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When working memory mechanisms compete: Predicting cognitive flexibility versus mental set

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ABSTRACT

Cognitive flexibility is a hallmark of individuals with higher working memory capacity (WMC). Yet, individuals with higher WMC sometimes demonstrate greater rigidity in problem solving. The present research examines a novel account for these contradictory findings—that different WMC mechanisms support versus constrain cognitive flexibility. Across three studies, participants completed the water jug task—a problem-solving task requiring them to first establish and then break mental set. Predictor measures targeted three WMC mechanisms: attention control, primary memory, and secondary memory. In Study 1, primary and secondary memory predicted breaking mental set in opposite directions. Higher primary memory facilitated breaking mental set, whereas higher secondary memory hindered it. Study 2 demonstrated that attention control moderates these effects. Study 3 replicated these results using a less restrictive sampling procedure (i.e., participants were provided the strategy needed to establish mental set). The present research supports the proposed theory of functional opponency in WMC.

1. Introduction

Working memory capacity (WMC) helps keep cognitive processes (memory and attention) organized around information relevant to the task at hand (Awh & Vogel, 2008; Conway, Cowan, & Bunting, 2001). Individual differences in WMC thereby predict many and varied cognitive abilities (Gruszka & Nęcka, 2017; Hambrick & Meinz, 2011; Hicks, Harrison, & Engle, 2015). For example, individuals with higher WMC (high WMs) demonstrate greater fluid intelligence (Gf)—the ability to solve novel reasoning problems (Kane, Hambrick, & Conway, 2005). High WMs are also better able to implement complex, cognitively-demanding strategies than lower WMC individuals (low WMs; Barrett, Tugade, & Engle, 2004; Thomassin, Gonthier, Guerraz, & Roulin, 2015). These abilities enable high WMs to better adapt to novel or changing task demands (e.g., Colflesh & Conway, 2007; Rummel & Boywitt, 2014; Weldon, Mushlin, Kim, & Sohn, 2013)—a hallmark of *cognitive flexibility* (Ionescu, 2012).

However, a superior capacity to restrict memory and attention to goal-relevant information may also lead high WMs to overlook potentially useful information (Amer, Campbell, & Hasher, 2016). For example, high WMs demonstrate greater bias for complex solutions that have worked in the past, while overlooking new, simpler solutions to problems (DeCaro, 2018; Wiley & Jarosz, 2012). This tendency can lead to cognitive *inflexibility*, or *mental set* (Bilalić, McLeod, & Gobet, 2010). These and related findings challenge the assumption that "more" cognitive abilities are always "better" (Beier & Oswald, 2012; cf. Hills & Hertwig, 2011)—the basis for a multi-billion dollar industry dedicated to cognitive training and enhancement (Katz, Shah, & Meyer, 2018; Simons et al., 2016).

Thus, the nature of the relationship between WMC and cognitive flexibility is unclear: How can high WMs be both more cognitively flexible and inflexible than low WMs? The answer may depend on how WMC is conceptualized. Regarded as a unitary construct, these findings appear contradictory. However, a view of WMC as a multifaceted construct may accommodate such contradictions, allowing a more comprehensive account of this relationship.

1.1. Mechanisms of working memory capacity

Traditionally, WMC is treated as a unitary construct, reducible to a single mechanism or common factor reflecting the overall effectiveness of a hierarchically organized system (e.g., Cowan et al., 2005; Kane & Engle, 2002). Recent studies, however, have demonstrated that multiple sources of variance are needed to account for individual differences in WMC (Shipstead, Lindsey, Marshall, & Engle, 2014; Unsworth, Fukuda, Awh, & Vogel, 2014; see Unsworth, 2016, for a review). These

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studies support a *multifaceted view* of WMC that emphasizes the distinct contributions of three related mechanisms. *Attention control* (AC) refers to the set of attentional processes that enable individuals to actively maintain goals, sustain focus on task-relevant information, and resist distractions (McVay & Kane, 2012; Unsworth & Spillers, 2010). *Primary memory* (PM) is the ability to maintain and manipulate limited amounts of information in a temporary state, in and around the focus of attention (Cowan, 2001; Oberauer, 2002). *Secondary memory* (SM) is the ability to access or recover information via strategic search and retrieval processes (Unsworth & Engle, 2007a; Unsworth & Spillers, 2010). These mechanisms vary both between and within individuals, and jointly account for the relationship between WMC and Gf (Unsworth, 2016).

The multifaceted view thus seeks to parse the predictive power of WMC by delimiting the relative contributions of component processes. According to this view, tasks that rely on WMC demand each of these mechanisms (AC, PM, and SM) to a greater or lesser extent (Unsworth et al., 2014). Accordingly, tasks commonly used to assess individual differences in WMC place greater demands on some of these mechanisms over others. For example, Shipstead et al. (2014) demonstrated that running span tasks (e.g., running letter span: remember the last n letters from lists $n + m$ letters long) reflect PM more strongly than complex span tasks. Complex span tasks (e.g., operation span: remember a series of letters while alternately solving simple math equations) are more closely associated with AC and SM (see also Healey & Miyake, 2009; McCabe, 2008; Unsworth & Engle, 2007b). Furthermore, running span tasks include a component of PM that is not reflected in complex span tasks.

Shipstead et al. (2014) proposed that this PM component reflects the ability to disengage no-longer-relevant information from the focus of attention. *Disengagement* is thought to contribute to PM capacity—and by extension cognitive flexibility—by facilitating the breaking of temporary bindings between attention and active mnemonic representations, thereby allowing novel combinations of information to be generated (see also Shipstead, Harrison, & Engle, 2016; Singh, Gignac, Brydges, & Ecker, 2018). However, this PM mechanism of disengagement has not been tested as a predictor of cognitive flexibility.

The multifaceted view provides new opportunities to revisit classic effects and reexamine long-standing assumptions to generate novel hypotheses that better capture the distinct contributions of WMC mechanisms (Harrison, Shipstead, & Engle, 2015; Redick et al., 2016). However, a better understanding of the interplay of these mechanisms is needed. For instance, both classic and contemporary views of WMC emphasize the interaction of memory and attention (e.g., Engle & Kane, 2004; Shipstead et al., 2014). Yet, these interactions are rarely tested. Failing to account for interactions among overlapping mechanisms may mask true distinctions where they exist (Badre, 2011). Closer inspection of the functional dynamics of this multifaceted construct may clarify seemingly contradictory findings within the literature (Stroebe & Strack, 2014).

1.2. Cognitive flexibility versus cognitive stability

The virtues of “being flexible” are extolled in colloquial discourse—*cognitive flexibility* enables individuals to update their plans or expectations in response to new information, explore alternative strategies for solving problems, and generally adapt behaviors to changing environmental demands (Diamond, 2013; Ionescu, 2012). Equal and opposite to cognitive flexibility stands *cognitive stability*, the ability to maintain internal representations of current goals and context in a robust state, in the service of ongoing behavior (Cools & D'Esposito, 2011; Dreisbach & Fröber, 2019). Cognitive stability helps individuals resist non-adaptive changes (e.g., inappropriate reflexive responses, goal neglect) and promotes consistency over time (Kiyonaga, Scimeca, Bliss, & Whitney, 2017). However, excessive cognitive stability can lead to *cognitive rigidity*, a mental state in which adaptive changes are also resisted (see Schultz & Searleman, 2002, for a review).

The notion that goal-directed behavior relies on a cognitive system that is simultaneously stable and flexible has been described as a “control dilemma” (Goschke, 2000; Goschke & Bolte, 2014), as there are both adaptive and maladaptive aspects to each process (cf. Altamirano, Miyake, & Whitmer, 2010; Joormann, Levens, & Gotlib, 2011). For instance, cognitive flexibility facilitates adaptive changes (e.g., updating goals based on new information, switching between multiple task-sets), and thus combats cognitive rigidity. In contrast, cognitive stability helps individuals stay on-task, and thus combats distraction, more likely in cases of excessive cognitive flexibility (Dreisbach & Goschke, 2004). Because cognitive stability and flexibility serve functionally opposing computational goals, they sometimes conflict (see Herd et al., 2014). The relationship between cognitive stability and flexibility is thus characterized as one of “functional opponency” (Cools & D'Esposito, 2011).

Functional opponency is based on the theory that adaptive biological and cognitive abilities function meaningfully only within a system of constraints (Cohen, Aston-Jones, & Gilzenrat, 2004). Opponent functions are antagonistic (more of one, less of the other), resulting in trade-offs (Durstewitz & Seamans, 2008). A system is adaptive to the extent that opponent functions are appropriately balanced (e.g., maximally aligned to current demands), minimizing trade-offs and optimizing overall function (Chrysikou, Weber, & Thompson-Schill, 2014; Hills & Hertwig, 2011).

1.3. Cognitive flexibility and working memory capacity

Cognitive control, a set of processes supporting adaptive goal pursuit (Fan, 2014), is one such system thought to require a dynamic balance between cognitive stability and flexibility (Cools & D'Esposito, 2011). Individual differences in these abilities may contribute to an imbalance between stable versus flexible cognition. WMC is an important predictor of cognitive control (Kane & Engle, 2002). Thus, individual differences in WMC mechanisms may reflect functional opponency. Indeed, contradictory findings within the WMC and cognitive flexibility literature appear to support the notion that functional opponency is at play.

Positive correlations are typically found between WMC and performance on tasks that require alternating flexibly (i.e., quickly and appropriately) between sets of stimulus-response rules (e.g., task switching, set shifting, multitasking; Draheim, Hicks, & Engle, 2016; Gulbinaite, van Rijn, & Cohen, 2014; Redick et al., 2016; Weldon et al., 2013). Commonly cited as measures of cognitive flexibility, these tasks often require maintaining two or more active sets of stimulus-response rules in WM, and thus place relatively high demands on stability (Dajani & Uddin, 2015). Positive correlations with WMC are also found for tasks where flexibility is contingent upon the ability to suppress distraction (e.g., Colflesh & Conway, 2007; Rummel & Boywitt, 2014). In sum, cognitive flexibility tasks that tend to correlate positively with WMC may actually rely on stability to a greater extent than flexibility.

