The Cognitive Underpinnings of

Multiply-Constrained Problem Solving

by

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ABSTRACT

In the daily life of an individual problems of varying difficulty are encountered. Each problem may include a different number of constraints placed upon the problem solver. One type of problem commonly used in research are multiply-constrained problems, such as the compound remote associates. Since their development they have been related to creativity and insight. Moreover, research has been conducted to determine the cognitive abilities underlying problem solving abilities. We sought to fully evaluate the range of cognitive abilities (i.e., working memory, episodic and semantic memory, and fluid and crystallized intelligence) linked to multiply-constrained problem solving. Additionally, we sought to determine whether problem solving ability and strategies (analytical or insightful) were task specific or domain general through the use of novel problem solving tasks (TriBond and Location Bond). Results indicated that multiply-constrained problem solving abilities were domain general, solutions derived through insightful strategies were more often correct than analytical, and crystallized intelligence was the only cognitive ability that provided unique predictive value.

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The Cognitive Underpinnings of Multiply-Constrained Problem Solving

Humans possess an incredible ability to target remote information stored in semantic memory even when provided with only minimal cues to guide their search. For example, consider participating on the game show *Jeopardy!* where contestants are provided with an answer and their goal is to find the specific question that generated that answer. To the naive viewer this may seem like a nearly impossible problem to solve. However, contestants can use certain cues to delimit their search of memory. Specifically, the answers all come from a common category which narrows the search to a specific domain. Additionally, contestants' responses are almost exclusively limited to "Who is/are" or "What is/are" which means that dates are more often clues than answers. Lastly, the answer itself provides the final narrowing. Now imagine that you get to be a contest on *Jeopardy!* and the show is starting, there are different lighting apparatuses, cameras, and the timeless host Alex Trebek is standing before you. You are given the opportunity to select the first clue, and you select "A Knight for $200". Mr. Trebek begins to read, "Sir Galahad was the illegitimate son of this other knight". The category (A knight) directs you to a subset of individuals to search through. The clue indicates that the answer should be "Who is" rather than a "What is" question, and the name Galahad reminds you of *Monty Python and the Holy Grail*. You are tempted to buzz in with a response, but the stage lights are blinding, which makes you lose focus, and thinking about *Monty Python* brought forth memories of a ferocious bunny. Before long the contestant next to you has answered correctly and the realization sets in you had never even heard of Sir Lancelot. *Jeopardy!* questions, like the one above, can alternatively be classified as a multiply-constrained problem.

The *Jeopardy!* example highlights a type of convergent or multiply-constrained problem. While *Jeopardy!* questions have certainly been used in the classroom (Rotter, 2004), in the laboratory a more commonly used set of multiply-constrained problems are the Compound Remote Associates Test. The Remote Associates Test, originally developed by Mednick (1962), requires an individual to search through memory for a target word ("ICE") that is semantically related to three cues ("CREAM, SKATE, WATER"). These problems were later adapted such that the target is paired with each cue to form a compound word or phrase (Bowden & Jung-Beeman, 2003). Furthermore, the *Jeopardy!* example highlights possible underlying cognitive processes that lead to successful problem solving, as well as, possible sources of interference in problem solving ability. Specifically, an individual's ability to maintain control of attention in the face of irrelevant distractors (focusing on answering the question rather than recalling your favorite scene from *Monty Python and the Holy Grail*), selecting and pursuing relevant memory search criteria (to narrow the search in favor successfully targeting Sir Lancelot), and having been exposed to the correct information and actually having that information stored in memory are all possible sources of variability in multiply-constrained problem solving. Therefore, the purpose of this experiment is to determine whether individual differences in working memory, attention control, long-term memory, and fluid or general intelligence predict strategy adoption and performance in multiply-constrained problem solving.

Multiply-Constrained Problem Solving & Strategies

When an individual attempt to solve a multiply-constrained problem they may employ a strategy, and the two most commonly reported strategies are analytical (sometimes referred to simply as strategy; Zedelius & Schooler, 2015) and insight. The analytical approach is defined as a more stepwise approach like one would employ while solving a math problem. For a compound remote associates (CRAT) problem the analytical approach would be systematically testing possible solutions against each cue word. Conversely, the insight strategy is exemplified by the "A-ha" moment where the solution appears spontaneously (see Weisberg, 2015 for a review). We use the term strategy to be consistent with published research on this topic. However, our usage of the term strategy in this paper simply denotes the participants' assessment of their subjective experience of discovering the solution to each problem they solve correctly and not necessarily their approach to solving the problem. Some have found that accuracy for analytical responses is better than insight (Chuderski & Jastrzebski, 2018). However, the more consistent finding is that insight responses are more often correct (Chein & Weisberg, 2014; Salvi, Bricolo, Kounios, Bowden, & Beeman, 2016; Zedelius & Schooler, 2015). As will be reviewed, prior studies have investigated individual differences in problem solving and relations with various cognitive abilities. However, much less research has examined individual differences in the strategies applied to solving multiply-constrained problems.

Working Memory Capacity, Attention Control, & Multiply-Constrained Problem Solving

Initial work by Lavric, Forstmeier, & Rippon (2000) identified that individual differences in WMC was predictive of both creative (which the compound remote associates (CRAT) are thought to measure) and analytical problem solving. More recently, Chein & Weisberg (2014) provided further evidence that WMC was related to multiply-constrained problem solving ability, as measured by the CRAT (see also Ellis & Brewer, 2018; Lee & Therriault, 2013; Ricks, Turley-Ames, & Wiley, 2007). Individual differences in working memory capacity are thought to arise due to differences in attention control, capacity, and cue-dependent retrieval from secondary memory (Unsworth, 2016). Variability in CRAT performance is thought to be related to attentional focus (Wiley & Jarosz, 2012). Specifically, the focusing of attention allows an individual to actively search memory for possible solutions, resist distracting information, and let incorrect solutions decay (i.e., to reduce interference from previously generated but incorrect targets; Moss, Kotovsky, & Cagan, 2011). Accordingly, there is some evidence that distractibility (Kim, Hasher, & Zacks, 2007) or intoxication (Benedek, Panzierer, Jauk, & Neubauer, 2017; Jarosz, Colflesh, & Wiley, 2012) can aid performance by augmenting attention control functioning.

