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Functional opponency in working memory capacity predicts cognitive flexibility in problem solving.

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FUNCTIONAL OPPONENCY IN WORKING MEMORY CAPACITY PREDICTS COGNITIVE FLEXIBILITY IN PROBLEM SOLVING

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ABSTRACT

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Cognitive flexibility is a hallmark of individuals with higher working memory capacity (WMC). Yet, research demonstrates that higher WMC individuals are sometimes more likely to adopt rigid problem-solving approaches. The present research examines a novel account for these contradictory findings—that different WMC mechanisms interact in ways that both support and 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 using a complex strategy. Participants then completed measures targeting three WMC mechanisms: attention control, primary memory, and secondary memory. Study 1 demonstrated that primary memory and secondary memory predict breaking mental set in opposite directions. Study 2 replicated these findings while also demonstrating that attention control moderates these effects. Study 3 replicated these results using a less restrictive sampling procedure (i.e., participants were provided the complex strategy). The present research supports the proposed theory of functional opponency in WMC.

Keywords: working memory; cognitive flexibility; attention; problem solving; mental set

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CHAPTER I

INTRODUCTION

Working memory capacity (WMC) helps keep cognitive processes (memory and attention) organized around task-relevant information (Adam & Vogel, 2016; Awh & Vogel, 2008; Conway, Cowan, & Bunting, 2001). Individual differences in WMC thereby predict many and varied cognitive abilities (Alloway & Alloway, 2010; 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; Oberauer, Schulze, Wilhelm, & Süß, 2005). High WMs are also better able to implement complex, cognitively-demanding strategies than lower WMC individuals (low WMs; Barrett, Tugade, & Engle, 2004; Fischer, & Holt, 2017; Gonthier & Thomassin, 2015; Richmond, Redick, & Braver, 2015; Thomassin, Gonthier, Guerraz, & Roulin, 2015). These abilities enable high WMs to better adapt to novel or changing task demands (Bleckley, Durso, Crutchfield, Engle, & Khanna, 2003; Colflesh & Conway, 2007; Gulbinaite, van Rijn, & Cohen, 2014; Rummel & Boywitt, 2014; Shipstead & Broadway, 2013; Weldon, Mushlin, Kim, & Sohn, 2013; Wiley, Jarosz, Cushen, & Colflesh, 2011)—a hallmark of *cognitive flexibility* (Collins & Koechlin, 2012; 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 (e.g., Campbell, Hasher, & Thomas, 2010; Woehrle & Magliano, 2012; see 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 (Beilock & DeCaro, 2007; DeCaro, Thomas, & Beilock, 2008; see also Fischer, & Holt, 2017; Ricks, Turley-Ames, & Wiley, 2007). This tendency can lead to cognitive *in*flexibility, or *mental set* (Bilalić, McLeod, & Gobet, 2010; Schultz & Searleman, 2002). These and related findings challenge the assumption that "more" cognitive abilities are always "better" (e.g., Beier & Oswald, 2012; Newell, 2015; cf. Bocanegra & Hommel, 2014; Chrysikou, Weber, & Thompson-Schill, 2014; Hills & Hertwig, 2011), the basis for a billion-dollar industry devoted to cognitive training and enhancement (Hayes, Petrov, Sederberg, 2015; Matzen et al., 2016; Redick, Shipstead, Wiemers, Melby-Lervåg, & Hulme, 2015; Rabipour & Raz, 2012; Simons et al., 2016).

Thus, research appears contradictory—indicating that high WMs are both more cognitively flexible and inflexible than low WMs. How can we explain that WMC seems to be both positively and negatively related to cognitive flexibility? The answer may depend on how researchers have chosen to characterize WMC in the first place. That is, it is customary to treat WMC as a unitary construct, and the preponderance of positive associations in cognitive performance research (i.e., "positive manifold") constitutes a strong prior (Beier & Oswald, 2012; Chuderski & Jastrzębski, 2017). To overcome such a prior, further evidence that WMC either positively or negatively predicts cognitive flexibility may be less important than a theory for how asymmetrical findings such as these are even possible (see DeCaro, Van Stockum, & Wieth, 2016, 2017; DeCaro, 2018). A framework for treating WMC as a multifaceted construct may accommodate such contradictions, allowing a more comprehensive account of the relationship between WMC and cognitive flexibility to be articulated.

