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The role of working memory capacity in analytic and multiply-constrained problem-solving in demanding situations

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Abstract

Working memory processes are important for analytic problem-solving; however, their role in multiply-constrained problem-solving is currently debated. This study explored individual differences in working memory and successful completion of analytic and multiply-constrained problem-solving by having participants solve algebra and compound remote associate (CRAT) problems of varying difficulty under low and high memory demand conditions. Working memory was predictive of both algebra and multiply-constrained problem-solving. Specifically, participants with high working memory solved more problems than those with low working. Memory load did not differentially affect performance for low and high working memory participants. However, for multiply-constrained problem-solving the effect of item difficulty was more detrimental for high-span participants than low-span participants. Together, these findings suggest that working memory processes are important for both types of problem-solving and that participants with low working memory capacity may need to offload internal memory demands onto the environment to efficiently solve problems.

Keywords

Problem-solving; multiply-constrained problem-solving; analytic problem-solving; working memory; individual differences; compound remote associates

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Working memory capacity (WMC) refers to one's ability to maintain active control over task-relevant goals in the face of task-irrelevant thoughts and distractions. Working memory is an important individual difference construct because one's WMC is predictive of problem-solving abilities across a diverse set of domains including culture free tests (Unsworth & Engle, 2005), scholastic aptitude tests (Daneman & Hannon, 2001), neuropsychological batteries (Gathercole, 1994), and even in compound remote associate (CRAT) and the nine-dot problem tasks (Chein & Weisberg, 2014; Chein et al., 2010). The relation between working memory and various types of problem-solving has been a key aspect in various theoretical perspectives about the component processes that are shared between these individual constructs. In the current work, we explored the relation between WMC and problem-solving in analytic and multiply-constrained problem-solving domains. Furthermore, we assessed whether memory load and problem difficulty was a critical factor in exacerbating or eliminating the relation between working memory and problem-solving.

Problem-solving

Problem-solving is a complex higher order cognitive ability that typically requires multiple subprocesses to operate in tandem to be successful. However, at the most basic level problem-solving can be divided into two stages: a representation phase and solution phase (Newell & Simon,

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1972). The representation phase involves identifying the goals and constraints of the problem and translating it into a representation that can be used to query long-term memory, whereas the solution phase involves a selection process that determines the appropriate schema, strategy, or operation from long-term memory that allows for successful engagement of the appropriate sequence of operations or computations to solve the problem (Wiley & Jarosz, 2012).

Two widely studied types of problem-solving are analytic and multiply-constrained problem-solving. A critical distinction between the two problem types is that analytic problem-solving is thought to arise due to strategic processes that are available to conscious awareness, whereas solutions to multiply-constrained problems could arise from either an analytical approach or via spontaneous retrieval (Chein & Weisberg, 2014). In analytic problem-solving (e.g., solving mathematical equations), one must retrieve information from long-term memory (e.g., order of operations) and engage a series of stepwise procedures (e.g., multiplication, addition) to derive the appropriate solution (Wiley & Jarosz, 2011). Thus, analytic problem-solving is thought to occur incrementally (Metcalfe & Wiebe, 1987). In contrast, the initial problem representation formed during a multiply-constrained problem, such as the CRAT (Bowden & Jung-Beeman, 2003; Mednick, 1962), often fails to produce the correct representation. Given the shared and unique components of both analytic and multiply-constrained problem-solving, it is necessary to understand how individual differences in WMC and working memory demands influence problem-solving.

WMC

Working memory is broadly defined as a general-purpose cognitive system involved in flexible control of attention to actively maintain goal-relevant information in primary memory in the face of internal or external distraction (Baddeley, 2012; Engle & Kane, 2004; Kane et al., 2001) and controlled retrieval from secondary memory of momentarily displaced information (Unsworth & Engle, 2005). Although the exact mechanisms underlying WMC continue to be debated (e.g., Baddeley, 2012; Cowan, 2005; Kane et al., 2001; Unsworth & Engle, 2007), a wealth of evidence has accumulated demonstrating that WMC is an important predictor of a variety of higher order cognitive processes such as reading comprehension (Daneman & Carpenter, 1980), Scholastic Aptitude Tests (Turner & Engle, 1989), learning (Kyllonen & Stephens, 1990; Unsworth & Engle, 2005), and fluid abilities (Conway et al., 2002; Unsworth & Engle, 2007; Unsworth & Spillers, 2010).