Given the relation between WMC and attention control functions (Engle, 2002), it is possible that individual differences in WMC and attention control will account for a portion of the variance in multiply-constrained problem solving. For this experiment, we have chosen tasks that evaluate the different subcomponents of an individual’s attentional abilities utilizing, specifically the Stroop, Antisaccade, and Psychomotor Vigilance

(PVT) tasks. Performance on the Stroop is related to goal maintenance (Kane & Engle, 2003). Antisaccade performance is related to the ability to resist attention capturing stimuli (Engle, 2002). Specifically, the Stroop and Antisaccade are both measures of attentional restraint. While the PVT captures an individual's ability to sustain attention for periods of time (Dinges & Powell, 1985).

Memory & Multiply-Constrained Problem Solving

Recent work by Smith, Huber, & Vul (2013) and Davelaar (2015) highlighted the role of semantic memory search functions during CRAT problem solving. These researchers examined whether CRAT search behavior is like other semantic search tasks, such as a category fluency. In a category fluency task, a participant is asked to retrieve as many exemplars as possible given a specific cue (e.g., "Animals"). Both CRAT and fluency tasks require retrieval of exemplars from memory but in the CRAT there is only one possible target, whereas in a fluency task there are several possible targets. When an individual completes a fluency task they often cluster groups of responses together. For example, when given the category of "Animals" an individual will first choose a sub-category, like "aquatic animals", and provide several exemplars in rapid succession (Troyer, Moscovitch, & Winocur, 1997).

In many CRAT experiments the participant is only allowed to enter a single response for each problem, but others have allowed for multiple responses. For example, Davelaar (2015) utilized an externalized response procedure. In this procedure the participant is asked to enter any potential answers they generate during the problem solving period for each problem and then ultimately say which answer is they believe is the correct answer. This externalized procedure allows the researcher to examine the participant's semantic search path and the related associative distances between subsequent generated responses. Davelaar's examination of responses during CRAT problem solving found a clustering of responses similar to what is often found in a fluency task. However, others have argued that CRAT responses exhibit a sequential dependence, such that a subsequent response is partially related to the previous response, and further state that the supposed clustering is just a masked sequential dependence (Smith & Huber, 2015). Additional work has identified that performance on fluency tasks is positively related with CRAT performance (Lee & Therriault, 2013). Given the relation between semantic fluency and CRAT performance, along with the theoretical role that semantic search plays in solving CRAT problems, an individual's ability to effectively search semantic memory should be related to their problem solving ability. While semantic retrieval abilities are related to both WMC and multiply-constrained problem solving, it must be noted that fluency tasks represent only a single type of memory retrieval. Other commonly used tasks like cued-recall, source monitoring, and delayed free recall, which involve episodic retrieval mechanisms, have known relations to WMC (Unsworth & Engle, 2007; Unsworth & Spillers, 2010; Unsworth, Spillers, & Brewer, 2010). The ability to retrieve answers from memory is necessary to solve multiply-constrained problems and may have shared variance with the WMC, attention, and multiply-constrained problem solving relation. Additionally, memory retrieval could provide unique predictive value above and beyond the other measured cognitive abilities.

Intelligence & Multiply-Constrained Problem Solving

Lee & Therriault (2013) found that intelligence was predictive of problem solving ability. Similarly, reasoning ability as measured by tasks like Raven's Progressive

Matrices and Weschler Abbreviated Scale of Intelligence, was found to be related to problem solving ability (Chuderski & Jastrzebski, 2018; Kane, Hambrick, Tuholski, Wilhelm, Payne, & Engle, 2004). The strength of the relation is stronger to measures of general intelligence than reasoning (Harris, 2003; Kane, Hambrick, Tuholski, Wilhelm, Payne, & Engle, 2004; Lee & Therriault 2013). For a given problem, there is some fundamental knowledge one must have to solve it. For example, if given the CRAT cues “CREAM, SKATE, WATER”, to be able to solve the problem you would have to know at least these two things, 1) that “ICE” is a word, 2) that “ICE” forms a compound word or phrase with at least one of the cues. Therefore, knowledge of the target must serve as a limiting factor in problem solving. For the commonly used CRAT problems, knowledge of cues and targets is often assumed as the words are commonly used, however distant the associations between cues and targets may be.

The Current Study

Recently, there have been calls for more research focused on fundamental processes and abilities related to creativity and related multiply-constrained problem solving (Benedek, Konen, & Neubauer, 2012; Benedek & Fink, 2019; Cortes, Weinberger, Daker, & Green, 2019; Dietrich, 2018). Currently, the predominant theory is that working memory and associated control and inhibitory process are the most likely predictors of problem solving ability (see Wiley & Jarosz, 2012). Attention control is needed in problem solving to generate possible solutions, ignore distraction, and not retrieve previously retrieved solutions. However, another possible predictor is memory search dynamics of semantic memory but perhaps not episodic memory. Work by Smith et al. (2013) and Davelaar (2015) highlight different search procedures and put forth their arguments for the most effective strategies. However, memory retrieval processes may not be a unique predictor as Unsworth, Spillers, & Brewer (2013) have shown that WMC is related to number of retrieved items and the use of effective retrieval strategies. But, being able to generate more possible solutions should improve the odds of finding the target of multiply-constrained problems, like the CRAT, given that targets tend to be weakly related to the cues.

Therefore, for the current experiment we seek to use individual differences as a crucible to determine whether working memory, attention, memory, or knowledge are predictive of multiply-constrained problem solving ability (Underwood, 1975). While others have examined multiply-constrained problem solving ability and possible predictors of performance, none have evaluated the range of cognitive abilities present in this experiment. Participants completed multiple measures of WMC, multiply-constrained problem solving, attention control, long-term memory (episodic and semantic), and intelligence (crystallized and fluid). To better understand the role of these cognitive abilities in multiply-constrained problem solving we adopted two additional remote associate tasks, TriBond and Location Bond (LocBond). Therefore, we could assess whether multiply-constrained problem solving is domain specific versus domain general as well as evaluating how these various individual differences measures predict problem solving.

Methods

Participants and Design

Four hundred and ninety-one participants were recruited from the Arizona State University participant pool and received course credit for their participation. Forty-two participants were removed from all future analyses for either being identified as being English second language, failing to complete both laboratory sessions or being a multivariate outlier. Therefore, the final data set includes 449 participants. Participants completed all experimental tasks across two separate group laboratory sessions lasting approximately two hours per day (4-hours total). Participants completed four working memory tasks, three attention control tasks, three long-term memory tasks, three semantic fluency tasks, three general knowledge tasks, three fluid intelligence tasks, and three multiply-constrained problem solving tasks.

Materials

Demographics. Participants are asked to provide general demographic information, such as, age, whether they are a native English speaker or not, and if they are not a native English speaker, at what age did they learn English.