Mechanisms of Working Memory Capacity

Traditionally, WMC is treated as a unified construct reducible to individual differences in a single, critical component (e.g., temporary memory storage capacity, attention control; Cowan et al., 2005; Engle, 2002; Just & Carpenter, 1992; Kane, Bleckley, Conway, & Engle, 2001), or as the overall effectiveness (e.g., processing efficiency) of a hierarchically organized system (e.g., Conway & Engle, 1996; Harrison, Shipstead, & Engle, 2015; McCabe, Roediger, McDaniel, Balota, & Hambrick, 2010; Wilhelm, Hildebrandt, & Oberauer, 2013).

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, 2016a, for a review). These studies support a *multifaceted view* of WMC that emphasizes the distinct contributions of three related mechanisms. *Attention control* (AC) is the ability to constrain focal attention to relevant information and restrain inappropriate reflexive thoughts and responses (Hasher, Zacks, & May, 1999; Kane & Engle, 2003; McVay & Kane, 2012). *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; Unsworth & Engle, 2006). *Secondary memory* (SM) is the ability to access or recover information via strategic search and retrieval processes (Unsworth &

Engle, 2007a; Unsworth, 2016b; Unsworth & Spillers, 2010). These mechanisms have been found to vary both between and within individuals, and jointly account for the relationship between WMC and Gf (Shipstead et al., 2014; Unsworth et al., 2014).

The multifaceted view thus seeks to parse the predictive power of the WMC construct 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). Importantly, tasks commonly used to assess individual differences in WMC place greater demands on some of these mechanisms over others. For example, Shipstead and colleagues (2014) demonstrated that running span tasks (e.g., running letter span: remember the last *n* letters from lists that are $n + m$ letters long; Broadway & Engle, 2010) reflect PM more strongly than complex span tasks. Complex span tasks (e.g., operation span: remember a series of letters while alternately verifying solutions to simple math equations; Redick et al., 2012) are more closely associated with AC and SM (see also Healey & Miyake, 2009; Unsworth & Engle, 2007b; Unsworth & Spillers, 2010). Furthermore, running span measures of WMC include a component of PM that is not reflected in complex span measures.

Shipstead and colleagues 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 (Shipstead et al., 2014; see also Oberauer, Süß, Wilhelm, & Sander, 2007; Wiley et al., 2011). However, this PM mechanism of disengagement has not been tested as a predictor of cognitive flexibility.

The multifaceted view of WMC provides new opportunities to revisit classic effects and reexamine long-standing assumptions to generate novel hypotheses that better capture the interplay of WMC mechanisms (e.g., Engle, 2018; Martin et al., 2017; Redick et al., 2016; Sattizahn, Moser, & Beilock, 2016; Shipstead, Harrison, & Engle, 2016). One method for developing a deeper understanding of the multifaceted nature of WMC is by investigating interactions between AC, PM, and SM in the prediction of various outcomes. Of note, classic and contemporary definitions of WMC cite the importance of both memory *and* attention (Badre, 2011; Engle & Kane, 2004; Hutchinson & Turk-Browne, 2012; Mackie, Van Dam, & Fan, 2013; Richter & Yeung, 2012; Shipstead et al., 2016; Summerfield, Lepsien, Gitelman, Mesulam, & Nobre, 2006; Unsworth & Engle, 2007a). However, investigations of interactions between memory and attention are virtually nonexistent in the WMC literature (but see Sattizahn et al., 2016). Perhaps most importantly, a better understanding of how WMC mechanisms interact may clarify seemingly contradictory findings within the literature (see Stroebe & Strack, 2014).

Cognitive Flexibility versus Cognitive Stability

The virtues of "being flexible" are extolled in colloquial discourse—and for good reason: *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 (Collins & Koechlin, 2012; Ionescu, 2012). Greater cognitive flexibility is associated with favorable outcomes throughout the lifespan, including early math and reading skills (Yeniad, Malda, Mesman, van IJzendoorn, & Pieper, 2013), emotional resilience and psychological health in adulthood (Bonanno, Papa, Lalande, Westphal, & Coifman, 2004; Kashdan & Rottenberg, 2010), and fitness and mobility in older adults (Berryman et al., 2013).

Equal and opposite to cognitive flexibility stands *cognitive stability*, the ability to maintain goals and goal-relevant information in the face of distraction (Armbruster, Ueltzhöffer, Basten, & Fiebach, 2012; Cools & D'Esposito, 2011). 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). When an individual demonstrates excessive cognitive stability and resists adaptive changes, cognitive rigidity can occur (e.g., Altamirano, Miyake, & Whitmer, 2010; Joormann, Levens, & Gotlib, 2011). *Cognitive rigidity* (Schultz & Searleman, 2002) is characteristic of several psychiatric and neurologic disorders, including Parkinson's disease (Kehagia, Barker, & Robbins, 2014), autism spectrum disorder (Miller, Ragozzino, Cook, Sweeney, & Mosconi, 2015), and anorexia nervosa (Lao-Kaim et al., 2015). It is thus unsurprising that increasing cognitive flexibility is a goal of many cognitive and behavioral training and enhancement regimens (Coubard, Duretz, Lefebvre, Lapalus, & Ferrufino, 2011; Diamond, 2012; Masley, Roetzheim, & Gualtieri, 2009; Moore & Malinowski, 2009; Ritter et al., 2012).