In addition, considerable research has suggested that WMC is predictive of a variety lower order attention and memory control processes such as Stroop and Flanker interference (Heitz & Engle, 2007; Kane & Engle, 2003), antisaccade performance (Unsworth et al., 2004), and search from long-term memory (Brewer & Unsworth, 2012; Unsworth et al., 2012). For example, WMC is predictive of performance during tasks that require inhibiting prepotent response tendencies (e.g., saccade away from blinking cue), but not in tasks that require reflexive attention processes (e.g, saccade towards blinking cue; Kane et al., 2001; Unsworth et al., 2004). Similarly, WMC is predictive of long-term memory abilities when controlled search processes are needed to retrieve category exemplars during a semantic fluency task, but not when retrieval cues (i.e., categories) are provided that eliminate the need for controlled search (Unsworth et al., 2012). Importantly, it has been suggested that these same lower level attention and memory control processes underlie the relationship between WMC and various types of problem-solving (Wiley & Jarosz, 2011). However, recent evidence suggests that the role of working memory in problem-solving may differ depending on the type of problem type.

Problem-solving and working memory

There is a wealth of research demonstrating a strong relation between WMC and analytic problem-solving using mathematical tasks. For example, performing a secondary task that presumably disrupts executive attention processes has been shown to reduce mathematical problem-solving that requires initiating a sequence of steps, carrying, or borrowing (De Rammelaere et al., 2001; Furst & Hitch, 2000; Seyler et al., 2003). In addition, individual differences studies have shown a positive association between WMC and various types of mathematical problem-solving (Ashcraft & Kirk, 2001; Lavric et al., 2000; Wiley & Jarosz, 2012). It is suggested that working memory deficits produce decrements to mathematical problem-solving because individuals with low WMC have difficulties in maintaining and manipulating multiple pieces of information concurrently, are susceptible to distraction and interference, use inappropriate solution strategies, and/or are unable to appropriately retrieve math facts from long-term memory (Wiley & Jarosz, 2012).

One task often used to study multiply-constrained problem-solving is the CRAT whereby a set of cues are presented (e.g., basket, eight, snow) and participants are to produce a solution (e.g., ball) that forms a compound word with all items in the set (i.e., basket-ball, eight-ball, snow-ball). The solution is typically not highly associated (in terms of frequency) with the cues and therefore solvers must search memory for unusual or infrequent associations (Gupta et al., 2012). The CRAT was originally designed to measure creativity but can also be defined as a multiply-constrained problem-solving task, whereby each cue delimits the semantic area by which the solver must search (Smith et al., 2013). Unlike other measures of creativity such as alternative use tasks, the CRAT has the advantage of having unambiguous solutions and can be used to obtain multiple measures for each participant. To solve a CRAT problem, an individual must employ both divergent (i.e., generation of several potential solutions) and convergent (i.e., selecting a possible solution from those generated) processes (Gilhooly et al., 2015).

Although several studies have demonstrated a positive relation between WMC and CRAT (Chein & Weisberg, 2014; Chein et al., 2010; Chuderski, 2014; Ricks et al., 2007), other studies have found no relation (Ash & Wiley, 2006; Fleck, 2008) or even a *negative* relation (Beilock & DeCaro, 2007; DeCaro et al., 2016; Reverberi et al., 2005). Furthermore, although it has been found that secondary task demands reduce problem-solving through spontaneous retrieval (Ball & Stevens, 2009; De Dreu et al., 2012), this is not always the case (Ball et al., 2015; Lavric et al., 2000). In addition, although neuroimaging studies have provided evidence for dissociable neural correlates of creative and analytic problem-solving (Bowden et al., 2005; Jung-Beeman et al., 2004; Lavric et al., 2000; Luo & Niki, 2003), other studies have demonstrated that alpha synchronisation (recently suggested to reflect top-down attentional control processes; Fink & Benedek, 2012; Klimesch et al., 2007) occurs prior to solutions generated through spontaneous retrieval suggesting that working memory may be involved to some degree (Jensen et al., 2002; Schwab et al., 2014). Thus, existing findings are somewhat ambiguous as to when and how working memory processes may facilitate multiply-constrained problem-solving.

Current study

There is limited work exploring analytic and multiply-constrained problem-solving as a function of WMC in the same sample of participants to gain leverage on individual differences in problem-solving across domains. Therefore, the current study extended previous findings of a positive relation between WMC and CRAT performance by including multiple working memory measures, a larger sample size, and an objective measure of analytic problem-solving (i.e., mathematical problems). In addition, we were interested in examining how memory load influenced both analytic and multiply-constrained problem-solving, and whether this differed as a function of problem difficulty. Problem-solving load was manipulated by increasing the amount of information that needed to be maintained in working memory to successfully solve the problem. For CRAT problems, the three associates remained on the screen until the problem was solved under the no-load condition but were removed from the screen after initial learning under the load condition. For analytic problems, participants were able to use paper and pencil to solve the problem under no load but were unable to use these tools under load. Given the strong association between working memory and mathematical problem-solving, performance on algebra problems should be worse when pen and paper is not allowed. However, the effect of load on multiply-constrained problem-solving is not as straightforward as both on-task (i.e., attention driven search processes) and off-task thoughts (i.e., relaxation thereby alleviating fixation) are at play during problem-solving. Moreover, the effect of load may be particularly pronounced for easy items, as reaching the solution is possible but requires strategic search processes. In contrast, for hard items reaching the correct solution may be difficult regardless of the resources available to search memory.