Tasks that sometimes show negative correlations with WMC are those that require flexible problem solving (e.g., mental set and insight problem-solving tasks; DeCaro, 2018; Wiley & Jarosz, 2012). In problem solving, being flexible means being able to deviate from set procedures in order to find new and efficient solutions to problems (Dick, 2014; Star & Seifert, 2006). *Mental set* is a cognitive mechanism that biases attention to ensure a speedy response in familiar contexts but can also lead to errors when the optimal solution conflicts with familiar methods (Bilalić et al., 2010; Schultz & Searleman, 2002). Mental set problem-solving tasks thus require flexibility in “overcoming” a suboptimal approach that is strongly activated by prior experience solving similar problems (i.e., “breaking” mental set). For example, Beilock and DeCaro (2007) found that high WMs were more likely to persist in using a complex problem-solving strategy despite the availability of simpler, more efficient alternatives (see also Fischer & Holt, 2017; Richmond, Redick, & Braver, 2015). *Insight problems* are problems that have a high probability of triggering a "faulty" initial problem representation (i.e., a representation that has a low probability of activating the knowledge needed to solve the problem; Ohlsson, 1992). Solving insight problems is thought to require relaxing unnecessary constraints based on prior experience solving similar problems, analogous to breaking mental set (DeCaro, Van Stockum, & Wieth, 2016; Öllinger, Jones, & Knoblich, 2008). Mental set and insight problem-solving tasks demonstrate how old strategies may hinder new solutions (Knoblich, Ohlsson, Haider, & Rhenius, 1999). Thus, tasks that correlate negatively with WMC may rely on flexibility to a greater extent than stability (Barbey, Colom, & Grafman, 2013; Chrysikou et al., 2014).

Different tasks demand more or less flexible cognition: just as it is possible to be "too stable" (i.e., rigid) it is likewise possible to be "too flexible" (e.g., distracted). WMC may help balance these competing demands. However, individual differences in specific WMC mechanisms may determine who is likely to strike the appropriate balance or risk trade-offs in a given task. Such findings would support the theory that WMC both supports and constrains cognitive flexibility via functionally opposing mechanisms, and help explain inconsistencies in the literature.

2. Current studies

The goal of the present research was to test the novel hypothesis that WMC simultaneously supports and constrains cognitive flexibility, using a single outcome measure. In three studies, cognitive flexibility was measured using a classic problem-solving task assessing mental set—Luchins's (1942) water jug task. This task was selected for several reasons. First, mental set is a pervasive source of cognitive bias in everyday life (Bilalić et al., 2010). Second, the water jug task was used in previous research demonstrating a negative relationship between WMC and breaking mental set (Beilock & DeCaro, 2007). Third, we expected that breaking mental set would rely on disengagement from no-longer relevant information, a key aspect of the multifaceted view of WMC proposed by Shipstead et al. (2014). Finally, this task enabled us to examine both how mental set is established and broken within the same task, and test whether (and to what extent) functional opponency impacts both processes.

In the water jug task, the first three problems ("set problems") are intended to induce mental set, and can only be solved using a complex, multistep strategy (see Fig. 1). Individuals are deemed to have established mental set if they correctly solve the set problems. The last three problems ("critical problems") are used to assess cognitive flexibility. Participants can solve these problems by using the same, complex strategy used for the set problems. However, the critical problems can also be solved using simpler, single step strategies. Of interest is whether individuals flexibly switch to the simple strategies when they become available (i.e., "break" mental set). Importantly, participants are informed that multiple solutions might be possible and instructed to find the simplest solution.

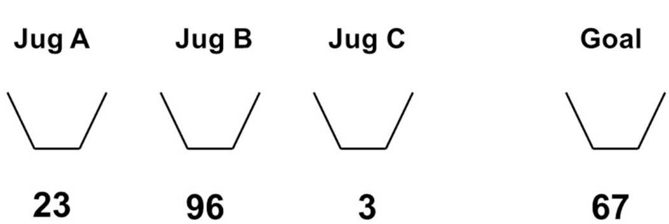

Fig. 1. Example water jug set problem. Participants mentally derived a formula to obtain a "goal" quantity of water by using three jugs (A, B, and C) of various capacities and a hypothetical unlimited water supply. All six experimental problems were solvable by the formula B − A − 2C (i.e., Fill Jug B, then pour out enough to fill Jug A once and Jug C twice, leaving the goal quantity in Jug B). The first three ("set") problems could only be solved using this formula, whereas the last three ("critical") problems were also solvable via a simpler formula (e.g., A − C).

In each study, the unique associations between three WMC mechanisms (AC, PM, and SM) and performance on the water jug task were examined. The WMC tasks were selected based on previous research demonstrating that these tasks place relatively higher demands on one or more of these mechanisms. The *antisaccade task* requires maintenance of a single goal (i.e., "look away from the flash"), and is thus considered a relatively process-pure measure of AC (see Engle, 2018; Kane, Bleckley, Conway, & Engle, 2001; Roberts, Hager, & Heron, 1994). The *running span task* requires remembering the last *n* items from lists $n + m$ items long (Pollack, Johnson, & Knaff, 1959). Participants do not know how many items will be presented in a given trial (i.e., participants are told *n*, but not *m*). Letters are presented at a rate of two per second (Broadway & Engle, 2010; Shipstead et al., 2014). Fast presentation of items in lists of unpredictable length is thought to impede proactive recall strategies (e.g., rehearsal, grouping; Cowan et al., 2005; updating, Bunting, Cowan, & Saults, 2006), yielding a more direct measure of the maximum amount of information that can be maintained in the focus of attention or "absolute capacity" of PM (see Shipstead et al., 2014).

The *operation span task* requires remembering a series of letters while verifying solutions to simple math equations (Unsworth, Heitz, Schrock, & Engle, 2005). This secondary verification task occurs after the presentation of each to-be-remembered letter, distracting participants from the recall task (the measure of interest). This procedure is thought to lead some to-be-remembered letters to be displaced from the focus of attention, that must then be retrieved (Unsworth & Engle, 2007a, 2007b). Thus, recall performance on the operation span is largely a product of individuals' ability to resist attentional capture via AC and search/retrieve to-be-remembered letters via SM (Shipstead et al., 2014; Unsworth & Spillers, 2010).

Shipstead et al. (2014) demonstrated that variance unique to running span measures of WMC (i.e., not shared with complex span measures of WMC) reflects PM, whereas operation span scores reflect both AC and SM (see also Healey & Miyake, 2009; Unsworth & Engle, 2007b). In line with Shipstead et al. (2014), residual variance unique to the running span task (i.e., PM) was interpreted as disengagement. If the operation span task reflects both AC and SM (e.g., Shipstead et al., 2014), it follows that, after controlling for AC and PM, variance unique to operation span would reflect SM. In each study, multiple linear regression was used to isolate effects of AC, PM, and SM, as measured by the antisaccade task, the running span task, and the operation span task, respectively.

2.1. Hypotheses

We examined the effects of AC, PM, and SM on both water jug set problems and critical problems. However, our main hypotheses of interest regarded whether participants used the simple strategies on the critical problems—breaking out of mental set. We expected that PM would facilitate disengagement from the complex strategy (Shipstead et al., 2014) and allow novel combinations of information to be generated (Oberauer, Süß, Wilhelm, & Sander, 2007). Therefore, we predicted that individuals higher in PM would be more likely to break mental set.

We expected that SM would facilitate retrieval of the complex strategy (Harrison et al., 2015; Verguts & De Boeck, 2002) and bias suboptimal persistence in this approach (Beilock & DeCaro, 2007). Therefore, we predicted that individuals higher in SM would be less likely to break mental set.

Because all tasks required some degree of goal maintenance, and AC is a critical component of this process (Engle, 2018; Shipstead et al., 2014), positive relationships with AC were generally expected. Therefore, we predicted that individuals higher in AC would be more likely to establish mental set and break it. The role of AC in the hypothesized model is further examined in Studies 2 and 3.

In sum, although both are typically associated with high WMs, the ability to retrieve previously used strategies versus disengage may determine who demonstrates cognitive flexibility. Such findings would support a multifaceted view of WMC in which component processes do not always act in concert.

3. Study 1

Study 1 provided an initial test of these hypotheses. The WMC mechanisms described above (AC, PM, and SM) were used to predict performance on both set problems and critical problems on the water jug task. We hypothesized that PM and SM would predict the tendency to break mental set on the water jug task in opposite directions.

3.1. Method

3.1.1. Participants

Eighty-one undergraduate students (46 females, 35 males; M_{age} = 20 years, *SD* = 2.8) participated for psychology course credit. Four additional participants were removed for (a) committing > 20 errors on the math portion of the operation span (n = 1; Conway et al., 2005), (b) prior exposure to water jug problems (i.e., reported having seen the problems before and having remembered the answer, and correctly answered at least one critical problem using the simpler strategy; n = 1), or (c) identification as a univariate outlier (i.e., scores > 3 SDs from scale means; n = 2). Exclusion criteria and sample size were based on Beilock and DeCaro (2007, Experiment 2). Thirty-nine of the total 81 participants (48%) solved all three set problems and were thereby deemed to have established mental set.

3.1.2. Procedure

Participants were tested individually in a single session with breaks. After providing informed consent, participants completed the tasks on a computer in the following order: operation span, antisaccade, running span, water jug. Afterwards, participants completed a questionnaire assessing prior experience with water jug problems and demographics and were debriefed.

3.1.3. Working memory capacity tasks

3.1.3.1. Antisaccade task (Hallett, 1978). Each trial began with a central fixation cross (1000 or 2000 ms), followed by an asterisk that appeared for 300 ms on either side of the screen. Upon seeing the asterisk, participants were instructed to immediately divert their gaze to the opposite side where one of two letters (O or Q) appeared for 100 ms (backwards masked) (see Fig. 2). Participants had 5000 ms to respond by pressing the key corresponding to the letter presented. Participants completed 32 practice trials, followed by 48 critical trials on which accuracy (proportion correct) served as the dependent measure (Shipstead et al., 2014).

3.1.3.2. Running span task (Broadway & Engle, 2010). Participants saw a series of unrelated letters and were asked to remember the last 3–7. Trials ranged from 3 to 9 letters in length, presented in blocks of three according to the number of to-be-remembered letters (5 blocks total, in random order). Each block included one "whole recall" trial, in which the number of to-be-remembered letters was equal to the number of letters presented, and two "partial recall" trials, in which the number of letters presented exceeded the number of to-be-remembered letters by one or two (see Fig. 3). The order of trials within each block was random. The number of to-be-remembered letters was displayed at the beginning of each block. Critically, participants did not know how many letters would be presented in a given trial. Each letter was presented for 300 ms, with an inter-stimulus interval of 200 ms. The dependent measure was the total number of to-be-remembered letters correctly recalled in the correct serial position (regardless of whether the entire sequence of letters was correct) across all trials, out of 75 possible (Shipstead et al., 2014).

