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Special Issue Article

Individual differences in college-age learners: The importance of relational reasoning for learning and assessment in higher education

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Background. The term individual differences refers to the physical, behavioral, cognitive, social, and emotional attributes that make each human unique. Late adolescence to young adulthood represents a time of significant neurobiological and cognitive transformations that contribute further to human variability. Those transformations include an increase in the white matter of the brain accompanied by an increased capacity for higher-order thinking, reasoning, decision-making, and selfcontrol. These capacities fall under the category of executive functions.

Aim. The purpose of this article is to overview one particular executive function, relational reasoning; to consider its significance to college students' learning and performance; and to argue for its inclusion in assessment programs within higher education.

Research summary. Relational reasoning can be defined as the ability to discern meaningful patterns within any informational stream. Through an orchestrated program of research, four forms of relational reasoning have been identified that reflect perceived similarities (analogical), discrepancies (anomalous), contradictions (antinomous), and contrasts (antithetical). These four forms have been documented in studies of doctors diagnosing cases, science and mathematics teachers providing instruction, and engineering students designing new products. These manifestations have also formed the structure of formal measures of relational reasoning that have been shown to be psychometrically sound indicators of this executive function.

Conclusions and implications. This article closes with an argument for the inclusion of relational reasoning in performance assessments designed for higher education. Consistent with views of competence as a continuum, it is argued that this inclusion should encompass the measurement of relational reasoning both as an underlying general competence and as a component of domain-specific performance.

One undeniable characteristic that humans share is their desire to understand what makes them unique – physically, socially, emotionally, and cognitively – from all others of their species. Although all humans are members of the same species, *homo sapiens*, and thus 99.9% genetically identical, the remaining 0.1% translates into millions of genetic variations that can manifest (National Human Genome Institute, 2018). When this

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biological fact is combined with the realization that the lives humans experience are equally idiosyncratic, the story of human uniqueness becomes extremely complicated. *Individual differences* are the term for the systematic investigation of human similarities and differences, and the study of human similarities and differences remains a cornerstone in educational psychology and educational assessment (Jonassen & Crabowski, 2011).

Sir Francis Galton (1869) is the individual most often credited with turning humans' fascination with uniqueness into the science of individual differences when he set out to test whether the frequent occurrence of eminence (i.e., exceptional mental ability) within certain families was inherited. Borrowing a technique that a Belgian astronomer, Quételet, used to track patterns in astronomic observations, Galton summarized thousands of measurements and found what is commonly described as the bell curve. In this way, he laid the groundwork for how we think about the 'normal distribution' of human characteristics (Alexander, 2006). Galton is also credited with introducing the mathematical concepts of correlation and regression into the lexicon. However, it fell to Karl Pearson (1895), his collaborator, to provide the mathematics required for correlational analyses; the way to ascertain the association that exists between characteristics or variables. Indeed, product–moment correlation coefficient still bears Pearson's name. Ultimately, this historical sojourn reminds us that the science of individual differences entails the systematic study of human typicality and atypicality for an indefinite number of cognitive and non-cognitive characteristics (Ackerman, 1988; Guilford, 1956). It also reinforces the notion that this science is intricately intertwined with assessment (Adams, 2014; Cronbach, 1956; Spearman, 1927).

In accordance with the aims of this Special Issue (Zlatkin-Troitschanskaia & Shavelson, this issue), my goal is to look at the topic of individual differences and assessment from the perspective of young adult learners. With the literature on adult differences as the backdrop, I overview research in which my colleagues and I have been engaged. This research establishes an association between younger and older adults' domain-specific learning and performance (Alexander, 1997, 2003) and their ability to discern meaningful relations within seemingly unrelated information (Alexander, Dumas, Grossnickle, List, & Firetto, 2016).

Mapping the neurobiological and cognitive landscape for college-aged learners

One does not have to be an expert in individual differences to recognize that with age comes marked changes in how humans look, think, and behave. One needs only to compare healthy 2-year-olds to 20-year-olds to see the effects of time on the human species. Yet, some of the more significant developments that occur in the first decades of life and in the decades that follow are not visible to the naked eye. They are the transformations occurring within the hardware (i.e., neuroanatomy) and software (i.e., neurophysiology) of the human mind. Moreover, with changes in the brain's architecture come concomitant changes in cognitive, psychological, and socioemotional processes that impact college students' learning and performance.

