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Individual Differences in Relational Reasoning

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Abstract

Relational processing has been linked to cognitive capacity measures, such as working memory and fluid intelligence. Sufficient capacity, however, does not ensure attention to relational structure, as propensity for relational processing may also be driven by an individual's cognitive style. The current study took an individual-differences approach to investigate the prerequisites for relational processing. College students completed a battery of standardized tests of individual differences related to fluid intelligence and cognitive style, as well as a series of experimental tasks that require relational reasoning. Moderate correlations were obtained between relational processing and measures of cognitive capacity, while the influence of cognitive style was restricted to individuals with greater cognitive capacity. These results support the hypothesis that a capacity threshold exists, above which cognitive style impacts relational processing.

Keywords: Relational reasoning, individual differences, cognitive capacity, cognitive style

Introduction

Relational reasoning—inferential processes constrained by the relational roles that entities play rather than the specific features of those entities—is a hallmark of human cognition. Languages would be severely limited without prepositions and verbs that represent relations between things (e.g., *give* expresses an exchange of something between a giver and a recipient). Analogical reasoning, in which a familiar source domain is mapped to a less understood target domain that shares its relational structure, underlies the powerful ability to derive plausible inferences about a target based on a source analog. In many cases, analogical reasoning is challenging because surface properties differ for entities that correspond across the analogs (e.g., Gick & Holyoak, 1980).

Given that many school subjects involve relational knowledge, understanding the cognitive underpinnings of such knowledge may help to improve education. Virtually all concepts in STEM fields are relational in nature (i.e., defined by shared relations rather than shared features). Furthermore, expertise in any domain requires rich knowledge of an interrelated set of concepts, many of which may themselves be relational in nature. Goldwater and Schalk (2016) suggest that abstract relational schemas are prerequisites for knowledge transfer, which is arguably the end goal of education. In addition, recent research has shown that effective use of relational processing separates successful from unsuccessful students (McDaniel, Cahill, Robbins, & Wiener, 2014). A better understanding of relational processing, and why some students embrace it while others do not, could lead to improved educational outcomes.

A great deal of research indicates that adequate cognitive capacity (often characterized in terms of concepts such as working memory, inhibitory control, executive functioning, and/or fluid intelligence; see Ackerman, Beier & Boyle, 2005) is necessary for relational processing (for a review see Holyoak, 2012). For example, imposing a working memory load causes college students to make fewer relational (and more featural) matches on a picture-mapping task (Waltz, Lau, Grewal, & Holyoak, 2000). Scores on the Ravens Progressive Matrices (RPM), a standard measure of fluid intelligence (Raven, 1938), have been shown to correlate positively with the probability of spontaneous analogical transfer in a problem-solving task (Kubricht, Lu, & Holyoak, 2017). Neuropsychological evidence links impaired prefrontal functioning with greatly diminished performance on analogy tasks (e.g., Krawczyk et al., 2008; Morrison et al., 2004). A number of computational models of analogical reasoning emphasize the centrality of capacity constraints (e.g., Halford, Wilson, & Phillips, 1998; Hummel & Holyoak, 1997, 2003).

While cognitive capacity is clearly an important contributor to performance in tasks that require relational reasoning, other sources of individual differences may also play a role. In particular, substantial evidence implicates variations in cognitive style—differences in preferred thinking strategies—in performance on reasoning tasks (e.g., Stanovich & West, 1997). One measure of cognitive style is the Need for Cognition (NFC) scale, which measures preferences for engaging in or avoiding analytic thinking (Day et al., 2007; Hill et al., 2013).

The relationships among cognitive style, cognitive capacity, and relational processing have been explored within a framework developed by Stanovich and colleagues (Stanovich & West, 1997, 2008). While recognizing the important contributions of both cognitive capacity and thinking dispositions to rational behavior, Stanovich (2012) emphasized that sufficient cognitive capacity is required to enable individuals to realize thinking dispositions that may predispose them to favor analytic thinking. If someone does not have sufficient cognitive capacity to provide an analytic response in a given situation, that individual's thinking disposition will have little impact on their ability to cope with the situation. This view suggests the possibility of a *capacity threshold* that must be met before a dispositional preference for analytic thinking will impact performance.