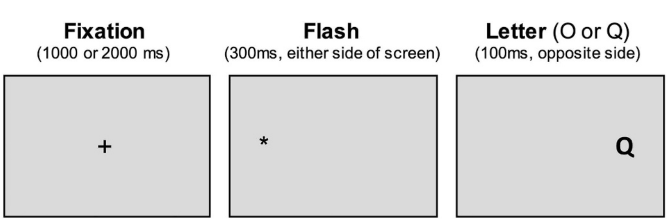

Fig. 2. Example of the antisaccade task. The antisaccade requires resisting attentional capture in the face of distraction (i.e., "look away from the flash").

3.1.3.3. Operation span task (Unsworth et al., 2005). Participant saw an arithmetic problem (e.g., (1 * 2) + 1 = ?) and were instructed to mentally derive the answer and then click the mouse. Participants were then shown a number (e.g., 3) and required to indicate whether this was the correct answer by clicking either "True" or "False". Finally, participants were shown a letter to remember, drawn randomly from a set of unrelated letters (see Fig. 4). Following a sequence of problem-letter strings ranging from 3 to 7 in length, participants were asked to recall the letters in the order presented. Participants completed 3 sequences of each string length in random order. The dependent measure was the sum of all letters recalled in the correct serial position (regardless of whether the entire sequence of letters was correct) across all trials, out of 75 possible (Shipstead et al., 2014).

3.1.4. Problem-solving task

3.1.4.1. Water jug task (Luchins, 1942). To assess cognitive flexibility, participants performed the water jug task, a classic "mental set" problem-solving task. Problems and procedure were the same as used by Beilock and DeCaro (2007). Problems were presented on a computer. Participants were instructed to solve the problems mentally (i.e., without paper/pencil) and then type their solutions. Each experimental problem depicted three jugs (A, B, and C) of various ungraduated capacities, and a fourth to be "filled" to a specified goal quantity (see Fig. 1). Participants were instructed to mentally derive a mathematical formula resulting in the goal quantity using the three jugs provided and a hypothetical unlimited water supply. Participants were informed that all three jugs need not be used to solve the problems, and that multiple solutions might be possible. Importantly, participants were also instructed to use the simplest method possible. All six experimental problems (see Table 1) were solvable via the same computationally demanding strategy (i.e., B − A − 2C). The first three problems ("set problems") were only solvable using this complex strategy; the last three problems ("critical problems") were also solvable via a simpler strategy (i.e., A + C or A − C). Prior to the experimental problems, participants saw one example problem (Jug A = 29, Jug B = 11, and Goal = 7) and answer (A − 2C or 29 − 11 − 11) and had an opportunity to ask questions. This example problem used only two jugs to limit similarity with the experimental problems. In line with previous studies (e.g., Beilock & DeCaro, 2007; Gasper, 2003), individuals were deemed to have established mental set if they correctly solved all three set problems. The primary dependent measure was the number of critical problems correctly solved using the simple strategies, with higher scores denoting greater cognitive flexibility.

3.2. Results and discussion

Individual differences in AC, PM, and SM were operationally defined as variance unique to the antisaccade, running span, and operation span (respectively), when all three were entered simultaneously into a multiple regression model (cf. Shipstead et al., 2014). Two dependent measures from the water jug task were examined: (a) the ability to establish mental set (i.e., learn the complex strategy),

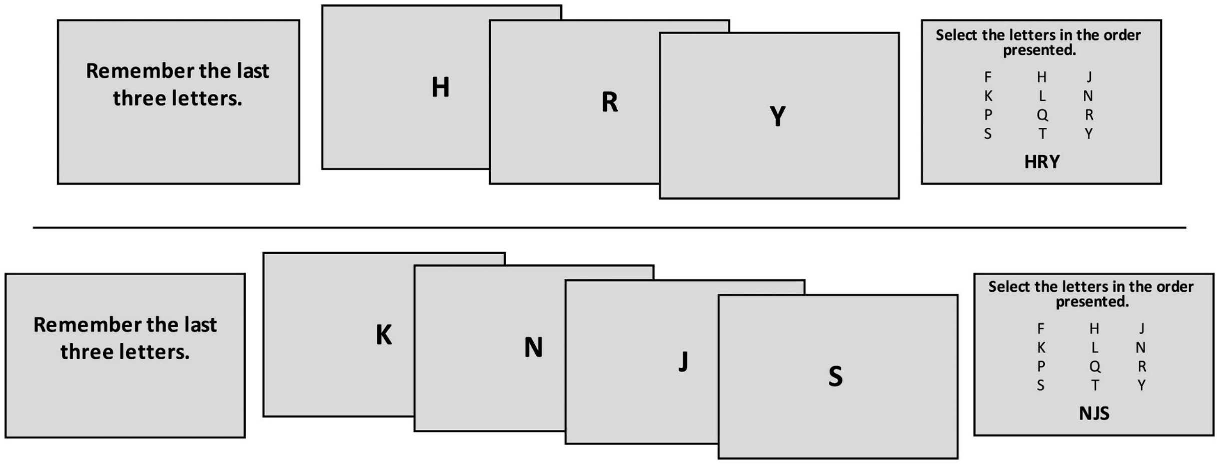

Fig. 3. Example of the running span task: whole recall trial (top) and partial recall trial (bottom). The running span requires remembering the last 3–7 letters from series of 3–9 letters.

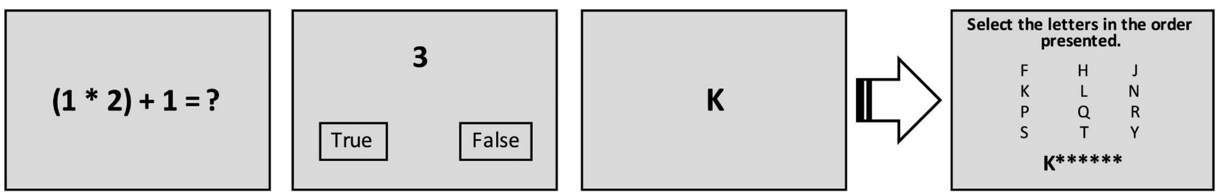

Fig. 4. Example of the operation span task. The operation span requires remembering series of 3–7 letters while alternately verifying solutions to simple math equations.

Table 1
Water jug problems.

Problem	Jug			
	A	B	C	Goal
1	23	96	3	67
2	11	48	6	25
3	20	59	4	31
4	23	49	3	20
5	15	39	3	18
6	14	36	8	6

operationalized by the number of set problems solved, and (b) the ability to break mental set once established, operationalized as the number of critical problems solved using simple strategies. Residuals and scatterplots indicated the assumptions of normality and homoscedasticity were met, and VIF values (< 1.4) indicated that multicollinearity was not an issue.

3.2.1. *Set problems*

Descriptive statistics and zero-order correlations among predictors variables and set problems correctly solved, for all participants, are presented in Table 2. The number of set problems solved was significantly positively associated with antisaccade, but not significantly associated with running span or operation span. Additionally, a negative but non-significant association was found between the number of set problems solved and the number of critical problems solved using simple strategies ($M = 1.47$, $SD = 1.32$, $r(79) = -0.22$, $p = .050$). This trend suggests that individuals who were more likely to establish mental set in the first half of the task were less likely to break mental set in the second half of the task, consistent with previous studies in which

Table 3
Simultaneous regression predicting the number of set problems solved for all participants in Study 1.

Predictor	β	*t*	Sig.	sr^2
Antisaccade (AC)	0.25	2.14	**0.036**	0.05
Running span (PM)	0.01	0.09	0.925	0.00
Operation span (SM)	0.06	0.48	0.630	0.00

Note. AC = attention control; PM = primary memory; SM = secondary memory. $N = 81$.

Table 2
Descriptive statistics and zero-order correlations among predictor variables and set problems solved for all participants in Study 1.

Measure	Mean	*SD*	Skew	Kurtosis	Correlations (*r*)			
					1	2	3	4
1. Antisaccade	00.82	00.09	−0.81	0.78	(0.71)			
2. Running span	25.90	10.02	0.21	0.20	0.16	(0.62)		
3. Operation span	59.78	08.98	−0.64	0.26	0.33**	0.43**	(0.64)	
4. Set problems solved	01.89	01.24	−0.54	−1.39	0.27*	0.08	0.15	(0.81)

Note. Cronbach's Alpha reliability estimates are on the diagonal. $N = 81$.
* $p \le .05$.
** $p < .01$.

Table 4
Descriptive statistics and zero-order correlations among predictor variables and critical problems solved using simple strategies for individuals who established mental set in Study 1.

Measure	Mean	*SD*	Skew	Kurtosis	Correlations (*r*)			
					1	2	3	4
1. Antisaccade	00.84	00.09	−0.71	0.14	(0.70)			
2. Running span	26.54	10.55	0.22	0.57	0.12	(0.66)		
3. Operation span	60.31	07.52	−0.39	0.18	0.21	0.38*	(0.63)	
4. Critical problems solved using simple strategies	01.18	01.25	0.40	−1.54	−0.27	0.14	−0.37*	(0.81)

Note. Cronbach's Alpha reliability estimates are on the diagonal. $n = 39$.
* $p < .05$.

mental set resulted from prior experience or domain-specific knowledge (e.g., Bilalić et al., 2010; Ellis & Reingold, 2014; Wiley, 1998).

Next, we examined whether individual differences in WMC mechanisms (i.e., AC, PM, and SM) predicted who was most likely to establish mental set. The number of set problems solved was regressed simultaneously on antisaccade, running span, and operation span (see Table 3). There was a significant main effect of antisaccade, but not running span or operation span. These results indicate that AC was important for establishing mental set. This finding corresponds with work linking AC to the ability to mentally represent novel problems and execute multistep operations (Chein & Weisberg, 2014; see DeCaro et al., 2016).

