they realized that the propellers on each side of their aircraft should rotate in opposite directions in order to balance their torque, and recognized a variety of anomalies, or unexpected results, when undertaking their initial test flights at Kitty Hawk. These unexpected results resulted in crucial fixes, such as the addition of the second wing to create the bi-plane that eventually allowed the Wrights to fly.

It should be noted here that Johnson-Laird has not been the only scholar within the psychological and cognitive sciences to analyze the process by which the Wright brothers invented the airplane in recordo. Notably, Bradshaw (1992) also undertook an in recordo analysis of the Wrights' process as a way to highlight the promise of a functional decomposition problem-solving strategy, in which instead of building and testing entire aircraft, the Wrights broke down the problem of flight into component parts: wing configuration, thrust, propellers, and stability, and among others. By using this cognitive strategy, the Wright brothers were able to individually test the component parts of an airplane before their actual test flights in Kitty Hawk.

Besides these analyses, in recordo research has been undertaken to explicate the reasoning that led to the discoveries of oxygen (Holmes 1987), electromagnetism (Nersessian 1984), and the cause of the extinction of the dinosaurs (Thagard and Croft 1999), to name a few. Although each of the aforementioned inquiries has focused on particular scientific discoveries, other researchers (e.g., Gentner and Grudin 1985; Gentner and Jeziorski 1989) have taken a broader historical approach, documenting the usage of relational thinking through the history of science. For example, Gentner and Grudin (1985) found that, between 1894 and 1975, a shift in the metaphors used to explain mental phenomena within the domain of psychology occurred. Specifically, spatial and animate-being metaphors dominated in the early years of psychology, giving way to systems metaphors taken from mathematics and physics.

From a psychological perspective, this body of work attempts to capture the thinking processes of eminent scientists and engineers. From an educational perspective, as Wertheimer (1945) hoped, the understanding of how such scientists and engineers reason, or have reasoned, may have potential to inform and inspire teaching practice. However, in order to produce meaningful recommendations for educational practice, studies of relational reasoning following different measurement paradigms must also be considered.

In Vitro

While the previous two measurement paradigms are relatively rare in the psychological literature, in vitro studies, which are laboratory-based investigations of thinking processes where the experimenter holds some control over the context of reasoning, are much more common. These studies of relational reasoning include any investigation that uses more traditional data collection techniques, such as laboratory or classroom-based psychometrics (Vendetti et al. 2014), eye-tracking (Thibaut and French 2016), think-aloud protocols (Grossnickle et al. 2016), or neuroimaging (e.g., Baldo et al. 2010; Dunbar et al. 2007; Green et al. 2006; Fugelsang and Dunbar 2005; Krawzcyk 2012; Waltz et al. 1999, 2000; Wharton et al. 2000). Indeed, each of these methods has been used by researchers within the field of educational psychology to more fully ascertain the process of relational reasoning as it pertains to scientists and engineers.

However, professional scientists, engineers, or medical doctors, as opposed to students, are almost never used as participants in in vitro studies, because of the logistical difficulties associated with bringing practicing professionals into a psychology lab. Yet, within the field of educational psychology, part-time graduate students in STEM domains who are also working full-time in their field can be recruited in order to give some insight into the relational reasoning of working professionals in the in vitro setting. For example, Dumas and Schmidt (2015) used a psychometric measure (Test of Relational Reasoning; TORR; Alexander et al. 2015) to predict the originality of just such graduate-level design engineers' solutions to design challenges. These researchers found a strong predictive relation between engineers' relational reasoning ability and the originality of their ideas.

Further, in an educational intervention designed to help students improve their divergent thinking within the engineering design context, the students in the Dumas and Schmidt (2015) study who had higher relational reasoning ability before the intervention showed greater increase in the originality of their ideas over the course of the intervention. Because the TORR incorporates scales designed to tap each of the four forms of relational reasoning, further analysis by form was possible. Specifically, of the forms of relational reasoning, antinomous reasoning ability was the most predictive of design originality. This finding may be explained by the fact that engineering design, especially within the instructional context of these studies, involves the conceptualization of possible constraints and contradictions within a design as a crucial step. The process of cognitive identification of such contradictions among physical and working principles may require antinomous reasoning.