If similar demands on working memory underlie both types of problem-solving, high WMC individuals should outperform low WMC regardless of problem type. However, problem-solving may differ as a function of memory load and/or item difficulty. In particular, it has been shown that although high WMC participants outperform low WMC participants in verbal fluency, secondary task demands only reduce exemplar retrieval for high WMC participants (e.g., Rosen & Engle, 1997). Thus, load may be particularly detrimental to high WMC participants who typically are able to use available resources to monitor retrieval processes to reduce the likelihood of resampling previously retrieved solutions.

Method

Participants and WMC screening

Two hundred and forty-five undergraduate participants were recruited from the research participant pool at Arizona State University. Thirty-six participants were removed from all subsequent analyses, leaving a final sample size of 209. Specifically, 22 participants were removed from the final data set for failing to complete the problem-solving task as instructed, three were removed for file corruption, and 12 were determined to be statistical outliers on the working memory measures. Individuals earned credit in an undergraduate course for participation in the study.

Operation span (Ospan). 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). 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 et al., 2005, for more details). Participants received three sets (of list-length two) of practice. For all of the span measures, items were scored if the item was correct and in the correct position. The score is the proportion of correct items in the correct position.

Reading span (Rspan). Participants were required to read sentences while trying to remember the same set of unrelated letters as Ospan. 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, whereas 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 to 7. The same scoring procedure as Ospan was used.

Symmetry span (Sspan). In this task, participants were required to recall sequences of red squares within a matrix while performing a symmetry-judgement task. In the symmetry-judgement task, participants were shown an 8 × 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 × 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 to 5. The same scoring procedure as Ospan was used.

Composite score. The working memory composite score was calculated using exploratory factor analysis with a maximum-likelihood estimation routine.

Materials

CRAT problems. In the CRAT task, participants were given three cue words (e.g., AGE/MILE/SAND) that are all related to a fourth word (e.g., STONE) through the formation of a compound word (e.g., STONEAGE, MILESTONE, and SANDSTONE). CRAT problems selected from the Bowden and Jung-Beeman (2003) normative compendium. There are 144 total problems in the set of which we selected 32 problems for the current study (see Supplementary Material). Based on the normative solution data, we classified 16 items as Easy (solved within 30 s: M = 73%) and 16 as Hard (solved within 30 s: M = 24%) solution. Eight items within each difficulty type were presented with load and eight items were presented without load, which was randomly determined for each participant.

Load was manipulated by the duration in which the three cue words remained on the screen. In the no-load condition, the three cues words remained on the screen until the participant responded. In contrast, the three cue words in the load block disappeared from the screen after 3 s. If participants were unable to retrieve the correct solution after 15 s, the problem was represented on the screen for another 3 s. In both cases, participants were given unlimited time to solve the problem.

Analytic problems. Problems were similar to those used by Metcalfe and Wiebe (1987). Participants solved 32 simple algebra problems (see Supplementary Material), with 16 classified as easy (average number of steps = 3.56) and 16 classified as hard (average number of steps = 5.06). When participants were in the no-load block, they were allowed to use paper and pencil, whereas during the load block they were not (although they were able to continue to look at the problem on the screen). In both cases, participants were given unlimited time to solve the problem.[1]

Procedure

The current experiment followed a 2 (Problem Type: CRAT vs. Analytic) × 2 (Load: Load vs. No Load) × 2 (Difficulty: Easy vs. Hard) within-subjects analysis of covariance (ANCOVA) with the composite WMC measure entered as a covariate. The primary measure of interest was the proportion of CRAT and analytic problems solved. All participants performed the task in the same order, which was as follows: CRAT easy no load, CRAT hard no load, CRAT easy load, CRAT hard load, analytic easy no load, analytic hard no load, analytic easy load, analytic hard load. Participants viewed the problem on the screen and entered their answers via keyboard. Participants had unlimited time to solve each problem.

Results

Descriptive statistics for all WMC 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 Table 2, measures within a construct (i.e., WMC, CRAT, and analytic) were positively correlated with each other. As such, an exploratory factor analysis was performed on the three working memory measures to form a maximum-likelihood estimated factor score to be entered as a predictor in subsequent analyses.

A generalised linear model was used to test whether WMC moderated the effect of memory load (Load: Load vs.