An individual-difference perspective may shed light on the component processes that underlie relational reasoning. The present study applied an individual-difference approach to investigate potentially separable components of relational reasoning, focusing on cognitive capacity, inhibitory control, and cognitive style.

Method

Participants

Participants were 202 undergraduate students (mean age = 20.1, 137 female) from the University of California, Los Angeles who received course credit for participating.

Measures

Each participant completed a series of individual difference measures, followed by experimental tasks likely to require relational processing.

Raven's Progressive Matrices. Participants completed a shortened, 12-item version of the RPM test, a common measure of fluid intelligence (Arthur, Tubré, Paul, & Sanchez-Ku, 1999). In this task, participants view a series of 3x3 grids with shapes in each cell except for the bottom right cell, which is blank. Systematic patterns are instantiated across the rows and down the columns of each matrix. From 8 alternatives, participants choose which shape correctly completes the matrix by following the relational rules instantiated in the filled cells. This task is untimed.

Need for Cognition. The NFC, developed by Cacioppo and Petty (1982), measures whether the individual enjoys engaging in analytic thinking. The shortened scale was used, which consists of 18 statements about processing preferences (e.g., "I would prefer complex to simple problems", or "Thinking is not my idea of fun"). Participants indicate how characteristic each statement is of themselves on a scale from 1 (extremely uncharacteristic) to 5 (extremely characteristic). Some items were reverse scored.

Cognitive Reflection Test. The Cognitive Reflection Test (CRT), developed by Frederick (2005), measures an individual's ability to inhibit an automatic response and engage in more effortful analytic thinking. This test consists of three problems, all of which have an "obvious" incorrect answer that immediately springs to mind. To answer these problems correctly, participants must inhibit these attractive automatically-generated answers and instead engage in more effortful processing to compute the correct answer. The role of inhibitory control as assessed by the CRT is of particular importance in the current study. To correctly answer CRT questions, an individual must exercise inhibitory control to resist reporting the obvious incorrect answer (Campitelli & Gerrans, 2014). The CRT is weakly correlated with other measures of inhibitory control, such as the Stroop task (Toplak, West, & Stanovich, 2011).

Analogical Transfer. In this task (Gick & Holyoak, 1980), participants read a story containing a source analog ("The General") and summarize it. Later, they are presented with the radiation problem (Duncker, 1945), which has an analogous "convergence" solution, and are prompted to solve it. After attempting to solve the problem without any prompt to use the source analog, participants are given a hint to think back to the source analog story and write down a solution that the story suggests. The total solution rate for the radiation problem is calculated based on convergence solutions generated either before or after the hint is given.

Algebra Translation Problem. In this task (Martin & Bassok, 2005; Simon & Hayes, 1976), participants read the statement, "There are six times as many students as professors at this university," and must translate it into an algebraic expression. Success on this problem requires successfully avoiding a deceptively-easy syntactic translation strategy, which would yield the incorrect expression $6S = P$. Producing the correct response, $S = 6P$, requires engaging in analytic processing and evaluating the relation between the number of students and of professors.

Picture-Mapping Task. The final measure of relational processing employed was a picture-mapping task developed by Markman and Gentner (1993), with additional items added by Tohill and Holyoak (2000). In this task, participants are shown a series of picture pairs and asked to map one object from the top picture to an object in the bottom picture. The two pictures are displayed for 10 s, after which an object in the top picture is visually highlighted. The participants must then decide which object in the bottom picture "goes with" the highlighted object in the top picture. The expression "goes with" is purposefully vague: for each picture pair, the highlighted object could be mapped either on the basis of object attributes or the basis of a shared relational role that each objects fills. The dependent measure of interest is how many relational mappings a participant makes out of 10 picture pairs.[1]

Procedure

Participants completed all tasks individually on a computer, using the keyboard to input responses. The tasks were ordered as follows. (1) Participants read the source analog for the analogical mapping task and summarized it. They then completed (2) the NFC scale, (3) the CRT, and (4) the RPM. Next, (5) participants were prompted to solve the radiation problem for the analogical mapping task; (6) they completed the algebra translation task; and (7) completed the picture-mapping task. At the end of the study, participants were asked whether or not they had seen any of the tasks in the study previously, and if so to describe them. The study took one hour to complete.