One resounding finding from the relational reasoning literature across all levels of schooling has been that some students struggle to map relations and discern meaningful patterns among information (Alexander et al. 2015; Greene et al. 2016). Therefore, some researchers within the field of educational psychology have been engaged in research that attempts to explain why this is. In order to accomplish this, in vitro methods are typically necessary. For example, researchers have identified functional and structural neurological differences (Krawczyk 2012), as well as differences in eye-gaze patterns (Thibaut and French 2016) among students based on their relational reasoning ability. However, very rarely are each of the four forms of relational reasoning included in such analyses.

One exception to this rule is Grossnickle and colleagues' (2016) analysis of think-aloud data during which students reasoned with visuo-spatial relational reasoning items from the TORR designed to tap each of the four forms of the construct. In this study, participants were separated in the analysis based on their total score on the TORR. A Bayesian network was used to identify where in the process of relational reasoning students were most likely to falter. In this study, four componential processes of relational reasoning, first put forward by Sternberg (1977) were utilized to guide the coding and analysis of think-aloud data. These componential processes were (a) encode, during which a participant visually identifies the stimuli, (b) infer, during which a participant forms lower-order associations among the pieces of information in the problem, (c) mapping, which entails connecting multiple lower-order inferences with a higher-order relation, and (d) apply, or selecting an answer choice for a reasoning item based on the mapped relation.

Findings from the Bayesian network analysis showed that students had the greatest difficulty at the mapping phase of the reasoning process, but that low-performing students experienced a significantly greater increase in difficulty at the infer and mapping stage than the high-performing students did. Further, the predictive relation between participants' working memory scores and their relational reasoning performance peaked at the mapping stage. Taken together, these findings suggest that students may have difficulty with relational reasoning specifically at the mapping stage, because their working memory capacity may not be sufficient to allow for the mapping of a higher-order pattern from lower-order relations. In this way, in vitro studies of relational reasoning, while typically not explicitly conducted with professionals, may provide valuable insight into the thinking processes of such individuals. In future research, an understanding that working memory capacity limits some students' ability to map relations may be highly informative.

In Silico

In silico methods utilize computational models or algorithms to simulate and study phenomena of interest (Mesirov 2010). Historically within the cognitive science literature (e.g., Dunbar and Fugelsang 2005; Klahr and Simon 1999), the term in silico has been used to represent solely computational systems that artificially simulate cognitive processes. However, such artificial intelligence approaches typically have limited educational implications, because it remains unclear how closely artificial intelligence systems can approximate the thinking of students (Michalski et al. 2013). Therefore, I contend that, in educational psychology, the term in silico can be used more broadly to signify not only artificial intelligence work, but also research that utilizes advanced computing techniques to simulate data, or to process data collected from human participants with machine-learning or natural language processing algorithms.

In the artificial intelligence of relational reasoning literature, a number of computational models have been built to reason relationally (e.g., Learning and Inference with Schemas and Analogies [LISA]; Hummel and Holyoak 1997; Knowlton et al. 2012). Because in silico studies, by definition, are conducted via computer and as such do not include scientists, medical doctors, or engineers as participants, they may seem less directly applicable to the purpose of this review than studies from other measurement paradigms. However, some findings from in silico studies allow insight into the way scientists and engineers may reason with relations. For example, computational systems that most successfully model human-like relational reasoning are all based on the identification of systematic structural correspondences between a source and a target (Holyoak 2012; Kokinov and Petrov 2001). Moreover, one system, DORA (Doumas et al. 2008), is capable of combining simple relations (i.e., inside, outside) into more complex ones (i.e., contains), in a way that mimics the way children learn about relations during development (e.g., Smith 1984).

Besides computational models of relational reasoning itself, cognitive scientists have also created models of the more general process of scientific discovery (e.g., Langley et al. 1987; Newell and Simon 1972; Shrager and Langely 1990). Moreover, some such models have been built with the explicit goal of simulating changes in problem-solving strategy-use that parallel the way students learn (Siegler and Araya 2005). As such, in silico research has shown promise not only in simulating the thinking process of experts but also in explicating the particular mechanisms by which learners alter their reasoning strategies as they move towards competence and expertise.