3.2.2. Critical problems

Because mental set must be established before it can be broken, performance on critical problems was examined only for those who correctly solved the set problems ($n = 39$; see Beilock & DeCaro, 2007; Gasper, 2003). Descriptive statistics and zero-order correlations among predictor variables and critical problems solved using the simple strategies, for individuals who established mental set, are presented in Table 4. The number of critical problems solved using simple strategies was significantly negatively associated with operation span, but not significantly associated with antisaccade or running span. Additionally, we found that errors on the critical problems were low (i.e., < 9% of all answers provided failed to produce the goal quantity), indicating that when these individuals were not using the simple strategies, they were using the complex strategy the majority of the time. Consistent with previous studies, the simple (i.e., one-step) strategies were more efficient than the complex (i.e., multistep) strategy: The more critical problems solved using the simple strategies, the faster the mean response times for critical problems correctly solved (i.e., regardless of which strategy was used) ($M = 22.17$ s, $SD = 14.70$ s, $r(30) = -0.49$, $p = .004$).[2]

The principal research question for Study 1 was whether WMC mechanisms differentially predict who is most likely to flexibly switch to the simple strategies when they become available (i.e., break mental set). To test this question, the number of critical problems solved using simple strategies was regressed on antisaccade, running span, and operation span, simultaneously, in order to estimate variance in strategy selection uniquely predicted by each mechanism (i.e., AC, PM, and SM, respectively; Table 5). Antisaccade was not significantly associated with simple strategy use, possibly because the sample included only those individuals who correctly solved the set problems and thereby had a restricted range of AC scores.

Operation span was significantly negatively associated with use of the simple strategies, indicating that individuals higher in SM were less likely to break mental set. This finding suggests that greater ability to efficiently retrieve previously used strategies via SM (Harrison et al., 2015) promotes persistent usage of those strategies. This persistence can lead to cognitive rigidity in situations where retrieval cues automatically elicit the wrong information (Verguts & De Boeck, 2002).

Table 5
Simultaneous regression predicting the number of critical problems solved using simple strategies for individuals who established mental set in Study 1.

Predictor	β	*t*	Sig.	sr^2
Antisaccade (AC)	−0.22	−1.46	0.153	0.04
Running span (PM)	0.34	2.19	**0.035**	0.10
Operation span (SM)	−0.46	−2.87	**0.007**	0.17

Note. AC = attention control; PM = primary memory; SM = secondary memory. $n = 39$.

In contrast, running span was significantly positively associated with simple strategy use, indicating that individuals higher in PM were more likely to break mental set and thus demonstrate greater cognitive flexibility. This finding provides novel evidence that greater ability to disengage PM from no-longer-relevant information enables individuals to discover new, more efficient solutions.

3.2.3. Conclusions

By demonstrating that different WMC mechanisms (i.e., PM and SM) influence the same cognitive flexibility outcome in opposite directions, Study 1 provides initial support for the proposed theory of functional opponency in WMC. These results run counter to the preponderance of evidence in individual differences research favoring positive associations between (and across) cognitive abilities (Beier & Oswald, 2012). Indeed, these findings may even be considered "problematic, as they conflict with the dominant view on the structure of cognitive abilities, which predicts a substantial 'positive manifold' among virtually all types of cognitive activity" (Chuderski & Jastrzębski, 2017, p. 1994; cf. DeCaro, Van Stockum, & Wieth, 2017). If the current findings reflect a real phenomenon, they would have important ramifications for both theory and practice (see Hills & Hertwig, 2011).

Study 1 employed a novel variance-partitioning method for estimating individual differences in WMC mechanisms. Although this method was based on a well-grounded theoretical model with clear a priori hypotheses, additional comparisons are needed to rule out alternative interpretations. Specifically, it is unclear whether the positive association between PM and breaking mental set extends to other measures of PM or is specific to the running span task (Shipstead et al., 2014). Study 2 examines additional markers of individual differences in PM.

Finally, a limitation of Study 1 was that the relationship between AC and breaking mental set could not be fully examined. The ability to break mental set could only be examined for individuals who first established mental set. Since AC was positively associated with the number of set problems solved, it follows that a reduced sample of

[2] To ensure that the RT measure was based on an equal number of observations for each participant, 7 participants who committed a combined total of 10 errors on the critical problems were excluded from this analysis (see Beilock & DeCaro, 2007). However, including these participants did not change the pattern of results ($M = 24.87$ s, $SD = 17.24$ s, $r(37) = -0.42$, $p = .007$).

individuals who solved all three set problems (i.e., established mental set) would be comprised of a greater proportion of those higher in AC. Thus, a larger, more representative sample was collected in Study 2, in order to more fully examine the relationship between AC and breaking mental set.

4. Study 2

Study 1 conceptually replicated Shipstead et al.'s (2014) findings and extended them to make predictions about the specific WMC mechanisms underlying mental set. Study 2 further examined these questions by replicating the methodology of Study 1 with a larger sample and an additional measure of PM (immediate free recall).

The same pattern of results was expected for the set problems (i.e., positive association with AC). Moreover, Study 2 tested the novel hypothesis that AC moderates the opposing effects of PM and SM on breaking mental set. This hypothesis was motivated, in part, by the finding in Study 1 that individuals higher in AC were more likely to establish mental set. If breaking mental set is contingent upon the ability to establish it, then higher AC may represent a boundary condition for observing these effects. However, the sample size in Study 1 was insufficient to test this idea. Thus, a larger sample was collected to ensure adequate representation of individual differences in AC, PM, and SM and sufficient power for analyses of moderation between AC and both PM and SM. This hypothesis was also based on the theory that cognitive stability and flexibility reflect functionally opposing computational goals (Cools & D'Esposito, 2011). We reasoned that, if AC is essential for effective goal pursuit, then AC may support processes that further either of these goals.

We hypothesized that individual differences in PM and SM would predict breaking mental set in opposite directions, but primarily for individuals with higher AC, consistent with the pattern of results observed in Study 1. We expected that PM would facilitate disengagement from no-longer-relevant information (Shipstead et al., 2014) and thus support breaking mental set. Disengagement may support breaking mental set by allowing novel combinations of information to be generated (Oberauer et al., 2007). Greater AC may help maintain the integrity of this process by mitigating attentional capture at a time when PM is susceptible to intrusion from SM (Cosman & Vecera, 2013; Dreisbach & Wenke, 2011; Mayr, Kuhns, & Hubbard, 2014; Richter & Yeung, 2012). Therefore, it was hypothesized that PM would be positively related to breaking mental set, but primarily for individuals with higher AC.

Additionally, we expected that SM would facilitate retrieval of the complex strategy (Harrison et al., 2015; Verguts & De Boeck, 2002) and thus bias suboptimal persistence in this approach on the critical problems (Beilock & DeCaro, 2007). Specifically, SM may support the ability to retrieve information consistent with prior knowledge or experience. Greater AC may enable the tendency of higher SM individuals to do so by facilitating the identification of retrieval cues consistent with prior knowledge or experience (Hills, Todd, & Goldstone, 2010; Liesefeld, Hoffmann, & Wentura, 2016; Lilienthal, Rose, Tamez, Myerson, & Hale, 2015; Unsworth, Brewer, & Spillers, 2013). Therefore, we hypothesized that SM would be negatively related to breaking mental set, but primarily for individuals with higher AC.

Although Shipstead et al. (2014) found that variance unique to running span measures of WMC was strongly related to more commonly used measures of PM (e.g., immediate free recall, forward digit span), it is unclear whether the ability to disengage from no-longer-relevant information is uniquely tapped by the running span. Therefore, an additional goal of Study 2 was to validate the use of the running span task as a marker of PM in the hypothesized model. To accomplish this goal, running span scores were split by trial type (i.e., whole recall versus partial recall) and treated as separate markers of PM.

As illustrated in Fig. 3, *whole recall trials* require remembering all letters from lists that are 3–7 letters long, whereas *partial recall trials* require remembering the last 3–7 letters from lists that are 4–9 letters long (see Table 6). Partial recall trials are thus distinguished from whole recall trials by the presence of distractors, in the form of "to-be-forgotten" items (i.e., letters appearing at the beginning of the list that are not required at recall). In contrast, whole recall trials are identical to trials on classic PM capacity tasks, such as the forward digit span, except the occurrence of whole recall trials is unpredictable within each block of the running span (Morris & Jones, 1990; Mukunda & Hall, 1992; Palladino & Jarrold, 2008).

Table 6
List length by target length (n), trial type (whole recall, partial recall), and distractors (m) for all trials in the Running Span task.

n	Whole recall trials	Partial recall trials	
	$m = 0$	$m = 1$	$m = 2$
3	3	4	5
4	4	5	6
5	5	6	7
6	6	7	8
7	7	8	9

Note: n = the number of targets (i.e., to-be-remembered letters) from end of list; m = the number of distractors (i.e., letters preceding targets); list length = $m + n$. Trials were presented in blocks of three ($m = 0$, $m = 1$, $m = 2$) according to n, in random order. The order of trials within each block was random. n was displayed at the beginning of each block.

In the current study, running span performance was examined separately by trial type in order to assess PM with and without the presence of distractors. Additionally, an immediate free recall task was included to compare the predictive utility of the running span measures. Immediate free recall is a traditional measure of PM that requires participants to recall a given list of words in any order (Unsworth, Spillers, & Brewer, 2010).

The presence of distractors, in the form of a secondary processing component, distinguishes complex span tasks from traditional measures of PM (Shipstead et al., 2014)—a distinction that has received exhaustive treatment in the literature (e.g., Colom, Rebollo, Abad, & Shih, 2006; Daneman & Merikle, 1996; Unsworth & Engle, 2007b). All span tasks are thought to involve some element of distraction, and thus require SM, to the extent that memory items become displaced from PM and must be retrieved at recall (Unsworth & Engle, 2006, 2007b). Given that the presence of distractors in span tasks is thought to increase reliance on SM, we hypothesized that running span partial recall scores would be less likely to evidence the expected conditional positive relationship with breaking mental set than running span whole recall and immediate free recall markers of PM.

4.1. Method

4.1.1. Participants

Undergraduate students (N = 191; 134 females; M_{age} = 20 years, SD = 4.5) participated for psychology course credit. An a priori power analysis (G*Power; Faul, Erdfelder, Lang, & Buchner, 2007) indicated that a minimum of 68 participants was required. Thus, the sample was more than sufficient to detect a medium-sized effect ($f^2 = 0.15$, $1 - \beta > 0.80$, $\alpha = 0.05$; Cohen, 1992) for the moderation analyses described below. Exclusion criteria were the same as in Study 1. Seventeen additional participants were removed for (a) committing > 20 errors on the math portion of the operation span (n = 5; Conway et al., 2005), (b) prior exposure to the water jug problems (n = 2), or (c) identification as a univariate outlier (i.e., scores > 3 SDs from scale means; n = 10). Eighty of the total 191 participants (42%) solved all three set problems and were thereby deemed to have established mental set.