No Load) and item difficulty (Difficulty: Easy vs. Hard) on performance of algebra problems (see Table 3 for descriptive statistics). This analysis revealed a main effect of load, $F(1, 207)=8.515$, $p=.004$, $\eta_p^2 = 0.040$, indicating that performance was better in the no-load condition ($M=0.719$, standard error [SE]$=0.013$) than the load condition ($M=0.684$, $SE=0.014$). There was a main effect of difficulty, $F(1, 207)=21.762$, $p<.001$, $\eta_p^2 = 0.095$, indicating that easy problems ($M=0.724$, $SE=0.011$) were solved more often than hard problems ($M=0.679$, $SE=0.015$). The hypothesised interaction between load and difficulty was significant, $F(1, 207)=8.219$, $p=.005$, $\eta_p^2 = 0.038$. The nature of this interaction can be seen in Table 3. Specifically, there was significant deleterious effect of load for hard items, $t(208)=3.991$, $p<.001$, $d=.276$, but not for easy items, $t(208)=0.380$, $p=.704$, $d=.026$.

WMC was a significant predictor of algebra problem-solving, $F(1, 207)=5.584$, $p=.019$, $\eta_p^2 = 0.026$. High WMC participants solved more algebra problems correctly on average than low WMC participants. There was not a significant interaction between WMC and load, $F(1, 207)=0.505$, $p=.478$, $\eta_p^2 = 0.002$. The interaction between WMC and difficulty was nonsignificant as well, $F(1, 207)=2.137$, $p=.145$, $\eta_p^2 = 0.010$ (see Table 4). Finally, the three-way interaction of load, difficulty, and WMC was also nonsignificant, $F(1, 207)=0.522$, $p=.471$, $\eta_p^2 = 0.003$.

A generalised linear model was used to test whether WMC moderated the effect of memory load (Load: Load vs. No Load) and item difficulty (Difficulty: Easy vs. Hard) on performance of multiply-constrained problems (see Table 3 for descriptive statistics). This analysis revealed a main effect of load, $F(1, 207)=56.130$, $p<.001$, $\eta_p^2 = 0.213$, indicating that performance was better in the no-load condition ($M=0.330$, $SE=0.011$) than in the load condition ($M=0.252$, $SE=0.011$). There was a main effect of difficulty, $F(1, 207)=631.730$, $p<.001$, $\eta_p^2 = 0.753$, indicating that easy problems ($M=0.440$, $SE=0.014$) were solved more often than hard problems ($M=0.141$, $SE=0.008$). The hypothesised interaction between load and difficulty was significant, $F(1, 207)=8.239$, $p=.005$, $\eta_p^2 = 0.038$. The nature of this interaction can be seen in Table 3. Specifically, the effect of load was less prevalent for hard items, $t(208)=4.479$, $p<.001$, $d=.310$, than for easy items, $t(208)=6.451$, $p<.001$, $d=.446$.

WMC was a significant predictor of multiply-constrained problem-solving, $F(1, 208)=22.388$, $p<.001$, $\eta_p^2 = 0.098$. High WMC participants solved more multiply-constrained problems correctly on average than low WMC participants. The tests for the interaction between WMC and difficulty were significant, $F(1, 207)=7.592$, $p=.005$, $\eta_p^2 = 0.038$, which suggests that WMC moderated the effect of item difficulty. This means that the item difficulty manipulation had a larger effect on CRAT problem-solving for high WMC individuals than low WMC individuals. However, the test of the WMC and load interaction was nonsignificant, $F(1, 207)=0.995$, $p=.320$, $\eta_p^2 = 0.005$ (see Table 4) Finally, the three-way interaction of load, difficulty, and WMC was also nonsignificant, $F(1, 207)=2.027$, $p=.156$, $\eta_p^2 = 0.010$.

Table 1. Descriptive statistics for working memory capacity measures.

Span task	Min	Max	Mean	*SD*	Skew	Kurtosis
Operation	20	75	60.53	10.33	−1.03	1.18
Reading	5	75	54.41	13.36	−0.92	0.83
Symmetry	8	42	30.31	7.42	−0.71	−0.09

SD: standard deviation.

General discussion

The study provided several interesting findings with regard to working memory and problem-solving. Perhaps most importantly, WMC was predictive of both analytic and multiply-constrained problem-solving. This finding is

Table 2. Correlations among working memory capacity measures and performance on CRAT and ALG problems as a function of item difficulty and memory load.