Some more generally in silico methods might also be applied to measuring the relational reasoning of human participants. For example, latent semantic analysis (LSA) is a natural language processing approach used to quantifying the semantic distance between and among terms. This method uses a massive database of naturally occurring language called a corpus to produce a matrix of word cooccurrence. From this matrix, vectors representing particular terms within a language can be identified, and the latent correlation between two terms in semantic space can be calculated by taking the cosine of the angle between their vectors. From this correlation, the semantic similarity or dissimilarity between terms can be inferred. LSA has been utilized by Green and colleagues (2012) to quantify the semantic distance between the source and target within an analogy. These researchers showed that the magnitude of participants' pre-frontal cortex activation during analogical reasoning was predicted by the semantic distance between the source and target—with greater semantic distance predicting greater activation. This finding illustrates that the process of reasoning analogically is not equivalent across reasoning contexts, but differs in neurologically measurable ways depending on the concepts being reasoned about. Moreover, LSA is currently being utilized to measure the originality of ideas on creativity tasks (Dumas and Dunbar 2014), an outcome that previous studies (Johnson-Laird 1989) show is closely associated with relational reasoning ability.

Unfortunately, nearly all of the in silico research on relational reasoning pertains most specifically to analogical reasoning, and less to the other forms of the construct. This finding parallels the relational reasoning literature in general, in which analogical reasoning has received greater empirical attention than the other forms of the construct for decades (Dumas et al. 2013). Based on this finding, in silico methods that specifically aim to increase knowledge of anomalous, antinomous, or antithetical reasoning may be important next steps for researchers in the field.

Going forward, in silico methods for simulating data with complex correlational structures may also be a necessary step for developing and perfecting statistical techniques for quantitatively estimating individual and group levels of relational reasoning ability, as well as the predictive relation between that ability and relevant outcome variables. For example, effectively measuring and modeling relational reasoning as it manifests within collaborative groups remain a methodological challenge to which in silico simulations may be meaningfully applied (Greene et al. 2016).

Principal Findings

Based on the extant literature, five key findings can be identified that represent a general summation of what is known about relational reasoning in professional scientists and engineers : (a) relational reasoning can be observed and measured in diverse ways, (b) relational reasoning is important for scientists and engineers, (c) relational reasoning is malleable and teachable, (d) the forms of relational reasoning operate in concert with one another, and (e) relational reasoning supports and is supported by collaboration. Each of these principal findings will now be further discussed.

Relational Reasoning can be Observed and Measured in Diverse Ways

Much of the organization of this review is driven by measurement. Here, studies have been presented depending on the measurement paradigm utilized by their authors. Specifically, I have separated studies depending on whether relational reasoning is measured by means of in vivo, in recordo, in vitro, or in silico methodologies. The ways in which these measurement paradigms differ have been explicated, but of course, that is not to say that the studies presented come from fundamentally different lines of inquiry. On the contrary, studies conducted in one measurement paradigm can, should, and do have meaningful influence on studies conducted in other paradigms. For example, Dunbar's (e.g., 1993; 1995; 1999) in vivo studies of molecular biologists deeply influenced his later in vitro studies of analogical reasoning (e.g., Dunbar and Blanchette 2001).

In fact, I would argue that no one measurement paradigm discussed here is capable of producing a sufficiently deep and broad understanding of relational reasoning. For this reason, educational and psychological researchers interested in relational reasoning typically employ diverse methodologies for measuring relational reasoning ability, including psychometric measures and tasks (e.g., Alexander et al. 2015; Richland et al. 2010), naturalistic observations (e.g., Chan and Schunn 2015; Dumas et al. 2014), and cognitive interview techniques (Jablansky et al. 2015). There may be much still to learn about relational reasoning, and for this line of inquiry, the entire gamut of measurement tools must be used: from selected-response assessments and neuroimaging methods to semi-structured interviews, naturalistic observations, and computer simulations. In this way, the nature of relational reasoning may be more fully uncovered.