Reading span. Participants solved a series of math operations while trying to remember a set of unrelated letters (F, H, J, K, L, N, P, Q, R, S, T, Y). For this task, participants read a sentence and determined whether the sentence made sense or not (e.g. "The prosecutor's dish was lost because it was not based on fact.?"). Half of the sentences made sense while the other half did not. Nonsense sentences were made by simply changing one word (e.g. "dish" from "case") from an otherwise normal sentence. Participants were required to read the sentence and to indicate whether it made sense or not. After participants gave their response they were presented with a letter for 1 s. At recall, letters from the current set were recalled in the correct order by clicking on the appropriate letters. There were three trials of each list-length with list-length ranging from 3–7. The dependent measure was the number of correct items in the correct position.

Operation span. Participants were required to read sentences while trying to remember the same set of unrelated letters as Reading span. Participants were required to solve a math operation, and after solving the operation they were presented with a letter for 1 s. Immediately after the letter was presented the next operation was presented. Three trials of each list-length (3-7) were presented, with the order of list-length varying randomly. At recall, letters from the current set were recalled in the correct order by clicking on the appropriate letters (see Unsworth, Heitz, Schrock, & Engle, 2005 for more details). Participants received three sets (of list-length two) of practice. For all span measures, items were scored if the item was correct and in the correct position. The same scoring procedure as Reading span was used.

Symmetry span. In this task participants were required to recall sequences of red squares within a matrix while performing a symmetry-judgment task. In the symmetry-judgment task participants were shown an 8 x 8 matrix with some squares filled in black. Participants decided whether the design was symmetrical about its vertical axis. The pattern was symmetrical half of the time. Immediately after determining whether the pattern was symmetrical, participants were presented with a 4 x 4 matrix with one of the cells filled in red for 650 ms. At recall, participants recalled the sequence of red-square locations in the preceding displays, in the order they appeared, by clicking on the cells of an empty matrix. There were three trials of each list-length with list-length ranging from 2-5. The same scoring procedure as Reading span was used.

Rotation span. The automated rotation span (Harrison et al., 2013) consists of to-be-remembered items that are a sequence of long and short arrows, radiating from a central point.

The processing task required subjects to judge whether a rotated letter was forward facing or mirror-reversed. Set sizes varied between two and five items. The sets were presented in a randomized order, with the constraint that a given set could not repeat until all other sets had been presented. Each set was used three times. The same scoring procedure as Reading span was used.

Stroop. Participants were presented with a color word (red, green, or blue) presented in one of three different font colors (red, green, or blue). All words were presented in Courier New with an 18-point font. The participants' task was to indicate the font colour via key press (red=1, green=2, blue=3). Participants were told to press the corresponding key as quickly and accurately as possible. Participants received 75 trials in total. Of these trials, 67% were congruent such that the word and font color matched (i.e., red printed in red), and the other 33% were incongruent (i.e., red printed in green). Congruent and incongruent trials were mixed throughout the task. The dependent measure was the Incongruent reaction time.

Antisaccade. In this task (Kane et al., 2001), participants were instructed to stare at a fixation point which was onscreen for a variable amount of time (200-2,200 ms). A flashing white "=" was then flashed either to the left or to the right of fixation (11.33° of visual angle) for 100 ms. This was followed by a 50-ms blank screen and a second appearance of the cue for 100 ms, making it appear as though the cue (=) flashed onscreen. Following another 50-ms blank screen, the target stimulus (a B, P, or R) appeared onscreen for 100 ms followed by masking stimuli (an H for 50 ms and an 8, which remained onscreen until a response was given). All stimuli were presented in Courier New with a 12-point font. The participants' task was to identify the target letter by pressing a key for B, P, or R (keys left arrow, down arrow, or right arrow on the keyboard) as quickly and accurately as possible. Participants received, in order, 9 practice trials to learn the response mapping, 9 trials of the prosaccade practice, 9 trials of the antisaccade practice, and 36 experiment trials of the antisaccade condition. The dependent measure is the proportion of correctly identified targets.

Psychomotor Vigilance. In this task participants monitor a computerized stopwatch that begins counting up in milliseconds (ms) at random intervals. The participant's goal is to stop the counter once it begins counting by pressing a key on the keyboard. Therefore, one can measure the amount of time it takes from the onset of the counter until the time that participants stop the counter as the dependent measure. The psychomotor vigilance task is a simple RT task and thus places minimal demands on the cognitive system (Loh et al., 2004). Previous research has shown that it is extremely difficult to improve task performance in simple RT tasks due to their relatively basic demands on sensorimotor processes. Participants complete the psychomotor vigilance task for 10 minutes. The dependent measure is the mean of a participant's 20 slowest trials.

Compound Remote Associate Test. 30 compound remote associate (CRAT) items were selected from the Bowden and Jung-Beeman (2003) normed item list. A typical CRAT problem requires an individual to search through memory for a target word ("ICE") that is semantically related to three cues ("CREAM, SKATE, WATER") and forms a compound word or phrase with each cue. Problems were chosen on the basis that they did not have shared cues with other items or a solution that was also a cue for another problem. A participant’s score is the proportion of items correctly solved.

TriBond. TriBond™ is a board game developed by Mattel, Inc. and functions similarly to the CRAT. In the game individuals are given three seemingly unrelated cues (e.g. GLASS, PAPER, ALUMINUM) and tasked with finding the category, name, event or specific association between them (Solution: RECYCLABLES). Four independent raters evaluated a list of potential problems from 0 (easy) to 9 (difficult). Using averaged difficulty ratings, we selected 30 items of moderate difficulty (between 1.5 and 8.5). A participant’s score is the proportion of items correctly solved.

Location Bond (LocBond). LocBond operates similarly to CRAT and TriBond. A LocBond problem consists of three clues (e.g. TOWER, CITY, and FRENCH) and requires finding the target location the clues identify (Solution: PARIS). We generated 30 problems where the target is a location on or in the immediate vicinity of the Arizona State University campus. A participant’s score is the proportion of items correctly solved.

CRAT, TriBond, and LocBond Strategy. After every CRAT, TriBond, and LocBond problem the participant identifies the strategy process that happened prior to submitting a solution (see Chein & Weisberg, 2014 or our Open Science Framework page for exact methods).

Picture Source. During the encoding phase, participants were presented with a picture (30 total pictures) in one of four different quadrants on-screen for 1 sec. Participants were explicitly instructed to pay attention to both the picture (item) and the quadrant it was in (source). At test, participants were presented with 30 old and 30 new pictures in the center of the screen. Participants were required to indicate whether the picture was new or old and, if old, in what quadrant it had been presented, via keypress. Participants had 5 sec to press the appropriate key to enter their responses. A participant's score was the proportion of correct responses.