Neurobiological changes

Much attention is paid to children's, cognitive, biological, and socioemotional development (Bjorklund & Causey, 2017). This is understandable given the amazing transformations that occur in the way that young children think and behave. Similarly, early adolescence is a period of dramatic change, as any parent of 10–16 years old can attest. However, the cognitive, behavioural, social, and emotional transformations taking place among college students are particularly vital to their ability to be independent and goal-directed and, ultimately, successful in their future endeavours (Ackerman, 2000). The shifts of particular importance here are situated in two types of brain matter that make up human's central nervous system (CNS) – the control centre for all human functions that consists of our brain and spinal cord. That CNS is composed of grey matter (GM) and white matter (WM), which serve different roles in human thoughts, behaviours, and emotions. GM contains the brain's neuronal elements (cell bodies, dendrites, axon terminals, and synapses), while the WM consists of axon bundles covered in myelin. The principal job of WM is conducting nerve signals up and down the spinal cord. WM makes up the bulk of the deep parts of the brain, what Newman (2017) called 'the brain's flexible but underrated superhighway.'

From childhood to early adulthood, there is a decrease in GM and a corresponding increase in WM (Sowell, Thompson, Tessner, & Toga, 2001). In fact, the frontal regions of the cerebral cortex associated with higher-level executive functions are the last to undergo myelination (Fields, 2010). With this increase in WM comes greater neurological efficiency and enhanced capacity to engage in more complex, higher-order cognitive functions (Blakemore & Choudhury, 2006). It is important to recognize that this neurological shift comes just as college students begin making crucial decisions about academic and career paths. Thus, they seem neurologically and cognitively better equipped to build the knowledge, interests, and problem-solving skills required to achieve future goals. Thankfully, what college students begin to lose in speeded performance, attention, or working memory, they gain in cognitive flexibility, reasoning, and decision-making (Ackerman, Beier, & Boyle, 2002).

Executive function and academic development

As noted, the neurobiological transformations during this period allow for higher-level mental processing and control, referred to as executive function or EF (Diamond, 2013). EF encompasses humans' ability to act intentionally, reflect on ideas, recognize and weigh alternatives, understand consequences, control emotion responses, make reasoned decisions, stay focused, set future goals, and be generally stable yet flexible (Jurado & Rosselli, 2007; McGivern, Andersen, Byrd, Mutter, & Reilly, 2002; Taylor, Barker, Heavey, & McHale, 2013). Such characteristics are valued for college students working to succeed in their studies and to do well in career pursuits. Indeed, 'examination of the literature on executive function leaves little doubt this domain of cognitive control and behavioural regulation is involved in numerous aspects of academics and everyday life' (Baggetta & Alexander, 2016; p. 10).

Also, there is the expectation that college students are increasingly more aware of their specific cognitive, psychological, social, and emotional strengths and have career aspirations matched to those strengths (Lent, Brown, & Hackett, 1994). Reflecting on these abilities and interests, students can decide on their programme of study and work towards whatever career goals they envision. Such actions are foundational to the development of expertise in specific fields of study (Ackerman, 2003; Alexander, 1997, 2018). As a consequence, EFs can manifest differently when measured in students' domains of study rather than generically (Romine & Reynolds, 2005). Specifically, with the increased domain-specific knowledge, interest, and problem-solving abilities that accompany expertise development, students can deepen their thinking and reflection, inform their decision-making, increase their focus, and exhibit more cognitive flexibility in that domain (Ackerman, 2000; Alexander, 2003; Ericsson, 2004). The three most studied EFs are working memory, inhibitory control, and relational reasoning.

Relational reasoning as a crucial executive function

Relational reasoning (RR) can be defined as individuals' ability to notice and attend to critical similarities and differences in what, on the surface, appear to be unrelated information or data (Alexander, Singer, Jablansky, & Hattan, 2016; Alexander, Dumas, *et al.*, 2016). These perceived relations further coalesce into meaningful patterns that guide thinking and action. In effect, RR is the ability to perceive deep and relevant associations where they do not obviously exist. For the past decade, our research team has been investigating nature, manifestations, assessment, and malleability of RR. As others before us (Cattell, 1940; Spearman, 1927), we regard this higher-order executive function as a defining difference in human cognition and development, and important to assess generally and domain-specifically. From our extensive work, we have garnered insights into RR that have bearing on college students' learning and performance and into issues of assessment.