[1] A word classification task developed by Little and McDaniel (2015) was also administered. However, task performance was poor (fewer than 33% of participants successfully learned to classify the words). Consequently, data from this task were not analyzed and the task will not be discussed further.

	N	*Maximum Possible Score*	*Mean*	*Std. Deviation*
RPM	198	12	6.93	2.84
CRT	195	3	1.05	1.11
NFC	201	90	60.63	10.49
Radiation total	198	2	.29	.46
Algebra problem	200	1	.53	.50
Relational matches on picture mapping task	148	10	6.35	2.93

Table 1. Descriptive statistics for each test and dependent measure.

Results

Data from one participant who failed to follow experimental instructions were excluded, leaving a total of 201 participants for analysis. Data for specific tasks were excluded for several additional participants. Data from the CRT were excluded for six participants, and data from the analogical mapping problem were excluded for two others, because these participants expressed familiarity with the respective tasks. Data from the RPM were removed for one participant who failed to follow instructions and for two others whose mean RTs for each problem exceeded 1.5 standard deviations below the grand mean of trial RTs (39.71 s, *SD* = 23.59 s), resulting in very low scores. Most seriously, the initial version of the instructions for the picture-mapping task proved confusing to participants, requiring us to modify the instructions. Data for the first 41 participants (who received the initial version) were excluded for this task. Data on this task were excluded for 12 additional participants because they gave five or more responses coded as "other", indicating a misunderstanding of the task.

Coding

Open-ended responses were coded by two independent raters. Any disagreements were decided by a third party.

Analogical transfer. Solutions to the radiation problem were scored according to criteria adapted from previous research (Gick & Holyoak, 1980). If participants expressed at least two out of three critical ideas, they received full credit: (1) multiple radiation sources, (2) low intensity of rays, (3) arrangement of rays around the tumor with rays converging on the tumor. Responses were scored either as correct or incorrect (no partial credit was awarded). In addition, participants were scored as to whether they had solved the radiation problem spontaneously (without the hint) or after receiving the hint. Inter-rater reliability was high for this task, with Cohen's Kappa equal to .73.

Picture mapping. Responses on the picture-mapping task were scored according to previously established criteria as featural, relational, or other (Markman & Gentner, 1993). The key dependent measure for this task was the number of relational mappings (out of 10 possible) that participants made. Inter-rater reliability on this task was high, with Cohen's Kappa equal to .84.

Descriptive analyses

Raw means and standard deviations for the three key individual-difference measures and relational-processing measures are displayed in Table 1. These descriptive results show that performance on the analogical transfer task was poor. The spontaneous transfer rate in the current study (.09) was close to the solution rate found by Gick and Holyoak (1980) for participants who did not read a source analog (i.e., the control level). The total solution rate (.29) was much lower than that observed in the same study (.7). The poor performance on this task may have been due to the extended time interval between presentation of the source analog and the target problem, coupled with interference from the demanding set of tasks that participants performed in between. Because spontaneous transfer was not obtained, total solution rate was used as the dependent measure for this task.

Correlational analyses

Prior to running analyses, each participant's score on each task was standardized. A relational composite measure was created by summing participants' standardized scores on each of the relational-processing measures (relational responses on the picture-mapping task, score on the algebra translation problem, and total-solutions score on analogical transfer task).