4.1.2. Procedure and tasks

Participants in Study 2 performed the same three WMC tasks (antisaccade, running span, and operation span), and the same problem-solving task (water jug), as in Study 1. Study 2 deviated from Study 1 as follows: (a) running span scores were split by trial type, (b) participants additionally performed an immediate free recall task, and (c) participants performed the water jug task first, followed by the WMC tasks in counterbalanced order.

4.1.2.1. Running span task (Broadway & Engle, 2010). As described above and in Study 1, the running span task required participants to remember the last 3–7 letters from lists that were 3–9 letters long. The dependent variables were the total number of to-be-remembered letters correctly recalled in the correct serial position (regardless of whether the entire sequence of letters was correct) on whole recall trials (5 trials, 25 letters) and partial recall trials (10 trials, 50 letters).

4.1.2.2. Immediate free recall task (Unsworth et al., 2010). Participants were shown a list of 8 words and asked to recall the words in any order. All words were common nouns containing 3–5 letters and one syllable. Each word was presented for 750 ms, followed by a 250 ms delay. Immediately following each list (2 practice, 7 critical), participants were given 1 min to type as many of the words as possible. Estimates of PM were derived using the Tulving and Colotla (1970) scoring method (see Shipstead et al., 2014). If seven or fewer words fell between presentation and recall of a given word within each list, it was deemed recalled from PM. The dependent variable was the total number of words correctly recalled from PM (regardless of order) across all critical lists, out of 56 possible.

4.2. Results and discussion

Operational definitions of individual differences in AC, PM, and SM were the same as in Study 1, except that multiple measures of PM were examined (i.e., running span whole recall, running span partial recall, and immediate free recall). Model assumptions were tested using the same method as described in Study 1 and no evidence for violations were found (VIFs < 1.35).

4.2.1. Set problems

Descriptive statistics and zero-order correlations among predictor variables and set problems correctly solved, for all participants, are presented in Table 7. The number of set problems solved was significantly positively associated with all of the WMC measures except immediate free recall. Additionally, the number of set problems solved was significantly negatively associated with the number of critical problems solved using simple strategies (M = 1.30, SD = 1.23, $r(189) = -0.20$, p = .006).

4.2.1.1. Moderation analyses. Next, we examined whether AC moderated the relationships between PM and SM, and success on set problems. We regressed the number of set problems solved on antisaccade (AC), operation span (SM), and either running span whole recall (PM, Model 1), running span partial recall (PM, Model 2), or immediate free recall (PM, Model 3), together with product terms for the two interactions of interest (i.e., AC × PM, AC × SM). All predictor variables were mean centered.

Table 8
Moderation analyses predicting the number of set problems solved for all participants in Study 2.

Model	Predictor	β	t	Sig.	sr^2
1	Antisaccade (AC)	0.21	2.77	**0.006**	0.04
	Running span *whole recall* (PM)	0.10	1.34	0.183	0.01
	Operation span (SM)	0.02	0.20	0.841	0.00
	AC × PM	−0.01	−0.08	0.940	0.00
	AC × SM	−0.09	−1.13	0.261	0.01
2	Antisaccade (AC)	0.19	2.37	**0.019**	0.03
	Running span *partial recall* (PM)	0.11	1.35	0.178	0.01
	Operation span (SM)	0.02	0.29	0.772	0.00
	AC × PM	−0.03	−0.41	0.683	0.00
	AC × SM	−0.07	−0.87	0.383	0.00
3	Antisaccade (AC)	0.21	2.79	**0.006**	0.04
	Immediate free recall (PM)	0.01	0.14	0.888	0.00
	Operation span (SM)	0.05	0.58	0.566	0.00
	AC × PM	−0.04	−0.55	0.582	0.00
	AC × SM	−0.08	−1.03	0.307	0.01

Note. AC = attention control; PM = primary memory; SM = secondary memory. All variables reflect mean-centered scores treated as continuous variables. N = 191.

These three models yielded similar results (Table 8). Each model significantly accounted for 7–8% of the variance in success on set problems [Model 1: $R^2 = 0.08$, $F(5, 185) = 3.16$, p = .009; Model 2: $R^2 = 0.08$, $F(5, 185) = 3.21$, p = .008; Model 3: $R^2 = 0.07$, $F(5, 185) = 2.82$, p = .018]. Each model also resulted in a significant simple effect of antisaccade. These findings indicate that higher AC was associated with greater success on set problems, regardless of which measure was used to index PM. No simple effects of PM or SM were found, and no interactions were obtained. Removing these non-significant interactions from the models did not change the results. These findings indicate that the magnitude and direction of the relationship between AC and success on the set problems did not depend on individual differences in either PM or SM. Thus, consistent with Study 1, AC was important for establishing mental set.

4.2.2. Critical problems

Descriptive statistics and zero-order correlations among predictor variables and critical problems solved using the simple strategies, for individuals who established mental set (i.e., correctly solved all three set problems; n = 80), are presented in Table 9. The number of critical problems solved using simple strategies was not significantly associated with any of the other variables. Additionally, errors on critical problems

Table 7
Descriptive statistics and zero-order correlations among predictor variables and set problems solved for all participants in Study 2.

Measure	Mean	SD	Skew	Kurtosis	Correlations (r)					
					1	2	3	4	5	6
1. Antisaccade	00.76	00.14	−0.43	−0.59	(0.81)					
2. RunSpan whole recall	17.49	04.62	−0.73	0.54	0.19**	(0.62)				
3. RunSpan partial recall	22.55	06.95	0.30	0.12	0.34**	0.57**	(0.62)			
4. Operation span	53.95	14.10	−1.02	0.76	0.35**	0.29**	0.32**	(0.87)		
5. Immediate free recall	26.23	05.13	0.52	−0.03	0.05	0.18**	0.25**	0.04	(0.66)	
6. Set problems solved	01.85	01.16	−0.43	−1.32	0.24**	0.15*	0.19**	0.15*	0.03	(0.71)

Note. Cronbach's alpha reliability estimates are on the diagonal. N = 191.
* p < .05.
** p < .01.

Table 9
Descriptive statistics and zero-order correlations among predictor variables and critical problems solved using simple strategies for individuals who established mental set in Study 2.

Measure	Mean	*SD*	Skew	Kurtosis	Correlations (*r*)					
					1	2	3	4	5	6
1. Antisaccade	00.80	00.12	−0.49	−0.50	(0.80)					
2. RunSpan whole recall	18.30	04.32	−1.07	1.94	0.21	(0.63)				
3. RunSpan partial recall	23.74	06.83	0.08	0.38	0.31**	0.56**	(0.63)			
4. Operation span	55.95	12.67	−1.24	1.73	0.36**	0.17	0.27*	(0.85)		
5. Immediate free recall	26.26	04.97	0.66	0.26	−0.02	0.28**	0.28**	0.06	(0.65)	
6. Critical problems solved using simple strategies	00.94	01.15	0.79	−0.93	0.20	0.10	−0.14	−0.19	0.08	(0.78)

Note. Cronbach's alpha reliability estimates are on the diagonal. $n = 80$.
* $p < .05$.
** $p < .01$.

were low (i.e., < 10% of all answers provided failed to produce the goal quantity), indicating that when these individuals were not using the simple strategies, they were using the complex strategy the majority of the time. The simple (i.e., one-step) strategies were more efficient than the complex (i.e., multistep) strategy: The more critical problems solved using the simple strategies, the faster were mean response times for critical problems correctly solved ($M = 16.08$ s, $SD = 9.17$ s, $r(59) = -0.41$, $p = .001$).[3]

4.2.2.1. Moderation analyses. The principal research question for Study 2 was whether AC moderates the relationships between breaking mental set and both PM and SM. The three models tested had equivalent predictors, except for the measure used to index PM. PM was assessed by running span whole recall (Model 1), running span partial recall (Model 2), and immediate free recall (Model 3). The number of critical problems solved using simple strategies was regressed on AC, PM, SM, and the two hypothesized interactions (AC × PM, AC × SM). Models 1–3 significantly accounted for 24% ($F(5, 74) = 4.72$, $p = .001$), 22% ($F(5, 74) = 4.12$, $p = .002$) and 24% ($F(5, 74) = 4.70$, $p = .001$) of the variance in simple strategy use, respectively.

In each model (Table 10), there was a significant simple effect of antisaccade, indicating that AC was significantly positively associated with simple strategy use. Each model also showed a significant simple effect of operation span, indicating that SM was significantly negatively associated with simple strategy use. No simple effect of PM was found in any of the models. However, as predicted, significant AC × PM and AC × SM interactions were obtained, with the exception of the non-significant AC × PM interaction in Model 2 (using running span partial recall). Separate hierarchical regression analysis of the same variables confirmed that the joint contribution of the two interaction terms (entered in step 2) was significant in Model 1, $\Delta R^2 = 0.11$, $p = .007$, and Model 3, $\Delta R^2 = 0.10$, $p = .009$, but not in Model 2, $\Delta R^2 = 0.06$, $p = .052$. These findings suggest that running span whole recall and immediate free recall provided more valid estimates of PM than running span partial recall in the hypothesized model. Thus, Model 2 will not be analyzed further.

4.2.2.2. Simple slope analyses. The significant interactions found in Models 1 and 3 were further examined using simple slope analyses (Cohen, Cohen, West, & Aiken, 2003). For each interaction, the relationship between the focal predictor (i.e., PM or SM) and the number of critical problems solved using simple strategies was plotted and tested at higher and lower levels of AC (centered one standard deviation above and below the mean, respectively). Plots include point estimates with 95% confidence intervals for higher and lower levels of the focal predictor (also centered one standard deviation above and below the mean).

Table 10
Moderation analyses predicting the number of critical problems solved using simple strategies for individuals who established mental set in Study 2.