Relational Reasoning is Important for Scientists, Medical Professionals, and Engineers

All of the studies reviewed herein, from those conducted in vivo to those based in computer simulations, point to this principal finding: relational reasoning is an important cognitive ability for scientists, including medical doctors, and engineers. Whether relational reasoning is observed in pre-eminent innovators of the early twentieth century such as Albert Einstein (Wertheimer 1945) and the Wright brothers (Johnson-Laird 2005), or whether it is observed in modern molecular biology laboratories (Dunbar 1995), clinical neurology wards (Dumas et al. 2014), meteorologists (Trickett et al. 2009), or engineering designers (Chan and Schunn 2015), it is clear that relational reasoning is utilized by scientists and engineers and that it is important for their work.

Indeed, the continued pursuit of in vivo inquiry concerning relational reasoning by educational psychologists may also be taken as evidence for the ubiquity of the construct. This type of research is time consuming to conduct, and therefore researchers require some reasonable expectation of observing rich instances of relational reasoning before beginning a study. As far as I know, no researcher conducting an in vivo study of scientists, medical doctors, or engineers has failed to identify relational reasoning in their participants. In this way, the field does not yet know of a context in which humans are engaged in goal-driven thinking and reasoning in which no analogies, anomalies, antinomies, or antitheses are present. For this reason, relational reasoning can be described as pervasive and fundamental to human problem solving and decision making, especially in scientific domains.

Perhaps more importantly from the perspective of an educational psychologist, the observation that relational reasoning critically supports the thinking of STEM professionals logically leads to the inference that this ability may be critically important to support in the next generation of scientists and engineers—today's STEM learners. Unfortunately, a number of studies with students have shown that the discernment of meaningful patterns within information, however crucial and pervasive they may be, does not necessarily come easily to all learners (e.g., Alexander et al. 2015; Krawczyk et al. 2011). However, with continued efforts to understand the process of relational reasoning (e.g., Grossnickle et al. 2016), as well as to support relational reasoning and associated abilities in classroom-based interventions (e.g., Murphy et al. 2016), there is sufficient evidence to support the conclusion that relational reasoning is a malleable cognitive ability, capable of being taught to students.

Relational Reasoning is Malleable and Teachable

Relational reasoning is important for STEM professionals, and evidence suggests that STEM experts are generally adept at utilizing relational reasoning skills (e.g., Dunbar 1995; Johnson-Laird 2005). However, the field also knows that, in all likelihood, such experts were not always so cognitively skilled, but rather those relational reasoning abilities that support their thinking were developed at some point during their formal or informal education (Alexander 2003). Therefore, STEM learners who may not already be adept at relational reasoning can, and hopefully will, learn to be.

It is important to note that, throughout the history of educational psychology, the identification of cognitive abilities and capacities (e.g., intelligence; Sternberg 2000) that predict student success in school, or support the mental work of experts, has led to debates about the potential malleability or fixedness of those abilities (Devlin et al. 2013). Because the construct of relational reasoning does bear some definitional similarity to fluid intelligence (Cattell 1987), the issue of malleability is relevant within the domain of relational reasoning research. Consistently, researchers in the field have been in agreement that the ability to discern meaningful patterns within a particular body of information can be improved through strategy instruction (Alexander et al. 1989), increased knowledge of the domain (Jablansky et al. 2015), or through neurological maturation and growth (Crone et al. 2009). Therefore, there is reason to believe that most young learners, who are yet far from the expertise of those scientists, engineers, and medical professionals studied in the literature reviewed here, have the potential to develop a high level of relational reasoning ability.

Indeed, some studies have shown that explicit training on the component processes (i.e., encode, infer, map, and apply) of analogical reasoning facilitates the ability of students at various levels of schooling to solve analogical reasoning tasks, whether those tasks be linguistic or nonlinguistic (Alexander, et al. 1989; Alexander et al. 1983; Sternberg and Ketron 1982). Moreover, the relevance of the same component processes to other forms of relational reasoning has now been empirically established (Grossnickle et al. 2016). Therefore, each form of relational reasoning appears ripe for intervention research based on direct instruction of the component processes.