		1	2	3	4	5	6	7	8	9	10	11
1.	Ospan	1										
2.	Rspan	.61**	1									
3.	Sspan	.23**	.26**	1								
4.	$CRAT_{EL}$	.09	.24**	.18**	1							
5.	$CRAT_{ENL}$	.19**	.30**	.28**	.53**	1						
6.	$CRAT_{HL}$	.18**	.22**	.19**	.47**	.32**	1					
7.	$CRAT_{HNL}$	.09	.19**	.12	.44**	.42**	.38**	1				
8.	ALG_{EL}	.08	.10	.20**	.17*	.30**	.08	.13	1			
9.	ALG_{ENL}	.08	.09	.18**	.20**	.33**	.11	.23**	.34**	1		
10.	ALG_{HL}	.10	.18*	.18**	.29**	.35**	.18	.25**	.66**	.46**	1	
11.	ALG_{HNL}	.10	.08	.24**	.22**	.30**	.06	.23**	.57**	.55**	.54**	1

CRAT: compound remote associate; ALG: algebra; E: easy; H: hard; L: load; NL: no load.
$^*p<.05$, $^{**}p<.01$.

consistent with previous experiments showing a positive relation between WMC and CRAT problem-solving (Chein & Weisberg, 2014; Ellis & Brewer, 2018). However, although WMC was predictive of problem-solving regardless of item difficulty, the influence of load differentially affected low and high WMC participants only for easy problems. That is, although load reduced performance on both easy CRAT and analytic problems for low WMC participants, load only reduced CRAT accuracy for high WMC participants. These findings suggest low WMC participants may need to offload internal memory demands onto the environment to free available resources to more efficiently engage problem-solving (Risko & Dunn, 2015). However, the differential effect of load on problem-solving suggests different working memory processes may be engaged for CRAT versus analytic problem-solving.

Working memory and multiply-constrained problem-solving

Two findings from the current study suggest that analytic processes may be involved in problem-solving in the CRAT. First, load significantly reduced performance on CRAT problems (regardless of item difficulty and WMC). This is consistent with Ball and Stevens (2009) who found that performing a secondary task that disrupted verbal working memory processes reduced CRAT performance. Second, similar to findings of Chein and Weisberg (2014), WMC was predictive of CRAT problem-solving (regardless of item difficulty and load). These findings suggest that verbal working memory processes may be involved in comparing retrieved solutions with the cue words and keeping track of previously tested (but incorrect) solutions. When placed under load, participants were required to maintain cue words, thereby competing with their ability to compare and store retrieved solutions. These results are also inconsistent with the idea that CRAT problem-solving occurs by "loosening" one's attentional focus. That is, it has been suggested that WMC processes that typically facilitate analytic problem-solving, such as focused attention, resisting distraction, and narrowing search, may actually *hurt* multiply-constrained problem-solving (Wiley & Jarosz, 2012). By this view, individuals with higher WMC should exhibit *worse* CRAT performance, which was not the case. Instead, these findings suggest that attentional control processes may serve to actually inhibit dominant response tendencies (i.e., high frequency, but incorrect associates) to search memory for the appropriate solution (Chein & Weisberg, 2014; Gupta et al., 2012).

Interestingly, it was found that load actually hindered performance to a greater extent for high than for low WMC participants, at least for easy CRAT problems. Rosen and Engle (1997) found that category exemplar retrieval in a verbal fluency task was reduced for high, but not low, WMC participants when secondary task demands (digit tracking) were introduced. It was suggested that under normal (no load) retrieval conditions, high WMC participants were able to use working memory processes to efficiently monitor retrieval for repetitions and generate new category exemplars. Thus, secondary task demands reduced exemplar retrieval because available resources were used to monitor for repetitions rather than generation. In contrast, low WMC primarily used working memory processes to monitor retrieval for repetitions, and therefore additional load had little influence on exemplar generation. We suggest that load in the current study had a similar influence on performance. That is, because available resources had to be devoted to maintaining cue words under load, high WMC participants had less resources available to generate new associates related to the cue words thereby reducing performance. In contrast, low WMC participants may have primarily devoted available resources to monitoring retrieval for repetitions (i.e., previously sampled incorrect solutions), and therefore load had less of an influence on

Table 3. Means (standard errors) of correct solutions for each problem type as a function of load and item difficulty for all participants.

Difficulty	Algebra		CRAT	
	Load	No load	Load	No load
Easy	0.72 (0.01)	0.73 (0.01)	0.39 (0.02)	0.49 (0.02)
Hard	0.65 (0.02)	0.71 (0.02)	0.11 (0.01)	0.17 (0.01)

CRAT: compound remote associate.

Table 4. Means (standard errors) of correct solutions for each problem type as a function of load and item difficulty for participants falling in the lower and upper quartiles of overall WMC.