Inter-task correlations are presented in Table 2. Several interrelationships among the individual difference measures are apparent. The moderate correlation between RPM and CRT (r = .49) is stronger than correlations noted in previous studies, which have found these two measures to be correlated at about .3 (e.g., Brañas-Garza, García-Muñoz, & Hernán-González, 2012; Hanaki, Jacquement, Luchini, & Zylbersztejn, 2016). The weak relationship between RPM and NFC (.14) is similar to that found in previous studies (e.g., Hill et al., 2013). Finally, the somewhat stronger relationship between NFC and CRT (.24) is similar to correlations found in previous studies, supporting the hypothesis that the CRT is sensitive to both capacity and style components (e.g., Pennycook, Cheyne, Koehler, & Fugelsang, 2016).

Table 2 also shows the pattern of correlations among the individual-difference measures and the relational-processing measures. Analogical transfer showed a modest but reliable correlation with RPM scores (r = .27, p < .01), comparable to that observed in previous research (Kubricht et al., 2017), and a similar correlation with the CRT (r = .31, p < .01), suggesting that capacity and inhibitory control are related to performance on this task. Relational responses on the picture-mapping task were moderately correlated with RPM (r = .45, p < .01) and with the CRT (r = .37, p < .01), again

		1	2	3	4	5	6	7
1	*RPM*	1						
2	*CRT*	.49**	1					
3	*NFC*	.14*	.24**	1				
4	*Radiation total*	.27**	.31**	.13	1			
5	*Algebra problem*	.31**	.35**	.23**	.18**	1		
6	*Picture mapping*	.45**	.37**	.03	.22**	.29**	1	
7	*Composite*	.49**	.48**	.17*	.66**	.69**	. 73**	1

Table 2. Correlation matrix for all measures. Note: ** denotes $p < .01$, * denotes $p < .05$

suggesting the engagement of cognitive capacity and inhibitory control. The algebra translation problem showed a moderate correlation with RPM ($r = .31$, $p < .01$) and with the CRT ($r = .35$, $p < .01$). Unlike the other two relational processing tasks, this task was also weakly correlated with NFC ($r = .23$, $p < .01$), suggesting an impact of cognitive style on performance.

Next, correlations between the individual-difference variables and the relational composite were examined. The relational composite measure was correlated moderately with RPM ($r = .49$, $p < .01$) and CRT ($r = .48$, $p < .01$), and weakly with NFC ($r = .17$, $p < .05$). This pattern suggests that relational processing was influenced by cognitive capacity, inhibitory control, and to a lesser extent, cognitive style.

The weak relationship between NFC and the relational composite measure in the full dataset may be an underestimate of the true relationship. Within the framework proposed by Stanovich (2012), a certain threshold level of cognitive capacity may be required to engage in relational processing. Only if that threshold is met will variations in cognitive style also impact performance. Thus if an individual lacks sufficient capacity to engage in relational reasoning, then their information-processing preferences will have little impact, as their lack of adequate capacity will prevent those preferences from manifesting themselves in task performance.

Table 3 shows mean scores on the relational processing composite broken down by individuals who scored above and below the median on RPM and the NFC scale. To investigate the possibility that a capacity threshold is important, the data were split based on participants' scores on RPM, and correlations were rerun. For participants whose score was below the median (7) on RPM, the correlation between NFC and the relational composite measure was −.04 ($n = 60$), a negligible value. For participants who scored above the median on RPM, the correlation between NFC and the relational composite measure increased to .26 ($n = 68$), $p < .05$. A one-tailed z test of differences in correlations showed that these two correlations differed significantly in the expected direction: for participants who scored above the median on RPM, cognitive style was reliably related to relational processing performance, whereas for those who scored below the median the relationship disappeared ($z = 1.7$, $p = .04$). This pattern suggests that an individual's cognitive style only impacts their relational reasoning if that person has sufficient cognitive capacity.

	Below median on RPM	*Above median on RPM*
Below median on NFC	-.62	.56
Above median on NFC	-.82	1.10

Table 3. Mean score on relational composite measure for individuals above and below the median on RPM and NFC.