Further, a number of interventions that instruct students on relational strategies for understanding STEM topics (e.g., case comparisons; Alfieri et al. 2013) have shown success not only in improving students' use of such strategies but also in boosting their academic performance in the STEM classroom. For example, Greene and colleagues (2016) have shown that high-school physics and chemistry students' relational reasoning and scientific understanding increased through an intervention that focused on evidence-based discussions. The success of such interventions illustrates that conceptualizing relational reasoning not as a fixed entity, but rather as a malleable ability that students can learn and improve upon, can have practically significant implications for educational practice and STEM learners.

Of course, there is still much to learn about how best to intervene on students' relational reasoning ability within the context of STEM education—something in which intervention researchers are currently engaged (e.g. Murphy et al. 2016). However, mounting evidence suggests that the inclusion of multiple forms of relational reasoning in an intervention, and not only instructions based on analogical similarity, may be most effective (e.g., Greene et al. 2016; Vendetti et al. 2015). This finding may arise in part because the forms of relational appear to be deeply associated with one another, and many complex thinking tasks may require multiple forms of relational reasoning to be completed effectively (Dumas et al. 2014).

The Forms of Relational Reasoning Operate in Concert with One Another

Based on the literature already reviewed, the discernment of meaningful patterns in any stream of information, or relational reasoning, is an important cognitive ability within a variety of academic domains. However, because the kinds of patterns (e.g., similarity, discrepancy, incompatibility, or opposition) can differ in key ways, relational reasoning can be described as taking multiple forms, depending on the type of pattern being identified. Based on the existing data, it is clear that none of these specific forms of relational reasoning is the "most important" (Alexander et al. 2015; Dumas et al. 2014). Instead, each of the forms of relational reasoning are likely necessary for the complex thinking and reasoning of professional scientists and engineers, as well as students of those disciplines. Unfortunately, because only a few extant studies have explicitly included multiple forms of the construct, data on exactly how analogies, anomalies, antinomies, and antitheses operate together are scarce, although some studies do provide insight.

For example, in their study of clinical neurologists, Dumas and colleagues (2014) used a Markov chain transition analysis to identify the probabilistic pattern with which the forms of relational reasoning arose in discourse. As mentioned, anomalies tended to arise in clusters with the probability of an anomaly being verbalized increasing significantly after an initial anomaly was pointed out. Analogies and antinomies tended to arise after anomaly clusters, potentially as a way to explicate the cause of the previously mentioned anomalies. Finally, while antitheses were comparatively rare, they tended to arise at toward the end of the reasoning process, as a way for the medical team to position their decision in relation to hypothetical alternatives, or to compare their decision to the decision of other groups. In this way, the forms of relational reasoning did not independently exist within the medical team's discourse. Instead, the forms of relational reasoning operated in concert with one another to move the team closer to its goal of a viable diagnosis and treatment decision for a patient.

Moreover, in psychometric research using cognitive measures (e.g., TORR; Alexander et al. 2015; Dumas and Alexander 2016) that include items designed to tap each of the forms of relational reasoning, significant positive correlations at the latent variable level among the forms of relational reasoning are found. However, these correlations are not so large as to suggest that the forms of relational reasoning do not differ in measurable ways. Further, predictive models using the TORR (e.g., Dumas et al. 2016; Dumas and Schmidt 2015) have shown that, despite the significant positive correlations among them, each of the scales of the TORR is capable of accounting for unique variance in STEM-related outcome variables. For example, it has been observed that the antinomy scale of the TORR most strongly predicted the originality of engineering design ideas after an instructional intervention, while the analogy scale accounted for the least variance in design originality (Dumas et al. 2016). This finding allows for the inference that the cognitive process of engineering design ideation, at least in the context of that particular study, required conceptualizing incompatibilities and constraints more than it did similarities. Of course, without the measurement of multiple forms of relational reasoning, such an inference would not have been possible.

The measurement of multiple forms of relational reasoning also leads to the finding that, while the forms of relational reasoning are positively correlated, some individuals may be particularly strong at one or multiple forms and weaker in others (Alexander et al. 2015). This profile of relational reasoning abilities leads logically to the importance of collaboration because, if each of the forms of relational reasoning are required for most complex thinking tasks, and individuals have differing levels of ability with each of the forms, than collaboration among multiple individuals should help optimize the collective use of relational reasoning to solve problems in science, medicine, or engineering.