Cued Recall. Participants were given three lists of 10 word pairs each. All words were common nouns, and the word pairs were presented vertically for 2 sec each. Participants were told that the cue would always be the word on top and that the target would be on bottom. After the presentation of the last word, participants saw the cue word and ??? in place of the target word. Participants were instructed to type in the target word from the current list that matched the cue. Cues were randomly mixed so that the corresponding target words were not recalled in the same order as that in which they had been presented. Participants had 5 sec to type in the corresponding word. A participant's score was the proportion of items recalled correctly.

Delayed Free Recall. Items were presented alone for 1 s each. After list presentation, participants engaged in a 16 s distractor task before recall: Participants saw 8 three-digit numbers appear for 2 s each and were required to type the digits in descending order (e.g., Rohrer & Wilted, 1994; Unsworth, 2007). At recall participants saw three question marks appear in the middle of the screen. Participants had 45 s to recall as many of the words as possible in any order they wished from the current trial. Participants typed their responses and pressed Enter after each response clearing the screen. Prior to the practice and real trials, participants received a brief typing exercise (typing the words one-ten) to assess their typing efficiency. Participants completed 2 practice blocks and 6 experiment blocks. A participant's score is the proportion of items correctly recalled.

Category Fluency. Participants were instructed that they should retrieve as many exemplars from the category of animals, S-words, and things of importance as possible. Each category was completed individually, and the participant was given 3 minutes per block (9 minutes total). The participants were informed that they could retrieve the exemplars in any order that they wished; they were required to type in each response, and then press Enter to record the response. We instructed the participants that they needed to keep trying to retrieve exemplars for that category throughout the entire 3-min retrieval period.

General Knowledge. In this task participants complete three separate short general knowledge item blocks. In the first block participants are given 10 vocabulary words and are required to select the best synonym (out of five possible choices) that best matched the target vocabulary word (Hambrick, Salthouse, & Meinz, 1999). Participants were given unlimited time to complete the 10 items. In the second block participants are given 10 vocabulary words and are required to select the best antonym (out of five possible choices) that best matched the target vocabulary word (Hambrick et al., 1999). Participants were given unlimited time to complete the 10 items. In the third block participants are required to answer 10 general knowledge items (e.g. What is the coldest planet in our solar system? Answer: Jupiter). Participants were given unlimited time to complete the 10 items. All participants complete the synonym block first, then the antonym block, and lastly the general knowledge block. A participant’s score was the total number of items solved correctly.

Raven’s Advanced Progressive Matrices. This test is a measure of abstract, inductive reasoning (Raven, Raven, & Court, 1998). Thirty-six items are presented in ascending order of difficulty. Each item consists of a display of 3 × 3 matrices of geometric patterns, arranged according to an unknown set of rules, with the bottom right pattern missing. The task is to select, among eight alternatives, the one that correctly completes the overall series of patterns. After completing two practice problems, participants had 10 min to complete the 18 odd-numbered items from the test. A participant's score was the proportion of correct solutions. Higher scores represented better performance.

Number series. In this task, subjects saw a series of numbers, arranged according to an unstated rule, and were required to induce what the next number in the series should be (Thurstone, 1962). Participants selected their answer from five possible numbers that were presented. After working on five practice items, subjects had 4.5 min to complete 15 test items. A participant's score was the proportion of items solved correctly. Higher scores represented better performance.

Letter sets. In this task, participants saw five sets of four letters and were required to induce a rule that described the composition and ordering of four of the five sets (Edstrom, French, Harman, & Dermen, 1976). Participants were then required to indicate the set that violated the rule. After working on two example problems, participants had 5 min to complete 20 test items. A participant's score was the proportion of items solved correctly. Higher scores represented better performance.

Procedure

After consenting to participate in the experiment participants complete the tasks in the following order. During the Day 1, 2-hour laboratory session, they complete

Demographics, Reading Span, Rotation Span, Operation Span, Symmetry Span, Stroop, Anti-Saccade, Psychomotor Vigilance. During the Day 2, 2-hour laboratory session, they complete Compound Remote Associates, TriBond, LocBond, Picture Source, Cued Recall, Category Fluency, General Knowledge, Raven's Progressive Matrices, Number Series, and Letter Sets.

Open Science and Data Screening

All experimental procedures (E-Prime), experimenter/participant notes, data files, and analysis scripts (SPSS, RStudio, & Lavaan) will be made available through Open Science Framework (https://osf.io/vg8mu/?view_only=4612fbb3e94145ca94c0ac21cf396db5).

Prior to all statistical tests and modeling, the data were screened for outliers through several methods. First, individuals who failed to complete both days or were noted as being English second language were removed from the data set as to not influence outlier detection. Second, all dependent measures were plotted and participants whose data was marked as repeatedly having non-normal performance were removed from future analyses. Additionally, the manifests for the proposed latent factors (working memory, attention control, episodic memory, semantic memory, crystallized and fluid intelligence) were separately submitted for multivariate outlier detection using Mahalanobis distance. Multivariate outlier detection was done in a sequential fashion such that working memory measures had Mahalanobis distance calculated, outliers were then removed, and then Mahalanobis was then calculated for the next latent factor (attention). These steps were repeated until multivariate outlier detection had been done for each set of manifests.

Results

Descriptive statistics for all measures can be found in Table 1. As can be seen in the table, average performance mapped onto previously reported research and estimates of skew and kurtosis were at reasonable levels. Table 2 reports correlations among all dependent measures. As can be seen in the Table 2, measures within a construct (i.e., WMC, attention, episodic memory, semantic memory, crystallized intelligence, fluid intelligence, and multiply-constrained problem solving) were correlated with each other.

Prior research has indicated that performance on compound remote associate problems differs when the answers are derived from analytical or insight strategies. In order to test for this difference within compound remote associate problems, we submitted the conditionalized proportion correct for analytical (M = .375, SD = .281) strategies and conditionalized proportion correct for insight (M = .633, SD = .299) strategies to a paired samples t-test, t (424) = -14.536, p < .001, d = .705. Results indicated that when the participant reports using an insight strategy they are more often correct. Additionally, the same paired samples t-test was conducted for both TriBond, t (417) = -13.479, p < .001, d = .659, and Location Bond (LocBond), t (416) = -17.796, p < .001, d = .874. For TriBond, insight solutions (M = .381, SD = .261) were found to be more often correct than analytical solutions (M = .189, SD = .215). And for LocBond, insight solutions (M = .634, SD = .246) were also found to be more often correct than analytical solutions (M = .338, SD = .259). This means that for all three multiply-constrained problem solving measures insight response were more often correct than analytical responses. Additionally, performance on the multiply-constrained problem solving measures are generally correlated with one another (see Table 2). This provides some indication that the tasks are likely measuring the same construct.