Difficulty	WMC	Algebra		CRAT	
		Load	No load	Load	No load
Easy	Low	0.69 (0.03)	0.72 (0.03)	0.32 (0.03)	0.38 (0.03)
	High	0.72 (0.03)	0.75 (0.02)	0.44 (0.03)	0.58 (0.03)
Hard	Low	0.58 (0.04)	0.68 (0.04)	0.07 (0.02)	0.13 (0.02)
	High	0.65 (0.03)	0.69 (0.04)	0.14 (0.02)	0.20 (0.03)

CRAT: compound remote associate; WMC: working memory span score.

generation of new associates relative to high WMC participants. Interestingly, however, load had the opposite effect on easy analytic problems, suggesting that different processes may underlie to the types of problem-solving.

Differential processes in multiply-constrained and analytic problem-solving

Although load had a greater influence on multiply-constrained problem-solving for high than for low WMC participants, load only reduced performance on analytic problems for low WMC participants. Previous research investigating the role of WMC and load on analytic problem-solving with multidigit subtraction found that secondary task demands had a larger influence on low than on high WMC participants (Seyler et al., 2003). As the task used in that study relied heavily on transformation of initial problem information, it was suggested that secondary task demands interfered with the ability to efficiently engage appropriate mental transformations for problem solution for low WMC participants. Similarly, the analytic problems used in the current study involved considerable mental transformations (e.g., factoring, subtractions, additions) to be engaged to determine the appropriate solutions. However, under normal (no load) conditions, participants were able to offload onto the environment to reduce the number of mental transformations needed to solve the problem. Thus, when environmental support was not available, low WMC participants were more likely to make errors in mental transformations or maintaining the problem steps. Importantly, however, the differential effect of load across CRAT and analytic problems as a function of WMC suggests that different working memory processes were needed to determine the appropriate solution. We suggest that in the former, working memory processes are needed to generate and monitor information from long-term memory, whereas in the latter working memory processes are needed to engage mental transformations of information maintained in primary memory. It is possible that differences may have arisen due to differences in the load manipulation between the two problem types. Future research is needed to investigate the relative contributions of short-term and long-term memory processes in CRAT and analytic problem-solving to further test these claims.

Limitations and future directions

We manipulated two key independent variables in the current study which were problem difficulty and load which was defined as the degree to which participants could use environmental support for problem-solving. For the algebra problems, difficulty was manipulated by adding additional computational steps needed to correctly solve the algebraic problem. In contrast, multiply-constrained problems difficulty was manipulated based on normative measures from prior research (Bowden & Jung-Beeman, 2003) which indicated that fewer participants solved more difficult problems within specific time limits. Clearly, a major limitation of the current project is that difficulty was differentially manipulated between the two problem sets and that they were not matched on item difficulty. Importantly, our primary focus in the current study was to assess the effects of difficulty and load on the problem-solving *within* a type of problem and not on differences in performance *between* types of problems. That said, future research should better control the difficulty of the items sets by conducting normative tests on the algebraic problems and establishing a comparable rank order of item difficulty to the CRAT problems. An additional area of for future research is to evaluate the processes that participants used to arrive at solutions in the CRAT under various difficulty and load manipulations (Chein & Weisberg, 2014). Given the differences in CRAT accuracy under various conditions of environmental support, and the differences in correlations with WMC, it stands to reason that strategy usage may also differ in these conditions. In addition, as the order of the tasks were fixed, the possibility of order effects or fatigue causing uniquely affecting performance or interacting with the difficulty and load manipulations needs to be accounted for as well in future experiments.

Conclusion

Working memory is important for solving problems across many settings where cognitive processes need to be regulated to systematically follow rules or generate novel ideas. Future research should examine how working memory demands in these domains (i.e., analytic and multiply-constrained problem-solving) differentiate successful problem-solving depending on the engagement of specific cognitive processes such as task set maintenance, attention control, and episodic/semantic memory search and monitoring. Future research can extend the current findings regarding problem difficulty and environmental support by further examining key factors that may mitigate the hypothesised relation between working memory and problem-solving.

Authors' note

All materials and data from these experiments can be downloaded from the corresponding author's laboratory website asumaclab.com.

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Open practices

The data and materials from the present experiment are publicly available at the Open Science Framework website: https://osf.io/hr7gp/

Supplementary material

The Supplementary Material is available at: qjep.sagepub.com

Note

1. The keen reader will note that between task difficulty for analytical and multiply-constrained problem-solving are not equivalent. The focus of the current study was to not assess the effects of difficulty and load between the two types of problems (analytical and multiply-constrained) but to understand the effects on the task itself.

References

Ash, I. K., & Wiley, J. (2006). The nature of restructuring in insight: An individual differences approach. *Psychonomic Bulletin & Review*, *13*, 66–73.