The notion that goal-directed behavior relies on a cognitive system that is simultaneously both stable and flexible has been described as a *control dilemma* (Bilder, 2012; Blackwell & Munakata, 2014; Goschke, 2000; Hills & Hertwig, 2011), as there are both adaptive and maladaptive aspects to each process. For instance, cognitive flexibility helps facilitate adaptive changes (e.g., updating goals based on new information, switching between multiple goals), and thus combats cognitive rigidity, which can occur in cases of excessive cognitive stability. In contrast, cognitive stability assists individuals with remaining on-task and focused on goal-oriented behaviors, and thus combats distraction, which can occur in cases of excessive cognitive flexibility (e.g., Dreisbach & Goschke, 2004; Dreisbach & Wenke, 2011). Because cognitive stability and flexibility subserve functionally opposing goals, they sometimes conflict (Badre & Wagner, 2006; Hazy, Frank, & O'Reilly, 2007; Miyake & Friedman, 2012; see Herd et al., 2014, for a review). The relationship between cognitive stability and flexibility is thus characterized as one of "functional opponency" (Goschke, 2000).

Functional opponency is based on the theory that adaptive biological and cognitive abilities function "meaningfully" only within a system of constraints (Badre, 2011; Cohen, Aston-Jones, Gilzenrat, 2004; Hertwig & Todd, 2003). Opponent functions within a system are antagonistic (i.e., more of one, less of the other), resulting in trade-offs (Durstewitz and Seamans, 2008). A system is adaptive to the extent that opponent functions are appropriately balanced (e.g., maximally aligned to current demands on the system of the environment), minimizing trade-offs and optimizing overall function (Cools & D'Esposito, 2011; Chrysikou et al., 2014; Hills & Hertwig, 2011).

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 (e.g., Chiew & Braver, 2017; Cools & D'Esposito, 2011; Ionescu, 2017). Individual differences in these abilities may contribute to an imbalance between stable versus flexible cognition. WMC is an important predictor of cognitive control (e.g., D'Esposito & Postle, 2015; Engle, 2010; Gulbinaite et al., 2014); thus, individual differences in WMC mechanisms may reflect functional opponency. Indeed, contradictory findings within the WMC and cognitive flexibility literature appears to support the notion that functional opponency is at play.

Because cognitive stability and flexibility reflect a dynamic adaptive system, no task can be considered a “process-pure” measure of either. In particular, it is difficult to imagine a task that does not require some degree of goal maintenance (i.e., cognitive stability; Shipstead et al., 2014; Engle, 2018). Thus, different measures of cognitive flexibility may rely on cognitive stability to a greater or lesser extent (Chrysikou et al., 2014). Indeed, the extent to which the flexible behavior being measured is made possible by stable cognitions may help explain why some measures of cognitive flexibility tend to correlate either positively or negatively with WMC.

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 et al., 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 (Bunge & Zelazo, 2006; Dajani & Uddin, 2015; Kim, Johnson, Cilles, & Gold, 2011). 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 tend to correlate negatively with WMC are those that require flexible problem-solving (e.g., mental set and insight problem-solving tasks; Beilock & DeCaro, 2007; Van Stockum & DeCaro, 2014; 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, 2005). *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; Verguts & De Boeck, 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 Fischer & Holt, 2017, for a similar finding). *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 et al., 2016; Öllinger, Jones, & Knoblich, 2008). Mental set and insight problem-solving tasks demonstrate how old strategies may hinder new solutions (Collins & Koechlin, 2012; Knoblich, Ohlsson, Haider, & Rhenius, 1999). Thus, cognitive flexibility tasks that tend to correlate negatively with WMC may rely on flexibility to a greater extent than stability (Barbey, Colom, & Grafman, 2013; Chrysikou et al., 2014).

Thus, 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.

Present Research

The principal goal of the present research was to test the novel hypothesis that WMC simultaneously supports and constrains cognitive flexibility, using a single outcome measure. To accomplish this goal, three studies were conducted. An overview of general methodology and hypotheses common to each study is provided here. Methods and hypotheses specific to each study are presented in their corresponding sections (Chapters 2–4). Goals for each study are summarized at the end of this section.