The nature and forms of relational reasoning

My colleagues and I are by no means the first to recognize the power of relational reasoning. Spearman (1927), for one, considered reasoning by relations as the *sine qua non* for human cognitive ability, and his belief shaped the work of his students, Cattell (1940) and Raven (1941), who created intelligence tests around reasoning about complex relations. In fact, within cognitive science and cognitive neuroscience, the Raven's Progressive Matrices is still regarded as the gold standard for assessing this executive function (Dumas, Alexander, & Grossnickle, 2013). While our definition of RR is consistent with the research in cognitive neuroscience, we broadened its conceptualization to encompass not only the ability to recognize similarities (i.e., analogical reasoning), but also the dissimilarities. This effort to unearth reasoning patterns predicated on dissimilarities was informed by writings in intelligence, higher-order thinking, and mathematics set theory (Cattell, 1940; Russell, 1903; Spearman, 1927). Ultimately, three distinct forms representing varied patterns of dissimilarities were identified as follows: anomaly, antinomy, and antithesis (Alexander, Dumas, *et al.*, 2016; Alexander, Singer, *et al.*, 2016). Sample items from the Test of Relational Reasoning (TORR; Alexander & the Disciplined Reading and Learning Research Laboratory [DRLRL], 2012) help to explain these forms (see Figure 1). The TORR is a fluid measure of RR created for older adolescents and adults, which means it measures the ability to apply reasoning to a novel rather than a 'schooled' problem. It consists of 32 figural items organized in four 8-item scales, one for each form.

Of the aforementioned forms, *analogical reasoning* is the most familiar and involves the process of discerning similarities across objects, ideas, and experiences that are seemingly unrelated. As shown in Figure 1a, respondents must recognize the systematic changes in shape and number occurring within rows and columns in the array in order to select the missing piece from the options shown. As with the Raven's (1941), all items in this scale are configured as matrices. *Anomalous reasoning*, by comparison, is the