Table 1

Descriptive statistics for each dependent measure. For the compound remote associates (CRAT), TriBond, and Location Bond (LocBond) data shown are for the conditionalized (Analytical & Insight) proportion correct.

Task	N	Min.	Max.	Mean	Std. Dev.	Skew.	Kurt.	α
Reading Span	449	17	75	54.86	11.22	-.67	.11	.78
Operation Span	446	0	75	56.25	15.67	-1.41	1.53	.89
Symmetry Span	448	2	42	26.93	8.89	-.56	-.24	.82
Rotation Span	444	3	72	35.39	13.43	-.07	-.48	.87
Stroop (Incongruent)	449	464.30	1837.19	888.02	228.21	1.07	1.30	.89
Anti-saccade	448	.16	.98	.66	.17	-.52	-.39	.84
Psychomotor Vigilance	447	277.06	477.79	369.86	36.99	.16	-.63	.99
CRAT	425	.00	.73	.35	.15	-.10	-.29	.73
Strategy – Analytical	425	.00	1.00	.37	.28	.48	-.71	-
Strategy – Insight	425	.00	1.00	.63	.30	-.69	-.47	-
TriBond	418	.00	.63	.21	.14	.69	-.01	.79
Strategy – Analytical	418	.00	1.00	.19	.22	1.38	1.95	-
Strategy – Insight	418	.00	1.00	.38	.26	.36	-.63	-
LocBond	417	.00	.73	.40	.14	-.14	-.39	.74
Strategy – Analytical	417	.00	1.00	.34	.26	.36	-.57	-
Strategy – Insight	417	.00	1.00	.63	.25	-.75	.32	-
Picture Source	424	.00	1.00	.73	.19	-.97	.96	.85
Cued Recall	405	.00	.97	.35	.22	.67	-.21	.87
Delay Free Recall	404	.00	.92	.43	.19	-.03	.17	.88
Fluency - Animal	422	.00	72.00	35.38	10.41	.07	.46	-
Fluency - S-Word	422	11.00	72.00	40.06	10.46	.22	-.16	-
Fluency - Importance	422	4.00	61.00	27.62	10.91	.59	.01	
Synonym	423	.00	.90	.31	.19	.68	.15	.45
Antonym	423	.00	.90	.35	.18	.49	-.08	.34
General Knowledge	423	.00	1.00	.49	.22	.06	-.57	.58
Raven’s Prog. Matrices	261	.06	.94	.48	.19	-.08	-.45	.75
Number Series	204	.07	1.00	.61	.18	-.17	-.47	.71
Letter Sets	211	.10	.90	.51	.17	-.13	-.49	.70

Table 2

Correlations between dependent measures.

		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
1.	Operation Span												
2.	Reading Span	**.49***											
3.	Symmetry Span	**.49***	**.24***										
4.	Rotation Span	**.43***	**.32***	**.57***									
5.	Stroop (Incongruent)	**-.17***	-.05	**-.24***	**-.22***								
6.	Anti-saccade	**.18***	**.19***	**.24***	**.28***	**.17***							
7.	Psychomotor Vigilance	**-.15***	**-.12**	**-.17***	**-.14***	**.31***	**-.31***						
8.	Picture Source	**.10**	.07	**.23***	**.26***	**-.19***	**.21***	**-.11**					
9.	Cued Recall	**-.13***	**.22**	**.15***	**.21***	-.05	**.13***	.04	**.36***				
10.	Delay Free Recall	**.10**	**.28***	**.22***	**.28***	**-.11**	.19*	-.06	**.25***	**.52***			
11.	Fluency - Animal	**.14***	**.20***	**.19***	**.14***	-.08	**.18***	-.07	**.14***	**.28***	**.28***		
12.	Fluency - S-Word	**.10**	**.22***	**.18**	**.16***	**-.15***	.13*	-.05	**.18***	**.20***	**.20***	**.58***	
13.	Fluency - Importance	.09	.09	**.12**	.06	-.02	-.03	.05	.08	**.12**	.09	**.48***	**.43***
14.	Synonym	**.13***	**.27***	.09	.03	**-.10**	**.19***	-.07	**.11**	**.26***	**.20***	**.27***	**.21***
15.	Antonym	**.13***	**.20***	.08	.06	-.01	**.17***	-.09	**.16**	.33*	**.27***	**.27***	**.21***
16.	General Knowledge	**.13***	**.15***	**.11**	.05	**-.17***	**.22***	**-.20***	**.11**	**.18***	**.17***	**.28***	**.17***
17.	Raven’s Prog. Matrices	**.22***	**.17***	**.20***	**.20***	**-.22***	**.34***	**-.15**	**.33***	**.26***	**.22***	**.16**	**.14**
18.	Number Series	**.31***	**.15**	**.27***	**.31***	**.16**	**.30***	**-.15**	**.15**	**.28***	**.20***	**.24***	.07
19.	Letter Sets	**.22***	**.18***	**.17**	**.22***	**-.18***	**.30**	-.05	**.17**	**.24***	**.29***	**.28***	**.19***
20.	CRAT (Analytical)	**.13**	**.14***	**.13***	.08	-.06	**.25***	-.02	**.17***	**.23***	**.24***	**.17***	**.14***
21.	CRAT (Insight)	**.13***	**.25***	**.15***	**.14***	-.08	**.24***	**-.13***	.10	**.23***	**.23***	**.18***	**.13***
22.	TriBond (Analytical)	.08	**.14***	.09	**.12**	-.09	**.16***	-.01	**.22***	**.23***	**.19***	**.18***	**.18***
23.	TriBond (Insightl)	.08	**.20***	.08	.09	-.04	**.19***	-.09	**.12**	**.29***	**.21***	**.29***	**.18***
24.	LocBond (Analytical)	.02	.08	.01	-.04	.03	.09	-.08	.04	**.13***	**.10**	.05	-.05
25.	LocBond (Insight)	**.15***	**.13***	**.10**	**.15***	.01	.08	.00	.07	**.23***	**.14***	**.14***	.08

Note: Bolded = p < .05, Bolded with * = p < .01.

Table 2

Correlations between dependent measures.