Cognitive Flexibility

In each study, cognitive flexibility was measured using a classic "mental set" problem-solving task—Luchins's (1942) water jug task. This task requires individuals to discover a complex, multistep strategy to solve a series of problems (see Figure 1). This strategy may be used for all subsequent problems. However, halfway through the task, simpler, single step strategies can also be correctly applied to solve the remaining problems. Of interest is whether individuals flexibly switch to the simpler strategies when they become available (i.e., "break" mental set).

The water jug problems and procedure were the same as used by Beilock and DeCaro (2007). The first three problems ("set problems") were intended to induce mental set, and thus could only be solved using the complex strategy. Individuals were deemed to have “established” mental set if they correctly solved the set problems. The last three problems (“critical problems”) were used to assess cognitive flexibility, as indexed by the number of problems solved using the simpler strategies. Importantly, participants were informed that multiple solutions might be possible and instructed to find the simplest solution.

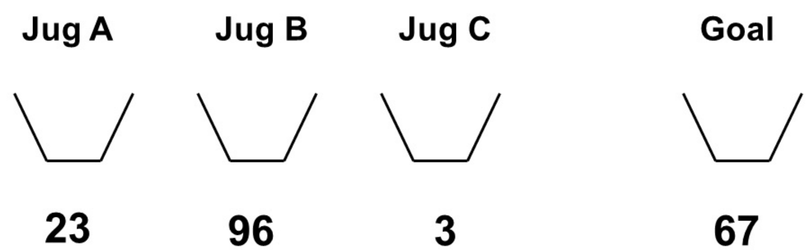

Figure 1. Example water jug set problem. Participants mentally derived a formula to obtain a “goal” quantity of water by using three jugs (A, B, and C) of various ungraduated capacities and a hypothetical unlimited water supply. All six experimental problems were solvable by the formula B − A − 2C (i.e., 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).

Working Memory Capacity Mechanisms

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 & Engle, 2003; Roberts, Hager, & Heron, 1994).

The running span task requires remembering the last *n* items from lists *n* + *m* items long (Pollack, Johnson, & Knaff, 1959). Critically, participants do not know how many items will be presented in a given trial (i.e., participants are told *n*, but not *m*). In the version of the running span used in the present research, letters were presented at a rate of two per second (Broadway & Engle, 2010; see also Shipstead et al., 2014). This 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, for a review).

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

Shipstead and colleagues (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, described above. 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.

General Analyses

For all studies, a manipulation check was first conducted by correlating the number of set problems solved and the number of critical problems solved via the simple strategies. This analysis determined whether success on the set problems was negatively associated with flexibility on the critical problems, indicating mental set was obtained overall. Then, regression analyses were conducted to test ancillary hypotheses regarding the ability to establish mental set (as indexed by the number of set problems solved) and its relations to WMC mechanisms (i.e., AC, PM, and SM).

For individuals who established mental set (i.e., solved all three set problems correctly), the correlation between the number of critical problems solved via the simple strategies and mean response times for critical problems correctly solved (regardless of which strategy was used) was examined to determine whether the expected negative association between simple strategy use and response times was obtained. Then, regression analyses were conducted to test principal hypotheses regarding the relationships between WMC mechanisms (AC, PM, and SM) and the ability to break mental set (as indexed by the number of critical problems solved via the simple strategies).

Hypotheses

General hypotheses common to each study were made for both set problems and critical problems.

Set problems. It was expected that AC would support the ability to form an initial mental representation of the water jug problems (DeCaro, 2018; DeCaro et al., 2016; Wiley et al., 2011), leading to greater accuracy on problems requiring the complex strategy. Therefore, it was predicted that individuals higher in AC would be more likely to establish mental set.

The set problems were not expected to place relatively higher demands on either stability or flexibility. Thus, it was predicted that establishing mental set would not be significantly related to either SM or PM. The relationship between establishing mental set and SM is further examined in Study 3.

Critical problems. It was expected that PM would facilitate disengagement from the complex strategy (Shipstead et al., 2014) and allow novel combinations of information to be generated (Oberauer et al., 2007), resulting in more frequent use of the simple strategies. Therefore, it was predicted that individuals higher in PM would be more likely to break mental set.

It was 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; DeCaro et al., 2008), resulting in less frequent use of the simple strategies. Therefore, it was 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, it was predicted that individuals higher in AC would be more likely to break mental set. 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.

Study Goals

Three studies were conducted in order to establish support for the hypothesized model, replicate findings and validate measures, and further explore and test boundary conditions. Study 1 examined whether different WMC mechanisms (AC, PM, and SM) differentially predict breaking mental set on the water jug task. Study 2 replicated Study 1 with a larger sample, examined multiple measures of PM, and tested for moderation between AC and each of the two memory-based WMC mechanisms (i.e., PM and SM). Study 3 utilized a modified water jug task designed to increase the likelihood that participants established mental set, in order to test the hypothesized effects with a more general sample.