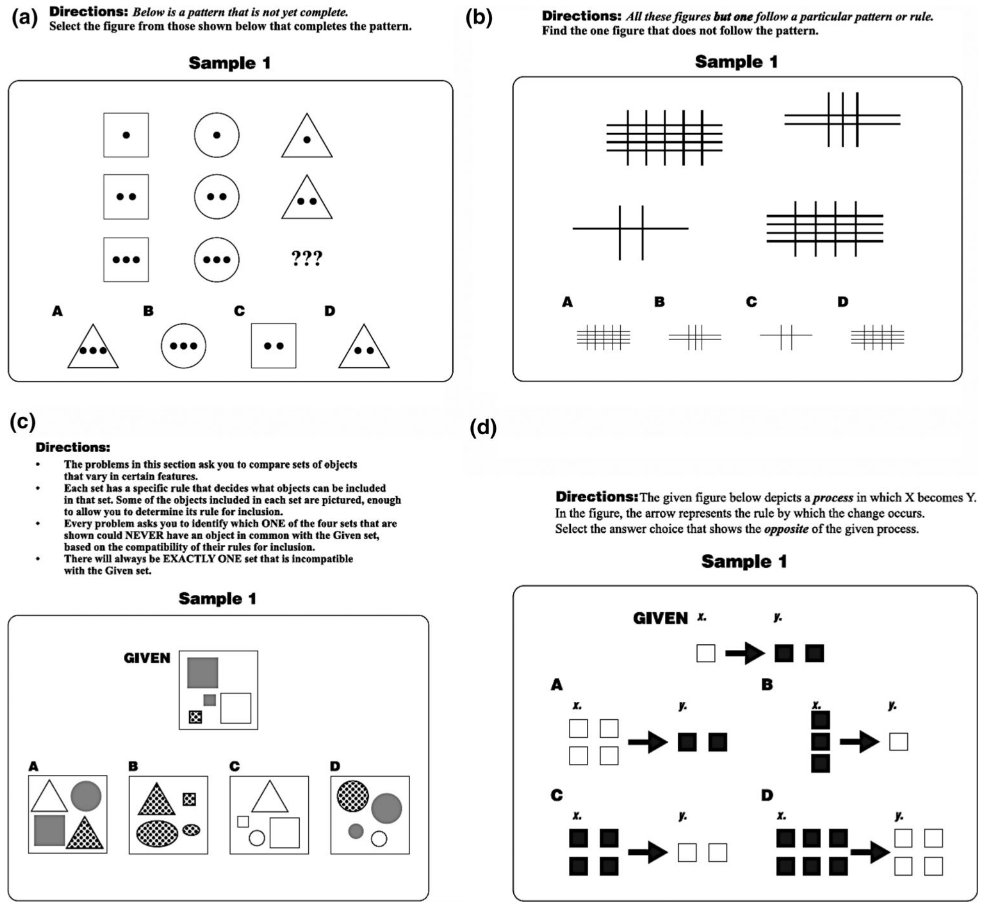

Figure 1. Sample items from the Test of Relational Reasoning (TORR) from the scales for (a) analogical reasoning; (b) anomalous reasoning; (c) antinomous reasoning; and (d) antithetical reasoning.

process of identifying a discrepant case or outlier within a set of objects, ideas, or experiences. For problem 1b, the set consists of figures composed of horizontal and vertical lines. In this problem, there is a particular ratio of horizontal to vertical lines common to all but one member – the anomaly.

Perhaps the least familiar form of RR identified was antinomous reasoning. *Antinomous reasoning* is the process of reaching a categorical judgment as to whether an object, idea, or experience can or cannot be a member of a given set of objects, ideas, or experiences. In effect, an antinomy represents an ontological distinction. To illustrate, the antinomy item (Figure 1c) requires respondents to determine which of the option sets can have no members in common with the given. Finally, for *antithetical reasoning*, the judgment to be made is not categorical but one of contrasts or opposition. Thus, in Figure 1d, respondents must discern the pattern of change represented in the given problem. Then, they must find the option that represents its opposite.

Over the course of multiple studies, the TORR has been shown to be a psychometrically sound measure. (Details on the TORR, including item difficulties, intercorrelations, reliability coefficients, invariance testing, and the resulting factor structure are provided in the Appendix S1). Even more importantly for this Special Issue, the TORR has been found to predict older adolescents' and adults' performance on a variety of demanding cognitive tasks including writing an argumentative essay (Singh, Sun, & Zhao, 2018), developing creative solutions to engineering design problems (Dumas, Schmidt, & Alexander, 2016; Jablansky, Alexander, & Schmidt, 2018), and thinking critically about maternity patients' care (Fountain, 2016). Although not the focus of this article, two additional measures of RR have been developed and validated: the Verbal Test of Relational Reasoning (vTORR, Alexander, Singer, *et al.*, 2016) for adolescents and adults; and the Test of Relational Reasoning-Junior (TORRjr; Alexander & the DRLRL, 2015) for children and younger adolescents. (See sample items in the Appendix S1).

While I have illustrated the forms of RR with sample items from TORR, it should be understood that these forms have been documented in everyday discourse and group problem solving. For instance, all four forms were evident in the verbalizations of mathematics and science teachers, undergraduate engineering students working on a design task, and residents and their attending physician diagnosing patients' conditions (Dumas, Alexander, Baker, Jablansky, & Dunbar, 2014; Jablansky *et al.*, 2018; Sun, Alexander, & Zhao, 2018).

Significance for adult learning and performance

What has this decade of research into relational reasoning revealed about adult differences and assessment methods that addresse the goals of this Special Issue? Here, we share insights that speak to between- and within-group findings, developmental and domain differences, as well as the co-occurrence of forms during problem solving.

Between- and within-group differences

In validating the TORR, Dumas and Alexander (2016) determined that relational reasoning is normally distributed among older adolescents and adults, but that total score does not tell the whole story. While most individuals scoring in the upper ranges of the test were consistently strong across all scales and those markedly below average were consistently weak, there was noticeable variability for those in the mid-ranges. For example, the same total score was achieved by students who scored moderately on each scale, as well as those who were high on one or two scales but low on the others. In effect, the specific scales of the TORR were informative sources of individual variability. Also, the investigation of differential item functioning for various groups (Dumas & Alexander, 2018, np) showed that the TORR was not only structurally invariant, but also could be 'meaningfully calibrated, normed, and scored in adolescent and adult populations like those enrolled in higher education, without explicitly accounting for the demographic group membership' (i.e., gender, race, and ethnicity).