Relational Reasoning Supports and is Supported by Collaboration

In most human pursuits, but especially for professional scientists, medical doctors, and engineers, collaboration between individuals with different strengths typically leads to better outcomes for the group (Dunbar 1995; Okada and Simon 1997). While in vitro and in silico methods within the relational reasoning literature tend to deemphasize the role of collaboration, in vivo methods especially are useful in ascertaining how collaboration leads to innovation in science and engineering. In fact, for many in vivo studies of relational reasoning (Chan and Schunn 2015) the collaborative aspect of the reasoning is inseparable from the context and goals of the reasoning. Potentially because the scope and complexity of professional scientific, medical, or engineering tasks are such that an individual reasoner may only rarely be effective, for such professionals, much real-world relational reasoning appears to happen in the collaborative context. This finding makes sense, given the differing thinking strategies (relational reasoning and otherwise) that are employed by different members of a group. For example, Trickett and colleagues (2009) found strategy differences for reasoning about anomalies among basic and applied scientists, as well as expert and novice scientists. It may be that these strategy differences support meaningful collaboration between these groups and that each type of strategy is necessary for the entire team to function as best it can.

The idea that each team member's relational reasoning ability contributes to a collaboration seems intuitive and has been borne out by a number of studies (e.g., Derry et al. 2014; Okada and Simon 1997). However, it may also be that the act of collaboration in turn supports the individual relational reasoning ability of each of the team members. For example, Dumas and colleagues (2014) found that medical residents were relatively unlikely to notice an anomaly in a patient case until an initial anomaly had been identified. At that point, the probability of any individual resident verbalizing an anomaly significantly increased. This finding may illustrate the role of collaboration and the social context of a team in shaping the relational reasoning of each team member, at least at the verbal level. Dunbar's (1995, 1999) in vivo work holds convergent findings, in which the process of reasoning with an anomaly—from first noticing the discrepant finding, to discerning it's cause—required a diversity of team members in order to be accomplished effectively.

Based on these findings, it appears that the line between individual and group relational reasoning, at least in collaborative scientific professionals, is not cut and dry. Indeed, it can be difficult to tell, in some data, from exactly which member of a team an analogy, anomaly, antinomy, or antithesis arose. In future work, determining how and under what conditions collaboration supports the relational reasoning of individuals may be an interesting goal. Further, identifying ways to support STEM learners as they begin to practice collaborative reasoning methods within and across domains may be a fruitful line of inquiry.

Enduring Questions

Despite these principal findings from the relational reasoning literature, a number of enduring questions remain to be answered through research. Two such questions are (a) how different is relational reasoning across domains of learning? and (b) how does relational reasoning interact with other individual differences?

How Different is Relational Reasoning Across Domains of Learning?

Although there is evidence that relational reasoning is a foundational ability associated with thinking and learning in STEM domains broadly construed, it must be remembered that STEM is not a unitary domain. Instead, the sciences, technological fields, engineering, and mathematics may require varied profiles of cognitive abilities for student and professional success. For example, it has long been hypothesized that STEM fields require different amounts of visuo-spatial rotation, an idea that has been supported by some data (Resnick and Shipley 2013). Relational reasoning may be no exception, and different domains within STEM may place greater emphasis on particular forms of the construct, or in particular reasoning contexts (e.g., collaborative or individual).

One source of the hypothesized variation among STEM fields may be found in the goals of reasoning. For example, a physician reasoning about a patient diagnosis holds different goals than an engineer reasoning about the design of a machine. Moreover, different fields within the medical domain may typically differ in terms of the goals of reasoning, and the same physician may hold different goals when reasoning across patients (Patel et al. 2012). This same observation can be drawn among fields within the sciences (e.g., chemistry or biology) and even individual experiments upon which a particular scientist may work. As of now, whether and how the forms of relational reasoning are generalizable across domains and contexts is not well understood. This enduring question currently limits the application of relational reasoning research to educational practice. More to the point, until researchers fully understand how relational reasoning is utilized in a particular domain of learning, educators risk resorting to "one size fits all" instruction that will likely not result in maximized benefit for all students across domains.