CHAPTER II

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. It was predicted that the WMC mechanisms would predict performance on the water jug task in different directions.

Method

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 more than 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 greater than 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.

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.

Working Memory Capacity Tasks

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 Figure 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).

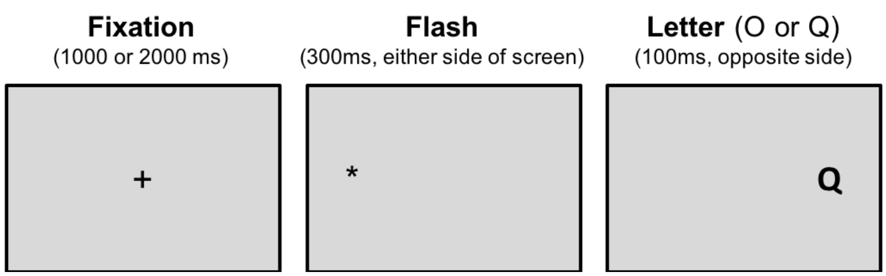

Figure 2. Example of the antisaccade task. The antisaccade requires resisting attentional capture in the face of distraction (i.e., "look away from the flash").

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 3–9 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 Figure 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).

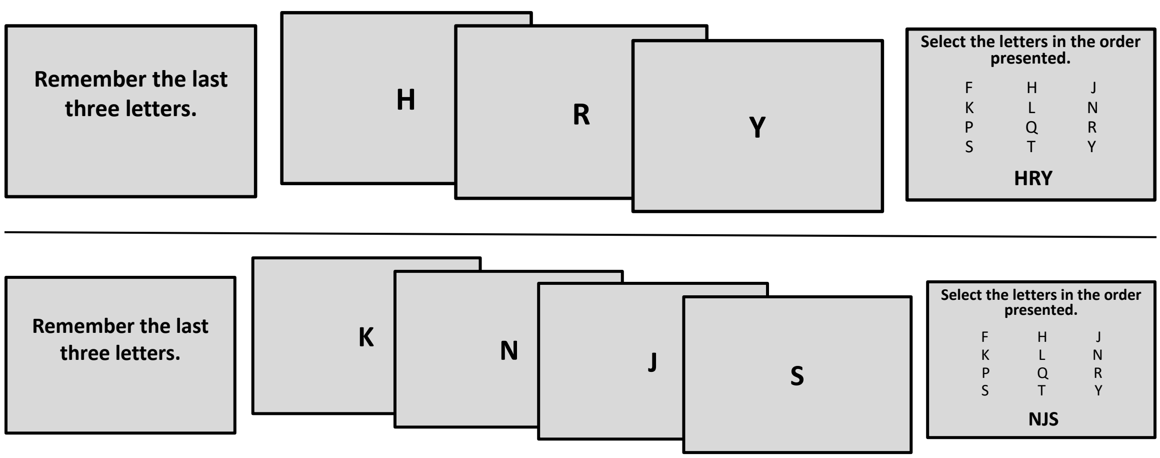

Figure 3. Example of the running span task: whole recall trial (top) and partial recall trial (bottom). The running span requires remembering the last 3–7 letters from series of 3–9 letters.

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 Figure 4). Following a sequence of problem-letter strings ranging from 3-7 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).

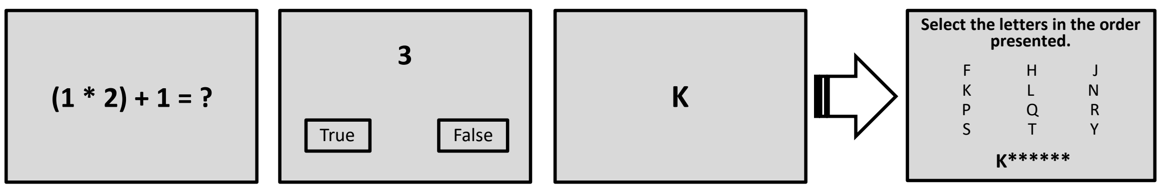

Figure 4. Example of the operation span task. The operation span requires remembering series of 3-7 letters while alternately verifying solutions to simple math equations.

Problem-Solving Task

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, and participants were asked to solve the problems mentally and then type their solutions (no paper was provided). 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 Figure 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.

Table 1
Water Jug problems.

	Jug			
Problem	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

Results and Discussion

Variables and Analyses

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), 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.