Developmental, task, and domain differences

Developmentally, there is evidence of relevant changes in relational reasoning over time (Jablansky, Alexander, Dumas, & Compton, 2016). Jablansky *et al.* found that even kindergartens were capable of reasoning analogically, anomalously, antithetically, and antinomously when presented in a familiar problem-solving task. Still, there were contrasting usage patterns by age. What was particularly striking was the differential reliance on various forms between the early grades (Kindergarten, second, and fourth) and later grades (tenth and eleventh). Specifically, there was strong reliance on analogies and antitheses and minimal evidence of anomalies and antinomies among the younger students. In contrast, older students voiced more anomalies and antinomies, and very few analogies and antitheses during task performance. In light of this evidence, we tentatively concluded that certain forms of RR may be later developing than others. However, there are intervening factors that come into play, most notably task or content familiarity.

To be more precise, when the 'technological' object the younger children were manipulating was familiar (e.g., juice box), their RR was more sophisticated than when the object was novel (e.g., an unusual vegetable cutter). Older students, by comparison, engaged in more frequent and more sophisticated RR when the object was novel. This suggests that the features of the problem should be taken into consideration when measuring RR. Should a given task be too commonplace or too simple, then there seemingly little need to reasoning relationally. Conversely, when a task is highly complex *and* novel, then perhaps even adult learners may not be able to reason at an optimal level.

The malleability of relational reasoning

The prior discussion raises the question as to whether RR is malleable? Can explicit training delivered generically or domain-specifically alter the developmental trajectory for RR? That question remains to be fully addressed. There are certain data that can shed some light on the malleability of this higher-order executive function. For one, my colleagues and I have been successful at training analogical reasoning in children and adolescents within the context of reading, history, or human biology instruction (Alexander, Pate, Kulikowich, Farrell, & Wright, 1989; White & Alexander, 1986). However, neither the durability nor the transfer of those effects was assessed.

Let me also state that I see no value in training RR by means of abstract, decontextualized problems like those on the TORR for two reasons. For one, the history of generic problem-solving programmes is not encouraging (Wagner & Sternberg, 1984). For another, the value of assessments like the TORR lies in their novelty and abstraction, so training to the test would be counterproductive and ill-advised. Rather, training should focus on nature of the forms as they manifest in different academic domains and the underlying processes they entail. In the past, my colleagues and I used Sternberg's (1977) componential processes (i.e., encoding, inferring, mapping, and applying) to train analogical reasoning (Alexander *et al.*, 1989). Using Bayesian network analysis, Grossnickle, Dumas, Alexander, and Baggetta (2016) found that these same componential processes – especially inferring and mapping – distinguished high-performing from low-performing students on the TORR.

There have been two recent studies that involved training the forms of relational reasoning, although the results were mixed. There were quite positive outcomes for an intervention Hattan (2018) conducted in language arts classrooms serving a rural, economically disadvantaged community. The middle-school students were trained in the forms of RR as a way to improve their comprehension and recall of expository texts. Students were taught to pose questions representing each form before, during, and after reading as a way to relate the unfamiliar content (i.e., Ancient Greece and Rome) to their own lives and experiences. For example, the students were asked to consider how something in the reading reminded them of their own lives (analogy) or could never be true in their lives (antinomy). This approach was compared to a knowledge mobilization technique (i.e., 'tell me what you know'), and a control (text annotation) condition. The effectiveness of the relational reasoning approach over the other treatment and control conditions was demonstrated on immediate and delayed comprehension assessments.

In contrast, two Israeli researchers taught the four forms as a way to enhance eighth graders' understanding of key physics concepts (Aharon & Eilam, 2018). The training involved 16 90-min lessons where students learned the RR forms using examples from their everyday lives. Then, the four forms were used as the physics content (e.g., acceleration and velocity) was taught. To assess the effectiveness of the intervention, the eighth graders took a researcher-developed measure that required students to identify and explain the similarities and differences between two types of motion being depicted (e.g., constant velocity and constant acceleration). The repeated-measures analysis showed no significant difference between treatment and control classes on this measure, suggesting that the intervention did not improve students' learning of physics. The researchers concluded that the students' struggle to deal both with the novelty of RR and the unfamiliar and challenging physics content may simply have been too much.

The interplay among relation reasoning forms

Finally, I want to share one other significant finding; the orchestrated ways in which the forms of RR work in concert. In those situations where we have examined RR as it occurs naturally among individuals jointly engaged in problem solving, one fact has become apparent. The forms do not function in isolation, but unfold in a systematic, almost rhythmic manner set in motion by the task at hand. We witnessed this with the residents and attending physicians diagnosing patients' conditions and determining appropriate treatment, a science teacher trying to instruct her students about weather patterns, and the engineering students coming up with a viable design for their senior project (Dumas *et al.*, 2016; Sun *et al.*, 2018). One particular form of reasoning utterance was predictably followed by another (see Dumas *et al.*, 2014 for an detailed example of the pattern among medical doctors). Collectively, these studies are critical reminders that the forms of RR are not only important singularly in problem solving, but also collectively.