Model	Predictor	β	*t*	Sig.	sr^2
1	Antisaccade (AC)	0.31	2.77	**0.007**	0.08
	Running span *whole recall* (PM)	0.12	1.10	0.275	0.01
	Operation span (SM)	−0.39	−3.40	**0.001**	0.12
	AC × PM	0.28	2.59	**0.012**	0.07
	AC × SM	−0.30	−2.65	**0.010**	0.07
2	Antisaccade (AC)	0.36	3.16	**0.002**	0.11
	Running span *partial recall* (PM)	−0.17	−1.50	0.138	0.02
	Operation span (SM)	−0.36	−3.04	**0.003**	0.10
	AC × PM	0.15	1.38	0.172	0.02
	AC × SM	−0.27	−2.32	**0.023**	0.06
3	Antisaccade (AC)	0.26	2.36	**0.021**	0.06
	Immediate free recall (PM)	−0.01	−0.12	0.904	0.00
	Operation span (SM)	−0.37	−3.21	**0.002**	0.11
	AC × PM	0.28	2.48	**0.016**	0.06
	AC × SM	−0.29	−2.56	**0.013**	0.07

Note. AC = attention control; PM = primary memory; SM = secondary memory. All variables reflect mean-centered scores treated as continuous variables. $n = 80$.

First, we examined the interaction between AC and PM. Specifically, we tested the relationship between simple strategy use and PM—as indexed by either running span whole recall (Model 1) or immediate free recall (Model 3)—when AC was one standard deviation above and below the mean. As shown in Fig. 5, these tests revealed strikingly similar results. For individuals higher in AC, PM was significantly positively associated with simple strategy use in Model 1 ($\beta = 0.41$, $t(74) = 2.45$, $p = .016$, $sr^2 = 0.06$) and Model 3 ($\beta = 0.24$, $t(74) = 2.10$, $p = .039$, $sr^2 = 0.04$). For individuals lower in AC, no relationship between PM and simple strategy use was found [Model 1: $\beta = -0.17$, $t(74) = -1.23$, $p = .221$; Model 3: $\beta = -0.27$, $t(74) = -1.50$, $p = .136$]. These results indicate that higher PM leads to a greater likelihood of breaking mental set, but only for individuals higher in AC. These findings are consistent with the overall positive association found between PM (indexed by running span total scores) and breaking mental set in Study 1 and reveal a possible boundary condition for this relationship. Specifically, the current findings suggest that PM relies on AC to support breaking mental set.

Next, we examined the interaction between AC and SM. Again, results were similar across models. As shown in Fig. 6, SM was significantly negatively associated with simple strategy use for individuals higher in AC in Model 1 ($\beta = -0.69$, $t(74) = -3.73$, $p < .001$, *sr*

[3] To ensure that the RT measure was based on an equal number of observations for each participant, 18 participants who committed a combined total of 22 errors on the critical problems, and 1 additional participant whose RT exceeded that of every other by a factor of 3, were excluded from this analysis. However, including these participants did not change the pattern of results ($M = 18.86$ s, $SD = 12.73$ s, $r(78) = -0.36$, $p = .001$).

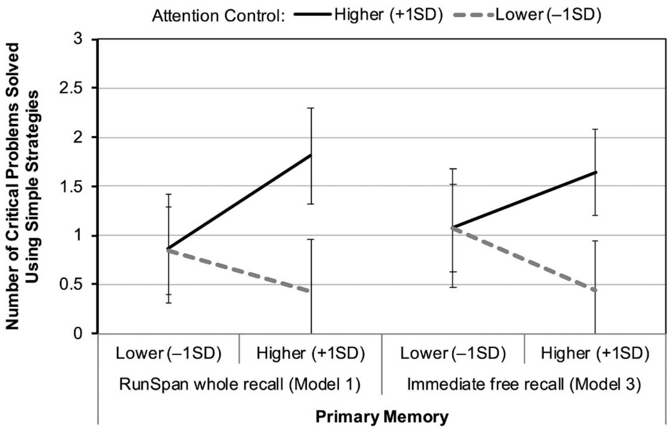

Fig. 5. Number of critical problems solved using simple strategies as a function of individual differences in attention control and primary memory in Study 2. Primary memory is indexed by running span whole recall (Model 1; left) and immediate free recall (Model 3; right). Error bars represent 95% confidence intervals.

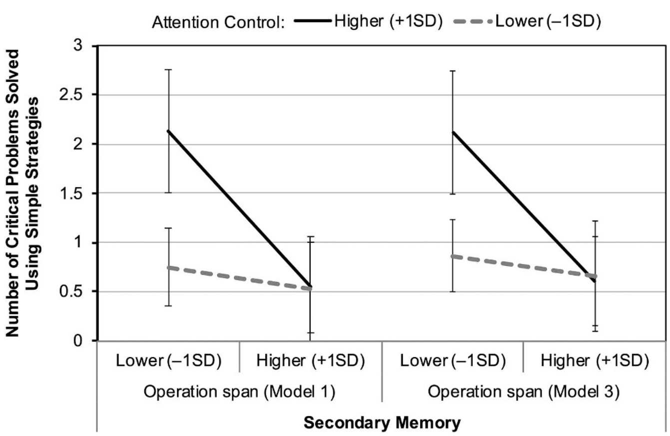

Fig. 6. Number of critical problems solved using simple strategies as a function of individual differences in attention control and secondary memory in Study 2. Primary memory is indexed by running span whole recall (Model 1; left) and immediate free recall (Model 3; right). Error bars represent 95% confidence intervals.

^{2} = 0.14) and Model 2 (β = −0.65, $t(74) = -3.57$, $p < .001$, $sr^2 = 0.13$). For individuals lower in AC, the relationship between SM and simple strategy use was not statistically significant [Model 1: β = −0.09, $t(74) = -0.74$, $p = .460$; Model 3: β = −0.28, $t(74) = -1.51$, $p = .136$]. These results indicate that higher SM leads to a lower likelihood of breaking mental set when combined with higher AC. These findings are consistent with the negative association observed between SM and breaking mental set in Study 1 but suggest that SM relies on AC to constrain breaking mental set.

In sum, simple slope analyses revealed that greater flexibility on critical problems was attained by individuals higher in both AC and PM, as well as individuals higher in AC but lower in SM. These results were the same regardless of whether PM was indexed by running span whole recall or immediate free recall, indicating that these measures provided comparable estimates of PM in the hypothesized model.

4.2.3. Conclusions

Study 2 offered additional support for our hypotheses based on the theory of functional opponency in WMC. Furthermore, Study 2 provided initial support for the novel hypothesis that AC moderates the relationships between breaking mental set and both PM and SM. Due to the larger sample in Study 2, a greater number of individuals established mental set. This sample size allowed for a more thorough examination of the relationship between AC and breaking mental set than was possible in Study 1. Additionally, Study 2 showed consistency between two measures of PM (running span whole recall and immediate free recall tasks), demonstrating that the PM results in Study 1 are not limited to the running span task. Moreover, we found that PM tasks that do not include distractors (running span whole recall and immediate free recall) had greater predictive utility in the hypothesized model than a task that includes distractors (running span partial recall). The latter may place comparatively greater demands on SM.

Although Study 2 replicated the results of Study 1, and further developed the theory of functional opponency by examining the role of AC in breaking mental set, one limitation of both of these studies is that the water jug task required participants to discover the complex strategy to solve the first three problems without assistance. Breaking mental set could only be examined for those who solved all three set problems and were thus deemed to have established mental set in the first place. This criterion drastically limited the critical sample size, and potentially introduced a selection bias (e.g., limiting our conclusions to those within a restricted range of AC scores). Study 3 addressed this limitation by using a modified version of the water jug task, designed to retain a higher proportion of participants in the critical sample.

5. Study 3

Study 3 further examined the hypothesis that AC moderates the relationships between the ability to break mental set and both PM and SM, using a modified version of the water jug task. Specifically, all participants were given an additional practice problem that used the same complex strategy as the set problems. After solving, they received feedback and a worked example of the problem solution. The goal of this modification was to equalize knowledge of the complex strategy in order to obtain a larger and more representative sample for analyzing strategy use (i.e., breaking mental set) on the critical problems. We hypothesized that we would replicate the critical problem results of Study 2, even though individuals were provided with the complex strategy prior to the set problems.

Study 3 also tested the novel hypothesis that AC moderates the relationship between SM and establishing mental set on the modified water jug task. Attention control may support the ability to form an initial problem representation (Chein & Weisberg, 2014; see DeCaro et al., 2016). On the standard water jug task (Studies 1 and 2), discovering the complex strategy needed to solve the set problems may rely on the ability to form an initial mental representation of the water jug problems. On the modified water jug task, we expected that providing the complex strategy would decrease reliance on the ability to form an initial problem representation (and thus AC) for establishing mental set. Instead, we expected the modified water jug task to increase reliance on SM for correctly retrieving and executing the complex strategy that had just been demonstrated. Additionally, we reasoned that AC would support the use of SM on the set problems, analogous to the way AC supported retrieval of this same strategy on the critical problems in Study 2. Therefore, we hypothesized that SM would be positively associated with success on the set problems at higher levels of AC. Finding that AC and SM interact to predict both stability on the set problems and flexibility on the critical problems in opposite directions would provide convergent support for the proposed the theory of functional opponency in WMC.

5.1. Method

5.1.1. Participants

Participants were undergraduate students ($N = 182$; 108 females, 74 males; $M_{age} = 20$ years, $SD = 3.5$) who participated for psychology course credit. Sample size was based on the same a priori power analysis used in Study 2. Exclusion criteria were the same as in Studies 1

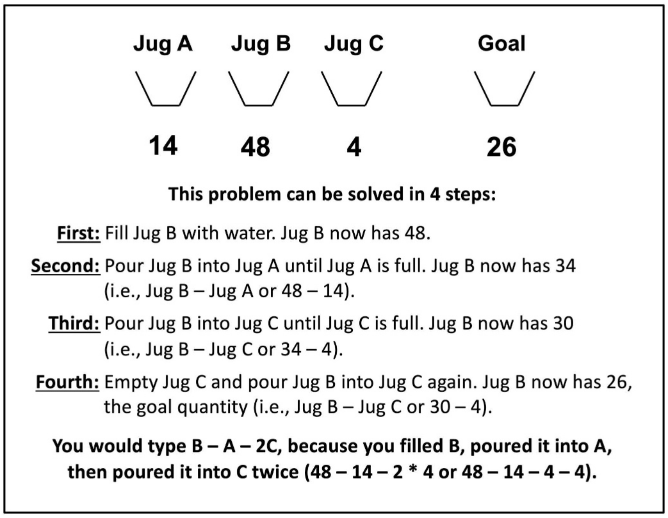

Fig. 7. Worked example set problem used in Study 3.

and 2. Nineteen additional participants were removed for (a) committing > 20 errors on the math portion of the operation span ($n = 7$; Conway et al., 2005), (b) prior exposure to the water jug problems ($n = 1$), or (c) identification as a univariate outlier (i.e., scores > 3 SDs from scale means; $n = 11$).