All multiple linear regressions were inspected for normality using normal Q-Q plots and histograms of studentized residuals. Homoscedasticity of error variance was assessed using scatterplots of studentized residuals versus standardized predicted values. Collinearity was examined using variance inflation factors (VIFs). For each regression in Study 1, studentized residuals showed little deviation from normality. Likewise, scatterplots did not reveal any clear patterns of data spread, indicating that homoscedasticity was adequate. VIFs did not exceed 1.4 for any of the predictors in either model (any value below 10 was deemed acceptable), indicating that multicollinearity was not an issue.

Set Problems

Descriptive statistics and intercorrelations among key variables 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 not 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) = −.22, *p* = .050). This finding 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 mental set resulted from prior experience or domain-specific knowledge (e.g., Bilalić et al., 2010; Crooks & McNeil, 2009; Ellis & Reingold, 2014; Wiley, 1998).

Table 2

Descriptive statistics and intercorrelations among key variables ***for all participants*** *in Study 1.*

			Correlations (*r*)			
Measure	Mean	*SD*	1	2	3	4
1. Antisaccade	00.82	00.09	—			
2. Running span	25.90	10.02	.16	—		
3. Operation span	59.78	08.98	.33**	.43**	—	
4. Set problems	01.89	01.24	.27*	.08	.15	—

N = 81. **p* < .05, ***p* < .01.

Next, it was 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 (β = .25, *p* = .036), but not running span (β = .01, *p* = .925) or operation span (β = .06, *p* = .630). These results indicate that AC (i.e., variance unique to the antisaccade when controlling for the other predictors in the model) was significantly positively associated with success on the set problems and thus important for establishing mental set. This finding corresponds with work linking AC to the ability to mentally represent novel problems and execute multistep operations (see DeCaro et al., 2016).

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)	.25	2.14	**.036**	.05
Running span (PM)	.01	0.09	.925	.00
Operation span (SM)	.06	0.48	.630	.00

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

Critical Problems

Because mental set must be established before it can be broken, performance on critical problems was examined only for those who solved the set problems (n = 39; see Beilock & DeCaro, 2007; Gasper, 2003). Descriptive statistics and intercorrelations among key variables for individuals who established mental set (i.e., correctly solved all three set problems) 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, it was 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 (regardless of which strategy was used) (M = 22.17 sec, SD = 14.70 sec, $r(30)$ = −.49, p = .004)[1].

Table 4

Descriptive statistics and intercorrelations among key variables ***for individuals who established mental set*** *in Study 1.*

			Correlations (r)		
Measure	Mean	*SD*	1	2	3
1. Antisaccade	00.84	00.09	—		
2. RunSpan whole recall	26.54	10.55	.12	—	
3. Operation span	60.31	07.52	.21	.38*	—
4. Critical problems solved using simple strategies	01.18	01.25	−.27	.14	−.37*

n = 39. *p < .05, **p < .01.

The principal research question for Study 1 was whether WMC mechanisms differentially predict who is most likely to flexibly switch to 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; see Table 5). Antisaccade was not significantly associated with simple strategy use (β = –.22, p = .153), possibly because the sample included only those individuals who correctly solved the set problems and thereby also had higher AC.

[1] 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).

Operation span was significantly negatively associated with use of the simple strategies (β = –.46, p = .007), 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 cues automatically elicit the wrong information (Verguts & De Boeck, 2002).

In contrast, running span was significantly positively associated with simple strategy use (β = .34, p = .035), 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.

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)	−.22	−1.46	.153	.04
Running span (PM)	.34	2.19	**.035**	.10
Operation span (SM)	−.46	−2.87	**.007**	.17

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

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 et al., 2017). If the current findings reflect a real phenomenon, they would have important ramifications for both theory and practice (see Hills & Hertwig, 2011).

It is standard practice in publications of new effects, especially of effects that are surprising, to publish one or two replications (Stroebe & Strack, 2014). Of note, 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 (cf. Shipstead et al., 2014). Further specification of the source of this effect will clarify interpretation and establish boundary conditions for directing future studies. Thus, Study 2 tests additional markers of individual differences in PM for purposes of comparison.

Finally, a key 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 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.

CHAPTER III

STUDY 2

Study 1 conceptually replicated Shipstead and colleagues' (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 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 moderation analyses of the critical problems. Moderation was also tested for the set problems, but no interactions were predicted because these problems were not expected to place relatively higher demands on either stability or flexibility.