		13.	14.	15.	16.	17.	18.	19.	20.	21.	22.	23.	24.	25.
1.	Operation Span													
2.	Reading Span													
3.	Symmetry Span													
4.	Rotation Span													
5.	Stroop (Incongruent)													
6.	Anti-saccade													
7.	Psychomotor Vigilance													
8.	Picture Source													
9.	Cued Recall													
10.	Delay Free Recall													
11.	Fluency - Animal													
12.	Fluency - S-Word													
13.	Fluency - Importance													
14.	Synonym	**.10**												
15.	Antonym	.05	**.37***											
16.	General Knowledge	.03	**.32***	**.30***										
17.	Raven’s Prog. Matrices	-.01	**.21***	**.19***	**.22***									
18.	Number Series	.00	**.25***	**.29***	**.25***	**.39***								
19.	Letter Sets	.05	**.15**	**.24***	**.15**	**.38***	**.51***							
20.	CRAT (Analytical)	.04	**.19***	**.19***	**.24***	**.27***	**.21***	**.21***						
21.	CRAT (Insight)	-.02	**.25***	**.28***	**.30***	**.26***	**.18**	**.23***	**.20***					
22.	TriBond (Analytical)	.04	**.31***	**.26***	**.30***	**.30***	**.16**	**.14**	**.43***	**.21***				
23.	TriBond (Insightl)	.07	**.30***	**.31***	**.37***	**.30***	**.20***	**.21***	**.21***	**.51***	**.26***			
24.	LocBond (Analytical)	-.01	**.14***	**.10**	**.18***	**.21***	-.02	.08	**.23***	.02	**.18***	**.10**		
25.	LocBond (Insight)	.04	**.16***	**.19***	**.23***	**.23***	**.18**	**.13**	.02	**.30***	.07	**.40***	**.10**	

*Note: Bolded = p < .05, Bolded with * = p < .01.*

Two confirmatory factor analysis models were generated and compared. Model 1 had a single multiply-constrained problem solving accuracy latent factor and Model 2 had separate latent factors for two possible solution strategies (i.e., accurate responses followed by Analytical versus Insight strategy response). Model 1, χ^2 (253) = 542.506, $p < .001$, CFI = .873, RMSEA = .050 [.045–.056], and Model 2, χ^2 (246) = 444.380, $p < .001$, CFI = .913, RMSEA = .042 [.036–.049], had acceptable fits. The likelihood ratio test indicated that the models were significantly different, Δ^2 (7) = 98.126, $p < .001$, and thus the more parameterized model (Model 2) was chosen (see Fig. 1). For Model 2, all latent factors were found to be significantly correlated with one another (see Table 3). Importantly, Model 2 shows that the three multiply-constrained tasks share enough common variance to form latent factors that reflect domain-general problem solving ability. Another notable feature in Model 2 is that these individual differences in successful strategy use is also domain-general in nature.

The general trend that emerged among the latent correlations was that crystallized intelligence had the strongest correlations with multiply-constrained problem solving. Given the strength of the correlations an additional model (Model 3) was evaluated with the crystallized intelligence manifests loading onto the multiply-constrained problem solving factors and the overall model fit was acceptable, χ^2 (250) = 470.732, $p < .001$, CFI = .903, RMSEA = .044 [.038–.050]. The likelihood ratio test indicated that the models were significantly different, Δ^2 (4) = 26.352, $p < .001$, and Model 2 was retained.