Ashcraft, M. H., & Kirk, E. P. (2001). The relationship among working memory, math anxiety, and performance. *Journal of Experimental Psychology: General*, *130*(2), 224–237.

Baddeley, A. D. (2012). *Working memory, thought, and action*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780198528012.001.0001

Ball, L. J., Marsh, J. E., Litchfield, D., Cook, R. L., & Both, N. (2015). When distraction helps: Evidence that concurrent articulation and irrelevant speech can facilitate insight problem solving. *Thinking & Reasoning*, *21*, 76–96.

Ball, L., & Stevens, A. (2009). Evidence for a verbally-based analytic component to insight problem solving. In N. Taatgen & H. van Rijn (Eds.), *Proceedings of the 31st annual conference of the cognitive science society* (pp. 1060–1065). Austin, TX: Cognitive Science Society.

Beilock, S. L., & DeCaro, M. S. (2007). From poor performance to success under stress: Working memory, strategy selection, and mathematical problem solving under pressure. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*(6), 983–998.

Bowden, E. M., & Jung-Beeman, M. (2003). Normative data for 144 compound remote associate problems. *Behavior Research Methods, Instruments, & Computers*, *35*(4), 634–639.

Bowden, E. M., Jung-Beeman, M., Fleck, J., & Kounios, J. (2005). New approaches to demystifying insight. *Trends in Cognitive Sciences*, *9*(7), 322–328.

Brewer, G. A., & Unsworth, N. (2012). Individual differences in the effects of retrieval from long-term memory. *Journal of Memory and Language*, *66*, 407–415.

Chein, J. M., & Weisberg, R. W. (2014). Working memory and insight in verbal problems: Analysis of compound remote associates. *Memory Cognition*, *42*, 67–83.

Chein, J. M., Weisberg, R. W., Streeter, N. L., & Kwok, S. (2010). Working memory and insight in the nine-dot problem. *Memory & Cognition*, *38*(7), 883–892.

Chuderski, A. (2014). How well can storage capacity, executive control, and fluid reasoning explain insight problem solving. *Intelligence*, *46*, 258–270.

Conway, A. R. A., Cowan, N., Bunting, M. F., Therriault, D. J., & Minkoff, S. R. B. (2002). A latent variable analysis of working memory capacity, short-term memory capacity, processing speed, and general fluid intelligence. *Intelligence*, *30*(2), 163–183.

Cowan, N. (2005). *Working memory capacity*. Psychology Press.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, *19*, 450–466.

Daneman, M., & Hannon, B. (2001). Using working memory theory to investigate the construct validity of multiple-choice reading comprehension tests such as the SAT. *Journal of Experimental Psychology: General*, *130*(2), 208–223.

DeCaro, M. S., Stockum, C. A., & Wieth, M. B. (2016). When higher working memory capacity hinders insight. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *42*, 39–49.

De Dreu, C. K. W., Nijstad, B. A., Baas, M., Wolsink, I., & Roskes, M. (2012). Working memory benefits creative insight, musical improvisation, and original ideation through maintained task-focused attention. *Personality and Social Psychology Bulletin*, *38*(5), 656–669.

De Rammelaere, S., Stuyven, E., & Vandierendonck, A. (2001). Verifying simple arithmetic sums and products: Are the phonological loop and central executive involved? *Memory & Cognition*, *29*(2), 267–273.

Ellis, D. M., & Brewer, G. A. (2018). Aiding the search: Examining individual differences in multiply-constrained problem solving. *Consciousness and Cognition*, *62*, 21–33.

Engle, R. W., & Kane, M. J. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. *Psychology of Learning and Motivation*, *44*, 145–200.

Fink, A., & Benedek, M. (2012). EEG alpha power and creative ideation. *Neuroscience & Biobehavioral Reviews*, *44*, 111–123.

Fleck, J. I. (2008). Working memory demands in insight versus analytical problem solving. *European Journal of Cognitive Psychology*, *20*, 139–176.

Furst, A. J., & Hitch, G. J. (2000). Separate roles for executive and phonological components of working memory in mental arithmetic. *Memory & Cognition*, *28*(5), 774–782.

Gathercole, S. E. (1994). Neuropsychology and working memory: A review. *Neuropsychology*, *8*(4), 494–505.

Gilhooly, K. J., Ball, L. J., & Macchi, L. (2015). Insight and creative thinking processes: Routine and special. *Thinking & Reasoning*, *21*(1), 1–4.

Gupta, N., Jang, Y., Mednick, S. C., & Huber, D. E. (2012). The road not taken: Creative solutions require avoidance of high-frequency responses. *Psychological Science*, *23*(3), 288–294.

Heitz, R. P., & Engle, R. W. (2007). Focusing the spotlight: Individual differences in visual attention control. *Journal of Experimental Psychology: General*, *136*, 217–240.