It was hypothesized that individual differences in PM and SM would predict breaking mental set in opposite directions, but only for individuals with higher AC, consistent with the pattern of results observed in Study 1. It was expected that PM would facilitate disengagement from no-longer-relevant information (Shipstead et al., 2014) and thus support breaking mental set. Specifically, disengagement may support breaking mental set by allowing novel combinations of information to be generated (Oberauer et al, 2007). Higher AC may improve 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; Kikumoto, Hubbard, & Mayr, 2016; Mayr, Kuhns, & Hubbard, 2014; Richter & Yeung, 2012; Robison & Unsworth, 2017). Therefore, it was hypothesized that PM would be positively related to breaking mental set, but only for individuals with higher AC.

Additionally, it was 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; DeCaro et al., 2008). Specifically, SM may support the ability to retrieve information consistent with prior knowledge or experience. Higher 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 (Colzato, Steenbergen, & Hommel, 2018; Hills, Todd, & Goldstone, 2010; Liesefeld, Hoffmann, & Wentura, 2015; Lilienthal, Rose, Tamez, Myerson, & Hale, 2015; Schilling, Storm, & Anderson, 2014; Unsworth, Brewer, & Spillers, 2013). Therefore, it was hypothesized that SM would be negatively related to breaking mental set, but only for individuals with higher AC.

Although Shipstead and colleagues (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 utility 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 Figure 3, *whole recall trials* required remembering all letters from lists that were 3–7 letters long, whereas *partial recall trials* required remembering the last 3–7 letters from lists that were 4–9 letters long (a complete breakdown of the running span task by trial parameters is shown in 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 (Blankenship 1938), 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).

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 for purposes of comparing the predictive utility of the two running span trial type measures. Immediate free recall is a traditional measure of PM that requires participants to recall a list of words in any order (Unsworth, Spillers, and Brewer, 2010).

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.

	Whole recall trials	Partial recall trials	
n	$m = 0$	$m = 1$	$m = 2$
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.

The presence of distractors, in the form of a secondary processing component, also 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., Bailey, Dunlosky, & Kane, 2011; Colom, Rebollo, Abad, & Shih, 2006; Engle, Tuholski, Laughlin, & Conway, 1999; Healey & Miyake, 2009; Kane et al., 2004; Unsworth & Engle, 2007b). Indeed, 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 (Faraco et al., 2010; Lewandowsky, Geiger, Morrell, & Oberauer, 2010; Unsworth & Engle, 2006; 2007a, b). Given that the presence of distractors in span tasks is thought to increase reliance on SM, it was 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.

Method

Participants

One hundred ninety-one undergraduate students (134 females, 57 males; M_{age} = 20 years, *SD* = 4.5) participated for psychology course credit. An *a priori* power analysis (G*Power; Faul, Erdfelder, Buchner, & Lang, 2009) indicated that a minimum of 68 participants was required. Thus, the sample was more than sufficient to detect a medium-sized effect [Cohen's (1992) $f^2 = .15$, $1 - \beta > .80$, $\alpha = .05$] for the moderation analyses described below. Exclusion criteria were the same as in Study 1. Seventeen additional participants were removed for (a) committing more than 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 greater than 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.

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. The dependent measure(s) for each task was also the same as in Study 1, except that running span scores were split by trial type. Participants in Study 2 additionally performed an immediate free recall task. The order of the WMC tasks was counterbalanced across participants.

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).

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 minute 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, 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.

Results and Discussion

Variables and Analyses

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). Again, performance on the critical water jug problems was examined only for individuals who established mental set (i.e., correctly solved all three set problems; $n = 80$).

Moderation analyses were conducted using multiple linear regression (Irwin & McClelland, 2001). Each moderated multiple regression model contained three mean-centered continuous predictors (reflecting individual differences in AC, PM, and SM), and product terms for the two interactions of interest (i.e., AC × PM, AC × SM; calculated using the centered variables). Each of the three PM measures (i.e., running span whole recall, running span partial recall, and immediate free recall) was tested separately using the same basic model in which AC and SM were indexed by antisaccade and operation span, respectively. The same three models were applied to each of the two dependent variables (i.e., number of set problems solved, number of critical problems solved using simple strategies). To control for shared variance, predictors and both interaction terms were entered simultaneously. A separate hierarchical regression was used to assess the joint contribution of the two interaction terms (entered in step 2) to model fit as indexed by ΔR^2. Significant interactions were probed using simple slope analyses (see Aiken & West, 1991; Cohen, Cohen, West, & Aiken, 2003). Model assumptions were tested using the same method as described in Study 1 and no evidence for violations were found. VIFs did not exceed 1.35 for any of the predictors across models.

Set Problems

Descriptive statistics and intercorrelations among key variables 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, it was found that 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) = −.20, *p* = .006), consistent with Study 1.