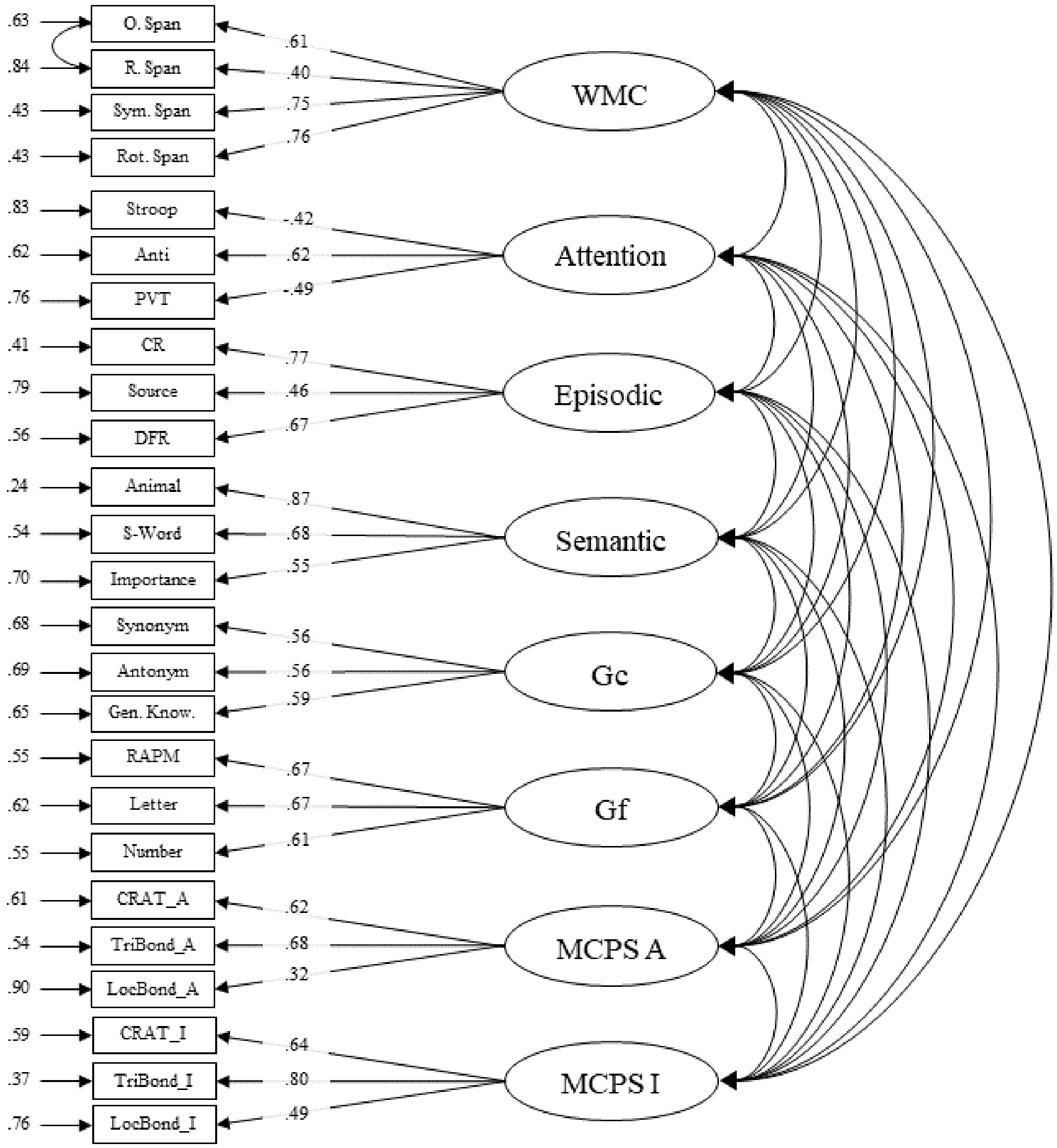

Figure 1. Confirmatory factor model (2) that was retained after fit comparisons. Single headed arrows to boxes (manifests) represent error variance. Single headed arrows from circles (latent factors) to boxes (manifests) represent the standardized factor loadings. WMC: Working Memory Capcity; gC: Crystallized Intelligence; gF: Fluid Intelligence; MCPS A: Multiply-Constrained Problem Solving Analytical; MCPS I: Multiply-Constrained Problem Solving Insight.

Table 3

Latent factor correlations between cognitive abilities and multiply-constrained problem solving (MCPS)

	1.	2.	3.	4.	5.	6.	7.
1. Working Memory							
2. Attention Control	.55						
3. Episodic Memory	.43	.30					
4. Semantic Memory	.28	.25	.41				
5. Crystalized Intelligence	.22	.48	.54	.51			
6. Fluid Intelligence	.53	.74	.61	.32	.53		
7. MCPS Analytical	.22	.33	.48	.28	.67	.51	
8. MCPS Insight	.23	.32	.43	.34	.72	.46	.43

Note: All correlations significant at $p < .001$, except working memory and crystalized intelligence, $p < .01$.

Model 2 was then used to conduct a structural equation analysis to determine the predictive nature of the cognitive abilities on multiply-constrained problem solving (see Fig. 2.). Although the cognitive abilities (working memory, attention control, episodic memory, semantic memory, crystallized and fluid intelligence) latent factors were correlated with both multiply-constrained problem solving factors, only crystallized intelligence was found to offer unique predictive value. Overall the model accounted for 51% of the variance in analytical multiply-constrained problem solving and 55% of insightful multiply-constrained problem solving variance.

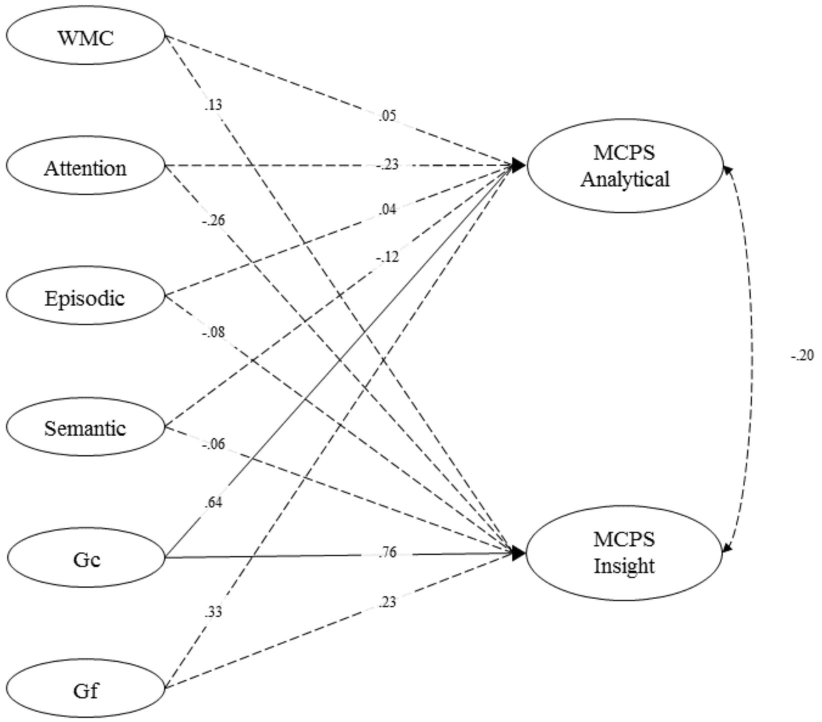

Figure 2. The full structural model of working memory capacity (WMC), attention control (attention), episodic memory (episodic), semantic memory (semantic), crystallized intelligence (gC) and fluid intelligence (gF) loading on both multiply-constrained problem solving strategies (analytical & insight). Dashed lines represent nonsignificant paths. Values on paths represent standardized regression coefficients.

General Discussion

We sought to provide the most complete picture of the underlying cognitive processes related to multiply-constrained problem solving. The results indicate that there exists a domain general multiply-constrained problem solving factor. More specifically, when a participant arrived at a solution from insight strategies that answer is more often correct than when it was derived from analytical processes. Additionally, the best fitting model contained latent factors for each of the cognitive abilities measured (working memory, attention control, episodic memory, semantic memory, crystallized and fluid intelligence) and two multiply-constrained problem solving latent factors (Analytical and Insight). The structural equation analysis accounted for 51% of the variance in analytical multiply-constrained problem solving and 55% of the variance in insightful multiply-constrained problem solving. Lastly, while each of the underlying cognitive abilities was correlated with the problem solving latent factors, only crystallized intelligence was found to have unique predictive value.

Across all three tasks our data demonstrate that answers retrieved through insight processes are more often correct than analytical strategies. Of primary importance is that the sets of strategy solutions between multiply-constrained problem solving tasks load onto unique factors, which indicates that strategy processes are domain general rather than task specific. While there is a debate to be had whether this is evidence for the special-processes view of insight (see Weisberg, 2015 for a thorough review), it is our opinion that differences in strategy reporting are an issue of phenomenological sensation and perception. Specifically, any retrieved answer is always going to contain an “Aha”-like sensation and the strength of that sensation may be related to the associative strength between cues and retrieved targets of the solver. Additionally, participants are instructed to solve as many problems as possible and if a solver wants to achieve best performance any retrieved answer, regardless of how the solver becomes consciously aware of the answer, should be compared against each cue to ensure its accuracy. Therefore, all retrieved answers should employ both analytical and insight strategies.