5.1.2. Procedure and tasks

Study 3 consisted of the same procedure and tasks as Study 1, with the following exceptions: (a) like Study 2, participants performed the water jug task first, followed by the WMC tasks in counterbalanced order, (b) running span performance was examined only for whole recall trials, and (c) participants performed a modified version of the water jug task.

5.1.2.1. Modified water jug task. Problems and procedure were the same as in Studies 1 and 2, except that after the first practice problem, participants were given a second practice problem that required use of the complex strategy for its solution (Fig. 7). Participants were given two attempts to solve the second practice problem with feedback ("correct" or "incorrect") before seeing a worked example that explained the solution. Two incorrect responses prompted the worked example screen, followed by a final opportunity to enter the correct response before proceeding to the experimental problems (set then critical problems). To control for possible differences in participants' mental representation of the problems resulting from seeing the worked example, individuals who correctly solved the example problem on their first or second attempt were also shown the worked example before proceeding to the experimental problems. Again, individuals were deemed to have established mental set if they correctly solved the three subsequent set problems.

5.2. Results and discussion

Analyses were conducted using the same approach as in Study 2, except that only 1 PM measure was used, and therefore one model was tested for each dependent variable. Residuals and scatterplots indicated the assumptions of normality and homoscedasticity were met, and VIF values (< 1.5) indicated that multicollinearity was not an issue.

5.2.1. Set problems

Descriptive statistics and zero-order correlations among predictor variables and set problems correctly solved, for all participants, are presented in Table 11. The number of set problems solved was significantly positively associated with operation span, but not significantly associated with antisaccade or running span whole recall. Additionally, the number of set problems solved was significantly negatively associated with the number of critical problems solved using the simple strategies ($M = 0.82$, $SD = 1.12$, $r(180) = -0.22$, $p = .003$), demonstrating again that the ability to establish mental set is negatively related to the ability to break it.

5.2.1.1. Moderation analysis. Next, we examined whether AC moderated the relationships between PM and SM, and success on set problems for the modified water jug task. The number of set problems solved was regressed on antisaccade (AC), running span whole recall (PM), and operation span (SM), together with product terms for the two interactions (i.e., AC × PM, AC × SM; see Table 12). This model significantly accounted for 7% of the variance in simple strategy use, $F(5, 176) = 2.66$, $p = .024$. There was a significant simple effect of operation span, demonstrating that SM was significantly positively associated with success on the set problems. There was also a positive but non-significant simple effect of antisaccade. No simple effect of running span whole recall was found, and no AC × PM interaction was obtained. As predicted, a significant AC × SM interaction was found. Removing the non-significant interaction from the model did not change these results.

5.2.1.2. Simple slope analysis. We further examined the significant AC × SM interaction by testing simple slopes. As shown in Fig. 8, for individuals higher in AC, SM was significantly positively associated with the number of set problems solved ($\beta = 0.36$, $t(176) = 3.10$, $p = .002$, $sr^2 = 0.05$). For individuals lower in AC, the relationship between SM and the number of set problems solved was not significant ($\beta = 0.02$, $t(176) = 0.23$, $p = .815$). These results indicate that individuals higher in SM were more likely to use the complex strategy, and establish mental set, if they were also higher in AC. Specifically, greater ability to efficiently retrieve previously used strategies via SM (Harrison et al., 2015), when coupled with a stable focus of attention, may facilitate performance on familiar problems.

5.2.2. Critical problems

Descriptive statistics and zero-order correlations among predictor variables and critical problems solved using the simple strategies, for individuals who established mental set (i.e., correctly solved all three set problems), are presented in Table 13. The modification made to the water jug task had the intended result of increasing the proportion of individuals included in the critical sample (by over 20%). Of the 182 total participants, 124 (69%) solved all three set problems and were thereby deemed to have established mental set. The number of critical problems solved using simple strategies was significantly positively associated with antisaccade, but not significantly associated with running span whole recall or operation span. Consistent with Studies 1 and 2, errors on critical problems were low (i.e., < 7% of all answers provided failed to produce the goal quantity), indicating that when these individuals were not using the simple strategies, they were using the complex strategy the majority of the time. Furthermore, the simple (i.e., one-step) strategies were again found to be more efficient than the complex (i.e., multistep) strategy: The more critical problems solved using the simple strategies, the faster were mean response times for critical problems correctly solved ($M = 18.30$ s, $SD = 12.50$ s, $r(98) = -0.20$, $p = .044$).[4]

[4] To ensure that the RT measure was based on an equal number of observations for each participant, 23 participants who committed a combined total of 25 errors on the critical problems, and 1 additional participant whose RT exceeded that of every other by a factor of 3, were excluded from this analysis. However, including these participants did not change the pattern of results ($M = 20.86$ s, $SD = 20.20$ s, $r(122) = -0.18$, $p = .046$).

Table 11
Descriptive statistics and zero-order correlations among predictor variables and set problems solved for all participants in Study 3.

Measure	Mean	*SD*	Skew	Kurtosis	Correlations (*r*)			
					1	2	3	4
1. Antisaccade	00.79	00.13	−0.54	−0.61	(0.81)			
2. RunSpan whole recall	17.63	04.42	−0.40	0.10	0.26**	(0.60)		
3. Operation span	58.63	11.57	−0.97	0.73	0.18*	0.27**	(0.80)	
4. Set problems solved	02.50	00.86	−1.75	2.15	0.08	0.04	0.17*	(0.66)

Note. Cronbach's Alpha reliability estimates are on the diagonal. $N = 182$.
* $p \leq .05$.
** $p < .01$.

Table 12
Moderation analysis predicting the number of set problems solved for all participants in Study 3.

Predictor	β	*t*	Sig.	sr^2
Antisaccade (AC)	0.15	1.96	0.052	0.02
Running span whole recall (PM)	−0.07	−0.81	0.416	0.00
Operation span (SM)	0.19	2.44	**0.016**	0.03
AC × PM	−0.02	−0.20	0.842	0.00
AC × SM	0.18	2.31	**0.022**	0.03

Note. AC = attention control; PM = primary memory; SM = secondary memory. $N = 182$.

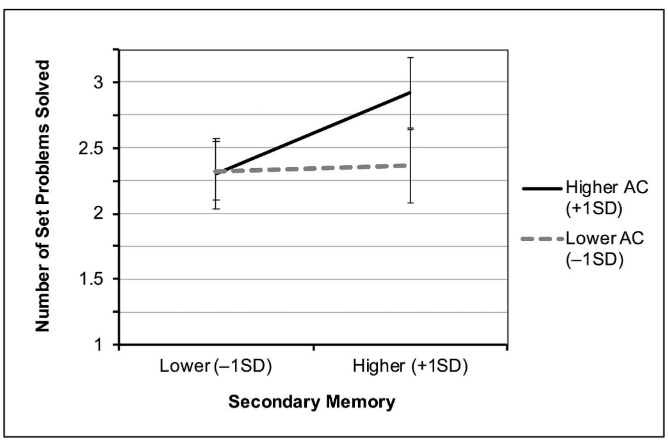

Fig. 8. Number of set problems solved as a function of individual differences in secondary memory and attention control (AC) in Study 3. Error bars represent 95% confidence intervals.

5.2.2.1. Moderation analyses. The number of critical problems solved using simple strategies was regressed on antisaccade (AC), running span whole recall (PM), operation span (SM), and the two hypothesized interactions (i.e., AC × PM, AC × SM). This model significantly accounted for 17% of the variance in simple strategy use, $F(5, 118) = 4.96$, $p < .001$.

Table 14
Moderation analysis predicting the number of critical problems solved using simple strategies for individuals who established mental set in Study 3.

Predictor	β	*t*	Sig.	sr^2
Antisaccade (AC)	0.24	2.54	**0.013**	0.04
Running span whole recall (PM)	0.27	2.71	**0.008**	0.05
Operation span (SM)	−0.40	−3.92	**0.000**	0.11
AC × PM	0.21	2.23	**0.028**	0.03
AC × SM	−0.25	−2.51	**0.013**	0.04

Note. AC = attention control; PM = primary memory; SM = secondary memory. $n = 124$.

As shown in Table 14, significant simple effects of antisaccade and running span whole recall were found, indicating that both AC and PM were positively associated with simple strategy use. There was also a significant simple effect of operation span, indicating that SM was negatively associated with simple strategy use. As predicted, significant AC × PM and AC × SM interactions were obtained. Hierarchical regression confirmed that the joint contribution of the two interaction effects (terms entered in step 2) was signficant, $\Delta R^2 = 0.06$, $p = .017$.

5.2.2.2. Simple slope analyses. The relationships between the number of critical problems solved using the simple strategies and both PM and SM was examined at higher and lower levels of AC (± 1 standard deviation). As shown in Fig. 9, results mirrored those of Study 2. For individuals higher in AC, PM was significantly positively associated with simple strategy use ($\beta = 0.44$, $t(118) = 3.07$, $p = .003$, $sr^2 = 0.07$). For individuals lower in AC, the relationship between PM and simple strategy use was not significant ($\beta = 0.09$, $t(118) = 0.86$, $p = .389$). Thus, individuals higher in PM were more likely to break mental set if they were also higher in AC.

Conversely, SM was significantly negatively associated with simple strategy use for individuals higher in AC ($\beta = -0.62$, $t(118) = -3.87$, $p < .001$, $sr^2 = 0.10$). For lower AC individuals, no significant relationship between SM and simple strategy use was found ($\beta = -0.19$, $t(74) = -1.82$, $p = .071$). These findings indicate that individuals

Table 13
Descriptive statistics and zero-order correlations among predictor variables and critical problems solved using simple strategies for individuals who established mental set in Study 3.

Measure	Mean	*SD*	Skew	Kurtosis	Correlations (*r*)			
					1	2	3	4
1. Antisaccade	00.80	00.13	−0.62	−0.44	(0.81)			
2. Run span whole recall	17.69	04.43	−0.50	0.52	0.27**	(0.62)		
3. Operation span	59.75	10.80	−0.99	0.57	0.32**	0.30**	(0.80)	
4. Critical problems solved using simple strategies	00.60	01.02	1.44	0.58	0.22*	0.14	−0.13	(0.82)

Note. Cronbach's Alpha reliability estimates are on the diagonal. $n = 124$.
* $p < .05$.
** $p < .01$.