Conclusion and implications

What can those interested in individual differences among higher education students and their assessment garner from this overview I have offered? For one, in light of neurobiological and cognitive transformations students of this age are undergoing, higher education is an opportune time to gather crucial data about college students' capabilities to think and reason relationally. It is also a time to build on those capacities by consciously embedding the language and processes of reasoning relationally in instruction and in assessments of learning and performance. In this way, I concur with Blömeke, Gustafsson, and Shavelson's (2015) conception of a competence continuum that encompasses not only underlying capacities but also the manifestation of those capacities in performance of complex, real-world problems. In effect, as a foundational cognitive ability that remains critical to learning and performance throughout formal education and beyond, relational reasoning should have an acknowledged the presence within that continuum. As a starting point, the TORR could be administered early in college, arming students with knowledge about their capabilities to perceive meaningful relations in what they see, hear, or read. What matters next, of course, is how those capabilities are enacted, refined, and reinforced in instruction.

As I have argued (Alexander, 2003), the trajectory that leads to competence and potentially expertise in any field of study requires individuals to forge principled knowledge – significant understandings representing complex interrelations of conceptual and procedural information encountered in diverse contexts and at varied times. Those progressing on the path to expertise must also recognize when and where to apply to problem-solving skills they have been taught. For that reason, through the instruction they receive, these students should be made aware of how the forms RR manifest in their specific field of study (e.g., how an anomaly in astronomy differs from an anomaly in medical practice). Moreover, they should recognize how those forms can assist them in forging connections among the content and topics to which they are exposed. Additionally, those responsible for providing young adults with a meaningful education should model those reasoning process in their teaching and build them into their assessments. Rather than being inundated with overly simplistic, one-dimensional questions, students routinely should be required to demonstrate a deeper understanding of learned content by making critical comparisons, noting discrepancies, offering counterarguments, or perceiving contradictions.

Regardless of the quality of the education experienced, its value will be significantly limited unless college students can recognize how academic content relates to what they experience in the outside world. The question remains whether students will be able to see how ideas, problems, or experiences encountered in the everyday life – and consequently messier, less stylized, and less familiar than those upon which they are schooled – are nonetheless occasions for transfer. Therefore, as part of the competence continuum, I see a place for performance assessments that draw on RR nested within complex, domain-specific, real-world problems, such as those devised by Shavelson, Zlatkin-Troitschanskaia, and Mariño (2018). Through such assessments, there is the opportunity to acquire valuable information on outcomes reflecting competence and rich data on the reasoning processes leading to those outcomes.

Of course, I am aware of the barriers that exist to higher education's embrace of RR in assessment and instructional practices. I am arguing for RR just at the time when analogies, the one form of RR that has had a presence on well-known assessments (e.g., SAT and GRE), have been excised in favour of text-based questions. There is also the reality that the other forms of RR are relatively unfamiliar to most students, educators, educational researchers, and even some assessment experts. Further, constructing either fluid or crystallized items for these less familiar forms, especially antinomies and antitheses, can be daunting tasks.

Yet, unlike the verbal analogies on the SAT or GRE, the items on the TORR are non-verbal and novel and found to be culturally-fair (Dumas & Alexander, 2018). More to the point, our research has documented that these forms manifest when individuals and groups engage in complex problem solving and are predictive of performance (Dumas *et al.*, 2016). It would seem, therefore, that if students, educators, educational researchers, and assessment experts remain in the dark about the nature and importance of relational reasoning, they cannot adequately harness whatever potential this ability holds for college-age learners.

I appreciate the incalculable differences that distinguish one human from another, and recognize that differences continue to manifest within higher education. Nonetheless, I maintain that the competence young adults manifest in their ability to perceive meaningful relations within all they see, hear, or experience will remain crucial to their academic development and future career pursuits. Therefore, whatever can be done to understand the nature, development, and assessment of relational reasoning is well worth whatever investment of thought, time, and effort it may require.

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Supporting Information

The following supporting information may be found in the online edition of the article:

Appendix S1. Data on the Test of Relational Reasoning

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