One of the most consistent findings in the compound remote associates literature is its relation to working memory (Wiley & Jarosz, 2012). Our data replicate the previous relation between working memory and CRAT, as well as, establishes a similar positive relation to the other multiply-constrained problem tasks (TriBond and LocBond). However, unlike previous literature we find that working memory is not a unique predictor of multiply-constrained problem solving (Chuderski & Jastrzebski, 2018; Kane et al., 2004). This may be due to our creation of a multiply-constrained problem solving factor rather than grouping it with other more common divergent (e.g., alternative uses) or convergent (e.g., “dot” problem) tasks. Moreover, we replicate the known positive relation between CRAT and Antisaccade, and no relation with the Stroop task (Chein & Weisberg, 2014; Chuderski & Jastrzebski, 2018). If the Antisaccade is a measure of inhibition, albeit the inhibition of a physical movement, it is not surprising to find it related to multiply-constrained problem solving. Gupta et al. (2012) demonstrated that an individual will perform better on CRAT problems when they can avoid prepotent or high-frequency candidate answers. It could be that individuals who are better at multiply-constrained problem solving are better at delaying the submission of spontaneously retrieved answers and waiting to confirm it is the correct answer.

Our data indicate a small, but largely consistent, correlation between tasks design to measure episodic memory and multiply-constrained problem solving, which to our knowledge has not been previously found in this literature. For both the source memory and cued recall tasks, at test, the participant is shown a cue from which they must retrieve information stored in memory. Therefore, it logically follows that they should be related to multiply-constrained problem solving, which are tasks where the participant is shown cues and asked to retrieve information stored in memory. More precisely, the associative binding or processes engaged during encoding and retrieval of episodic memories (see Kahana, Howard, & Polyn, 2008 for a review) may be similarly engaged during multiply-constrained problem solving. For example, while attempting a LocBond problem the solver may engage in a mental walk through the location they believe the target to be located (participants did report engaging in mental walks on opened ended questions at the end of the task). Previous work by Davelaar (2015) and Smith et al. (2013) demonstrated that semantic search is related to multiply-constrained problem solving. Additionally, Lee & Therriault (2013) found performance on fluency tasks was predictive of compound remote associate problem solving ability. Our data largely replicate the previous literature. However, despite strong correlations between the three fluency tasks, the three fluency tasks do not consistently correlate with multiply-constrained problem solving. The relation between semantic memory might improve if the “importance” category was replaced with a more domain general category. The issue with “importance” may explain why semantic search abilities were not found to be a unique predictor of multiply-constrained problem solving.

To date several researchers have identified that measures of fluid intelligence are related to the compound remote associates (Chermahini, Hickendorff, & Hommel, 2012; Chuderski, 2014; Chuderski & Jastrzebski, 2018; Kane et al., 2004; Lee & Therriault, 2013). We replicate the previous literature and extend the finding to the novel TriBond and LocBond tasks. However, unlike the recent findings of Chuderski & Jastrzebski (2018) fluid intelligence did not account for unique variance, but this may be partially due differences in tasks used to measure reasoning ability (they used Raven’s, Figural Analogies, Number Series, and Logic Problems) and our inclusion of other cognitive measures which may have shared variance with fluid intelligence. Additionally, the difference in latent correlations between problems solved with analytical strategies and insight strategies is present in both experiments.

To date, there has been a lot of discussion about the nature of intelligence in creativity, and compound remote associates by proxy (Benedek & Fink, 2019; Cortes, Weinberger, Daker, & Green, 2019; Marko, Michalko, Riecansky, 2018; Kim, 2005; Silvia, 2015). Replicating Lee & Therriault (2013) we find a positive relation between measures of intelligence (Raven’s and WAISRV in Lee & Therriault) and problem solving ability. Additionally, our data indicate that crystallized intelligence was the only latent factor to offer unique predictive value. Moreover, model comparisons indicate that multiply-constrained problems are different from measures of verbal and general knowledge. Individuals who perform better on measures of crystallized intelligence may have a flatter (greater ability to access both frequent and infrequent associations) and more interconnected semantic network, in addition to, a stronger associations between what are traditionally weakly associated cues and targets. Network analyses (see Kenett & Faust, 2019) between individuals of low and high crystallized intelligence may provide further elucidation on the relation between verbal knowledge and multiply-constrained problem solving. Alternatively, using tasks like TriBond and LocBond, which require more specific areas of knowledge, may have increased the relation between crystallized intelligence and multiply-constrained problem solving.

One possible limitation is that both TriBond and LocBond are new experimental tasks that have not been as rigorously validated as the CRAT. Specifically, the range and control over the difficulty of the problems may not be as strong as it is for the CRAT. Additionally, the LocBond problems for this experiment were specifically designed for the population the participants were recruited from and may perform differently with other participant samples. However, LocBond items that are less population specific can be easily generated.

In the future, an evaluation of whether these multiply-constrained problem solving tasks share any cognitive underpinnings with other measures of creativity should be conducted as since its conception the (compound) remote associates task has been linked to both creativity and insight. Previous work has shown for the CRAT how and when insight responses are submitted is not always the same (Cranford & Moss, 2012). Others have noted that the CRAT does not load onto factors with other insight tasks (Chuderski & Jastrzebski, 2018; Lee & Therriault, 2013;

Lee, Huggins, & Therriault, 2014). Our findings seem to indicate why this was the case. As noted, individuals do not always reach impasse when solving a CRAT problem (Cranford & Moss, 2012) and can intuitively arrive at the solution within seconds of seeing the cues (Bolte & Goschke, 2005; Topolinski & Strack, 2009). Additionally, given our model comparisons, while the multiply-constrained problem solving tasks are strongly related to crystallized intelligence measures there is not complete overlap. Not present in our experiment are common creativity measures (e.g., Alternative Uses). As both sets of tasks utilize both convergent and divergent processes and share strong relations to intelligence, it is difficult to predict whether multiply-constrained problem solving, and creativity will remain as unique factors or whether a combined creativity and multiply-constrained problem solving latent factor will emerge due to their shared underpinnings and processes. Therefore, an experiment that contains multiply-constrained problem solving, intelligence, and commonly used measures of creativity and insight should be conducted to fully assess the variance-covariance structure of these constructs.

As with any experimental or laboratory task the question must be asked, how do the current results map onto behavior in the *real-world*? The answer is, *Jeopardy!*. In 2014 their “Battle of the Decades” aired and late into the tournament the category “Common Bonds” appeared. The first clue in the category read “CUPID, DANCER, PRANCER” and within moments the correct response “REINDEER” was produced, and thus science and life intersected. The contestant who responded correctly could not have done had they not known any of those names or that they shared a connection with reindeer. More precisely, despite the demands on effective goal maintenance, attention control, memory search efficiency, and problem solving skill, one cannot retrieve an answer from memory if the answer does not already reside there.

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