Jensen, O., Gelfand, J., Kounios, J., & Lisman, J. E. (2002). Oscillations in the alpha band (9–12 Hz) increase with memory load during retention in a short-term memory task. *Cerebral Cortex*, *12*, 877–882.

Jung-Beeman, M., Bowden, E. M., Haberman, J., Frymiare, J. L., Arambel-Liu, S., Greenblatt, R., Reber, P. J., & Kounios, J. (2004). Neural activity when people solve verbal problems with insight. *PLOS Biology*, *2*(4), Article e97.

Kane, M. J., Bleckley, M. K., Conway, A. R., & Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General*, *130*(2), 169–183.

Kane, M. J., & Engle, R. W. (2003). Working memory capacity and the control of attention: The contributions of goal maintenance, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General*, *132*, 47–70.

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: The inhibition timing hypothesis. *Brain Research Reviews*, *53*, 63–88. 10.1016/j.brainresrev.2006.06.003

Kyllonen, P. C., & Stephens, D. L. (1990). Cognitive abilities as determinants of success in acquiring logic skill. *Learning and Individual Differences*, *2*, 129–160.

Lavric, A., Forstmeier, S., & Rippon, G. (2000). Differences in working memory involvement in analytical and creative tasks: An ERP study. *NeuroReport*, *11*(8), 1613–1618.

Luo, J., & Niki, K. (2003). Function of hippocampus in "insight" of problem solving. *Hippocampus*, *13*, 316–323.

Mednick, M. (1962). Research creativity in psychology graduate students. *Journal of Consulting Psychology*, *27*, 265–266.

Metcalfe, J., & Wiebe, D. (1987). Intuition in insight and noninsight problem solving. *Memory & Cognition*, *15*, 238–246.

Newell, A., & Simon, H. A. (1972). *Human problem solving*. Prentice Hall.

Reverberi, C., Toraldo, A., D'Agostini, S., & Skrap, M. (2005). Better without (lateral) frontal cortex? Insight problems solved by frontal patients. *Brain*, *128*(12), 2882–2890.

Ricks, T. R., Turley-Ames, K. J., & Wiley, J. (2007). Effects of working memory capacity on mental set due to domain knowledge. *Memory & Cognition*, *35*(6), 1456–1462.

Risko, E. F., & Dunn, T. L. (2015). Storing information in-the-world: Metacognition and cognitive offloading in a short-term memory task. *Consciousness and Cognition*, *36*, 61–74.

Rosen, V. M., & Engle, R. W. (1997). The role of working memory capacity in retrieval. *Journal of Experimental Psychology General*, *162*(3), 211–227.

Schwab, D., Benedek, M., Papousek, I., Weiss, E. M., & Fink, A. (2014). The time-course of EEG alpha power changes in creative ideation. *Frontiers in Human Neuroscience*, *8*, Article 310.

Seyler, D. J., Kirk, E. P., & Ashcraft, M. H. (2003). Elementary sub-traction. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *29*, 1339–1352.

Smith, K. A., Huber, D. E., & Vul, E. (2013). Multiply-constrained semantic search in the remote associates test. *Cognition*, *128*, 64–75.

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language*, *28*, 127–154.

Unsworth, N., & Engle, R. W. (2005). Individual differences in working memory capacity and learning: Evidence from the reaction time task. *Memory & Cognition*, *33*(2), 213–220.

Unsworth, N., & Engle, R. W. (2007). Working memory capacity and fluid abilities: Examining the correlation between Operation Span and Raven. *Intelligence*, *33*(1), 67–81.

Unsworth, N., Heitz, R. P., Schrock, J. C., & Engle, R. W. (2005). An automated version of the operation span task. *Behavior Research Methods*, *37*, 498–505.

Unsworth, N., Schrock, J. C., & Engle, R. W. (2004). Working memory capacity and the antisaccade task: Individual differences in voluntary saccade control. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *30*(6), 1302–1321.

Unsworth, N., & Spillers, G. J. (2010). Working memory capacity: Attention, memory, or both? A direct test of the dual-component model. *Journal of Memory and Language*, *62*, 392–406.

Unsworth, N., Spillers, G. J., & Brewer, G. A. (2012). Working memory capacity and retrieval limitations from long-term memory: An examination of differences in accessibility. *The Quarterly Journal of Experimental Psychology*, *65*(12), 2397–2410.

Wiley, J., & Jarosz, A. F. (2011). How working memory capacity affects problem solving. *Psychology of Learning and Motivation*, *56*, 186–219.

Wiley, J., & Jarosz, A. F. (2012). Working memory capacity, attentional focus, and problem solving. *Current Directions in Psychological Science*, *21*, 258–262.