Discussion

The goal of the current study was to begin an exploration of the component processes that underlie relational processing. This aim was accomplished through the administration of a short battery of individual-difference measures, including RPM as a measure of cognitive capacity, the CRT as a measure of inhibitory control and cognitive style, and the NFC scale as a measure of cognitive style. These individual-difference measures were examined in conjunction with three measures of relational processing: analogical transfer, an algebra translation problem, and relational matches on a picture-mapping task.

The key findings involve the composite relational processing measure constructed by summing participants' standardized scores on the three relational-processing measures. A moderate correlation was observed between the composite and both RPM and CRT. For the full dataset, the NFC was weakly correlated with the composite measure. However, the correlation between the NFC scale and the composite differed significantly for participants who scored below versus above the median on RPM: negligible for the former group, significantly larger for the latter.

Our findings are consistent with those of previous studies that found a link between relational processing and fluid intelligence (Kubricht et al., 2017; Vendetti, Wu & Holyoak, 2014). The current study also supports previous findings linking inhibitory control to relational processing (e.g., Krawczyk et al., 2008). Although no previous studies have explored this link using the CRT, this test has been examined in concert with many other individual differences and cognitive tasks. For example, studies have found the CRT to be positively correlated with performance on various decision-making tasks (e.g., Lesage, Navarrete, & de Neys, 2013; Toplak, West, & Stanovich, 2011), and rule transfer in a causal learning paradigm (Don, Goldwater, Otto, & Livesey, 2016); while it is negatively correlated with trust in intuition (Pennycook et al., 2016). Given that a link between relational processing and the CRT has now been established, the relevance of relational processing to each of these tasks should be considered. For example, an individual who is better at processing relations might be more likely to consider the relations between variables in a conjunctive probability problem.

The nature of the relationship between the NFC scale and relational processing found in the present study also supports previous findings. Specifically, cognitive style as measured by the NFC was found to be related to relational processing only for those participants who had sufficient cognitive capacity, in accord with the proposal by Stanovich and West (2008). Cognitive style measures are relevant to whether or not an individual will detect a situation in which a heuristic response is not warranted; but even if the need for an override is detected, an individual with insufficient cognitive capacity may not be able to correctly compute the appropriate response.

One limitation of the current project is related to the use of the RPM as a measure of cognitive capacity. Solving RPM problems requires consideration and integration of relations between cells in the matrix; thus the RPM itself is a task that requires relational reasoning. Accordingly, caution is warranted in interpreting the RPM as a specific measure of cognitive capacity. Future work should incorporate other measures of cognitive capacity, such as working-memory tasks.

The distinct contributions of executive functions and cognitive style to successful relational processing suggest two potential pathways to improve relational reasoning performance. Interventions that improve relational reasoning performance for individuals with low cognitive capacity may not benefit those with low propensity to process relations, and vice versa. Cognitive style and capacity have been identified as stable individual difference measures that affect individuals over the course of their lifetimes (Arthur et al., 1999; Sadowski & Gulgoz, 1992). Each of these sources of potential improvement should be explored in future studies.

Previous studies offer examples of the kinds of interventions that may help individuals with low cognitive capacity. Kubricht et al. (2017) found that supplying an animated diagram along with the source analog improved analogical transfer performance for individuals with low cognitive capacity as assessed by RPM. Vendetti et al. (2014) showed that generating solutions to semantically distant analogies induced a relational set for information processing, which increased the number of relational matches made subsequently on the picture mapping task. Moreover, induction of a relational set reduced the association between performance on the mapping task and score on RPM.

Each of the relational processing tasks selected in the current study involve explicit reasoning with relations. Some previous research suggests that relational processing may sometimes proceed implicitly, without recognition by the reasoner (e.g., Day & Goldstone, 2011). It is unclear whether the same cognitive mechanisms would be involved in implicit relational processing; hence future studies should examine this possibility.

Although other individual-difference measures need to be investigated, the present study is a step toward understanding the cognitive processes that underlie relational processing. There may be two separable pathways toward improving relational reasoning performance, which could lead to improved educational outcomes.

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