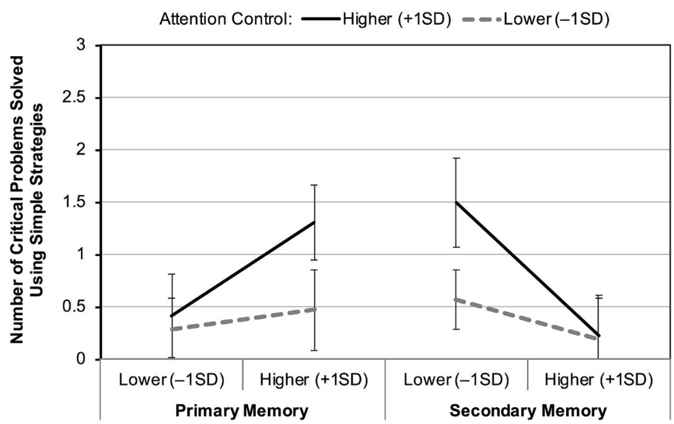

Fig. 9. Number of critical problems solved using simple strategies as a function of individual differences in primary memory and attention control (left), and secondary memory and attention control (right) for individuals who established mental set in Study 3. Error bars represent 95% confidence intervals.

lower in SM were more likely to break mental set if they were also higher in AC.

5.2.3. Conclusions

Using a modified water jug task, Study 3 replicated the results of Studies 1 and 2 by demonstrating that PM and SM have divergent impacts on breaking mental set, and that AC moderates these effects. These findings indicate results did not depend on whether individuals discovered the complex strategy freely (Study 2) or by example (Study 3). Study 3 also provided support for the novel hypothesis that AC moderates the relationship between SM and establishing mental set when the set procedure is provided in advance. This finding suggests that higher AC not only exacerbates the negative relationship between SM and breaking mental set, but also amplifies the positive relationship between SM and establishing mental set. By demonstrating convergent, functionally opponent effects across problem types, Study 3 strengthens the validity of the underlying theory of functional opponency in WMC (Schmidt, 2009).

6. General discussion

Although cognitive flexibility is often considered a hallmark of high WMC, high WMs also sometimes persist in using suboptimal strategies (e.g., Beilock & DeCaro, 2007; Fischer & Holt, 2017; Richmond et al., 2015). The present research examined a novel account for these seemingly contradictory findings: that WMC both supports and constrains cognitive flexibility via functionally opposing mechanisms.

Study 1 offered initial support for the proposed theory of functional opponency by demonstrating that different WMC mechanisms (PM and SM) predict the same cognitive flexibility outcome ("breaking" mental set on the critical water jug problems) in opposite directions. Study 2 replicated the basic pattern of results from Study 1, while also demonstrating that AC moderates these effects. Study 3 demonstrated that the same pattern of results can be obtained using a less restrictive methodology (i.e., by providing a worked example of the complex strategy needed to solve the set problems).

These findings offer at least three important contributions to the literature. First, the theory of functional opponency may be used to help explain disparate effects in prior studies examining the role of WMC in creativity and insight problem solving. Second, the results of Study 2 provide insight into how PM is measured and conceptualized. Finally, by demonstrating interactions between AC and PM, and AC and SM, our findings build upon and expand research on WMC.

6.1. WMC and creativity research

A perennial question in the creativity and insight problem-solving literatures is whether creative thinking is supported by more or less WM-dependent processes. Across studies, WMC has shown positive, negative, and null associations with creativity and insight tasks (DeCaro, 2018; Gilhooly & Webb, 2018). Some researchers maintain a strong stance in one direction, for example arguing that WMC can only be viewed as positively supporting insight (e.g., Chuderski & Jastrzębski, 2017). Others reason that important individual, task, and situational moderators may impact whether WMC benefits or hinders creativity or insight (DeCaro, 2018). For example, WMC may be important for some creativity measures and not others (DeCaro et al., 2017; Gilhooly & Webb, 2018). In the present work, we take a different approach to this question by examining a single creative process (i.e., breaking mental set) and measuring multiple WMC mechanisms. Our studies suggest that creative processes rely on some WMC mechanisms and not others. Thus, the way WMC is measured may also account for disparities across studies. By considering the WMC task(s) used to assess individual differences, researchers might also gain insights into the mechanisms at work in previous studies.

For example, Beilock and DeCaro (2007) and Ricks, Turley-Ames, and Wiley (2007) found that higher WMC was associated with greater mental set and reduced creativity, respectively. Relying on an executive attention view, these researchers posited that high WMs are better able to inhibit seemingly irrelevant strategies, leading them to overlook simpler or more creative solutions (see also Wiley & Jarosz, 2012). However, WMC was measured using complex span tasks, used to index SM in the current studies (i.e., operation span). Thus, these prior results may have instead been driven primarily by SM. Greater ability (and thus tendency) to retrieve previously used strategies may have led individuals to persist in using these strategies, curtailing search for alternative solutions.

Note, however, that individual differences in AC and PM were not controlled for in these previous studies, and thus may have impacted the results. In the current studies, zero-order correlations between operation span and breaking mental set were negative but significant only in Study 1. These findings suggest that negative relationships with SM may still be found without partialling out AC and PM, but the effect may be underestimated.

Thus, prior studies demonstrating negative relationships between WMC and creativity may be showing an effect of SM. It is also possible that studies demonstrating positive effects are driven by PM. However, these effects may be underestimated to the extent that a WMC measure conflates AC, PM, and SM. Moreover, the interaction effects found in the current studies suggest that these divergent effects may be strongest for individuals who are also better able to maintain the task goal in the first place—i.e., those with higher AC. Thus, a more nuanced view of WMC aligns with the perspective that the relationship between WMC and creativity is complex, and provides more leverage for interpreting prior results.

6.2. Measuring primary memory

PM has been conceptualized as the ability to disengage from no-longer-relevant information, based on the strong, positive association between PM and Gf (Shipstead et al., 2014). However, the relationship between PM and breaking mental set has not been examined. As breaking mental set on the critical water jug problems requires abandoning previously used strategies (i.e., those needed to solve the set problems), these results further validate the notion of PM as disengagement.

However, Study 2's findings demonstrate that closer inspection of the measures used to assess PM as disengagement is needed. In keeping with Shipstead et al. (2014), we used the running span to index individual differences in PM. Furthermore, we tested whole recall versus partial recall running span trials as separate markers of PM. We reasoned that, compared to whole recall, partial recall requires an additional distractor-processing component, increasing reliance on SM (Poole & Kane, 2009; Unsworth & Engle, 2007b). Whole recall trials, and not partial recall trials, were positively associated with breaking mental set. The whole recall results most mirrored those of immediate free recall, a more traditional measure of PM that consists only of whole recall trials (Unsworth et al., 2010).

These findings suggest that greater absolute PM capacity (i.e., the maximum amount of information that can be maintained in the focus of attention; Cowan et al., 2005) is positively related to the ability to break mental set (Oberauer et al., 2007; Shipstead et al., 2014). We suggest that the relationship between PM and breaking mental set may be driven by disengagement—the breaking of temporary bindings between attention and active mnemonic representations, allowing for novel combinations to be generated (see also Shipstead et al., 2016; Singh et al., 2018). However, more work is needed to better understand the exact nature (and direction) of this relationship, for example by experimentally manipulating flexibility versus stability demands for a given task (cf. Richmond et al., 2015).

6.3. Interactions with attention control

The present research also sheds light on the dual role that AC plays in establishing and breaking mental set. For the set problems, AC was positively associated with accuracy in Studies 1 and 2. This effect went away in Study 3, when the complex solution was given to participants. These results suggest that AC was critical to discovering the complex solution. In Study 3, when participants did not need to discover the solution, we found an interaction between AC and SM. Higher AC appears to have instead helped individuals use SM to apply the given solution on the set problems. Similarly, in Studies 2 and 3, we found interactions between AC and the other two WMC mechanisms on the critical problems. Higher AC again helped individuals with higher SM apply the complex solutions to the problems, increasing mental set. At the same time, higher AC supported the work of PM in breaking mental set.

Prior studies have not examined interactions between AC and PM, or AC and SM, and thus our approach is novel. However, this approach aligns with Engle's (2018) most updated view of WMC (see also Shipstead et al., 2016). In contrast to previous views considering WMC as a unitary construct (Engle, 2002), Engle (2018) argues for three separable functions: disengagement, maintenance, and ability to control attention (akin to PM, SM, and AC in the multifaceted view). Engle notes that measures of disengagement and maintenance are often highly correlated, and reasons that "both abilities rely on the ability to control attention to do the mental work necessary to either maintain information or to disengage from information" (p. 193). This statement could be interpreted to mean simply that AC must be partialed out in order to assess either outcome. However, we interpret it to suggest an interaction effect—i.e., all tasks likely require some degree of goal maintenance and thus benefit from higher AC. Our results support this interpretation of Engle's (2018) updated view of WMC. Future research would benefit from adding multiple indicators of each construct (PM, SM, and AC) and even greater sample sizes, to further test these ideas.

Future studies may benefit from testing AC as a moderator for both new and established WMC effects. Further research is also needed to develop a better understanding of the interplay of WMC mechanisms. For example, we did not have sufficient power, or theoretical justification, to test a potential interaction between all three WMC mechanisms. Thus, our studies cannot speak to cases such as when an individual is high on AC, PM, and SM (but see Unsworth et al., 2014). Research examining intra-individual differences in WMC mechanisms may offer further insights in the dynamic nature of cognitive abilities.

6.4. Conclusion

The multifaceted view of WMC provides new opportunities for reexamining classic effects and long-standing assumptions (e.g., Shipstead et al., 2016). The present research extends the multifaceted view of WMC by demonstrating that WMC mechanisms sometimes show opposing patterns of correlations with other measures. These findings have important implications for individual differences research. The theory of functional opponency in WMC cautions against simple low/high WMC dichotomies, suggesting that characteristics of "high WMs" can lead to conflicting patterns of results. A better understanding of how WMC mechanisms both independently and jointly support and constrain cognitive performance may further the development of effective training regimens and intervention strategies to facilitate learning and problem solving across the lifespan (Ionescu, 2019).

CRediT authorship contribution statement

Charles A. Van Stockum, Jr.: Conceptualization, Methodology, Software, Investigation, Formal analysis, Writing - original draft, Visualization, Writing - review & editing. **Marci S. DeCaro:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision.

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