In order to tease apart the effect of the reasoning context, the academic task, and individual differences in relational reasoning ability, in vitro studies that systematically vary such factors are likely required. Indeed, experimental research that attempts to ascertain the effect of context on creativity (Dumas and Dunbar 2016) is underway, and contextual and goal-related variables have been examined in the broader reasoning literature (Klaczynski et al. 1997). However, as far as I am aware, no study of this type has been attempted explicitly with the four forms of relational reasoning. Going forward, addressing such contextual and domain-related questions may be a priority for those in the relational reasoning literature. However, the complete picture of relational reasoning as it operates within STEM domains may not be available until the interaction among relational reasoning and other cognitive processes and abilities is fully understood.

How Does Relational Reasoning Interact with Other Individual Differences?

It seems impossible to identify a mental ability or trait that is measured by educational and psychological researchers that does not affect and is not affected by other abilities or traits (Cucina et al. 2016). In this way, mental abilities are highly interrelated, varying systematically together and even causing one another to vary. Of course, relational reasoning fits this description, and the way it relates to other identified abilities and constructs is of interest in the field. Of particularly salient theoretical and empirical importance in the literature is the relation between relational reasoning and working memory. For example, a number of studies have identified a significant positive relation between the constructs (Alexander et al. 2015; Cho et al. 2007; Fales et al. 2003; Grossnickle et al. 2016). This relation is potentially important, because efforts have been underway to train individuals with memory tasks in order to improve their working memory capacity (Melby-Lervåg and Hulme 2013).

However, recent research has found that observed gains in working memory capacity associated with training may not transfer to other cognitive tasks (Sprenger et al. 2013). Also, even if working memory gains occur after training, and transfer to other working memory tasks does occur, evidence suggests that relational reasoning ability may not concomitantly increase (Richey et al. 2014). Going forward, understanding this null effect, and potentially identifying methods to make working memory training more relevant to relational reasoning, may be an important next step in the field.

Another as-yet-unanswered question concerning relational reasoning and other individual differences pertains to prior knowledge. Based on the findings of a number of studies, we know that those individuals who know more about a particular topic or domain are more likely to discern meaningful patterns within information arising from that domain (Jablansky et al. 2015; Ozkan, and Dogan 2013; Vendetti et al. 2015). However, we also know that relational reasoning strategies can be leveraged to help individuals with comparatively low prior knowledge solve domain-specific scientific problems more effectively (Trey and Khan 2008). So, it remains unclear whether knowledge of a given domain is a requirement for effective relational reasoning, or strong relational reasoning ability is a requirement for bringing previously existing knowledge to bear on a novel situation, or both. In vitro investigations resulting in empirically derived path models that include moderation or mediation effects might help to answer this question. Moreover, the observation of collaborative problem solving among groups of individuals who systematically differ in either their relational reasoning ability or topic knowledge may be observed in vivo, or computational models that are altered to reflect those differences may be used. Going forward, a nuanced understanding of precisely which mental abilities and individual differences most affect a professional's ability to solve problems arising in their work may be required to effectively describe STEM thinking with reliability and accuracy.

Closing Thought

Based on the studies presented here, the evidence is mounting that, in order to effectively solve problems within their domain, scientists, medical professionals, and engineers employ each of the four forms of relational reasoning. Although the degree to which each form of relational reasoning is equally critical across domains, and whether or not other individual differences can help alleviate difficulties brought on by a lack of relational reasoning ability remains an open question, the central importance of the construct within science, medicine and engineering is clear. Within the field of educational psychology, researchers continue to be interested in both improving students' relational reasoning ability (Alexander et al. 1987), and leveraging relational reasoning to improve students' academic performance in a particular academic domain (e.g., Greene et al. 2016; Murphy et al. 2016). Moreover, this special issue holds multiple examples of the relevance of relational reasoning to learners in STEM domains. This particular contribution has been a review of research on four forms of relational reasoning as they pertain to the mental work of scientists, medical professionals, and engineers. These findings should help to inform efforts to support the relational reasoning ability of STEM learners, as they develop into professional practitioners of their chosen discipline.

Compliance with Ethical Standards

Conflict of Interest The author declares no conflicts of interest.

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