Table 7

Descriptive statistics and intercorrelations among key variables ***for all participants*** *in Study 2.*

			Correlations (*r*)				
Measure	Mean	*SD*	1	2	3	4	5
1. Antisaccade	00.76	00.14	—				
2. RunSpan whole recall	17.49	04.62	.19**	—			
3. RunSpan partial recall	22.55	06.95	.34**	.57**	—		
4. Operation span	53.95	14.10	.35**	.29**	.32**	—	
5. Immediate free recall	26.23	05.13	.05	.18**	.25**	.04	—
6. Set problems solved	01.85	01.16	.24**	.15*	.19**	.15*	.03

N = 191. **p* < .05, ***p* < .01.

Moderation Analyses. Next, it was examined whether AC moderated the relationships between PM and SM, and success on set problems. The number of set problems solved was regressed 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).

These three models yielded similar results (see Table 8). Each model significantly accounted for 7–8% of the variance in success on set problems [Model 1: R^2 = .08, *F*(5, 185) = 3.16, *p* = .009; Model 2: R^2 = .08, *F*(5, 185) = 3.21, *p* = .008; Model 3: R^2 = .07, *F*(5, 185) = 2.82, *p* = .018]. As predicted, each model resulted in a significant simple effect of antisaccade [Model 1: β = .21, *p* = .006; Model 2: β = .19, *p* = .019; Model 3: β

= .21, p = .006]. 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 AC × PM or AC × SM interaction was obtained (all Fs < 1.8, all ps > .17). Removing these non-significant interactions from the models did not change the results. These findings indicate that the magnitude or 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.

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)	.21	2.77	**.006**	.04
	Running span *whole recall* (PM)	.10	1.34	.183	.01
	Operation span (SM)	.02	0.20	.841	.00
	AC × PM	–.01	–0.08	.940	.00
	AC × SM	–.09	–1.13	.261	.01
2	Antisaccade (AC)	.19	2.37	**.019**	.03
	Running span *partial recall* (PM)	.11	1.35	.178	.01
	Operation span (SM)	.02	0.29	.772	.00
	AC × PM	–.03	–0.41	.683	.00
	AC × SM	–.07	–0.87	.383	.00
3	Antisaccade (AC)	.21	2.79	**.006**	.04
	Immediate free recall (PM)	.01	0.14	.888	.00
	Operation span (SM)	.05	0.58	.566	.00
	AC × PM	–.04	–0.55	.582	.00
	AC × SM	–.08	–1.03	.307	.01

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

Critical Problems

Descriptive statistics and intercorrelations among key variables for individuals who established mental set (i.e., correctly solved all three set problems) are presented in Table 9. The number of critical problems solved using simple strategies was not significantly associated with any of the independent variables. Additionally, it was found that errors on critical problems 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. Consistent with Study 1, the simpler (i.e., one-step) strategies were more efficient than the complex (i.e., multistep) strategy: The more critical problems solved using the simpler strategies, the faster were mean response times for critical problems correctly solved (i.e., regardless of which strategy was used) ($M = 16.08$ sec, $SD = 9.17$ sec, $r(59) = -.41$, $p = .001$).[2]

[2] 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 (see Beilock & DeCaro, 2007).

Table 9

Descriptive statistics and intercorrelations among key variables ***for individuals who established mental set*** *in Study 2.*

			Correlations (*r*)				
Measure	Mean	*SD*	1	2	3	4	5
1. Antisaccade	00.80	00.12	—				
2. RunSpan whole recall	18.30	04.32	.21	—			
3. RunSpan partial recall	23.74	06.83	.31**	.56**	—		
4. Operation span	55.95	12.67	.36**	.17	.27*	—	
5. Immediate free recall	26.26	04.97	–.02	.28**	.28**	.06	—
6. Critical problems solved using simple strategies	00.94	01.15	.20	.10	−.14	−.19	.08

n = 80. **p* < .05, ***p* < .01.

Moderation Analyses. The principal research question for Study 2 was whether AC moderates the relationships between breaking mental set and both PM and SM. Again, each measure of PM was tested separately using the same basic model in which AC and SM were indexed by antisaccade and operation span, respectively. The results are described below and summarized in Table 10, followed by simple slope analyses.

In the first model tested, running span whole recall was used to index PM (see Table 10, Model 1). Specifically, 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 (AC × PM, AC × SM). This model significantly accounted for 24% of the variance in simple strategy use, $F(5, 74) = 4.72$, $p = .001$. There were significant simple effects of antisaccade (β = .31, $p = .007$) and operation span (β = –.39, $p = .001$). No simple effect of running span whole recall was found (β = .12, p = .275). However, as predicted, significant AC × PM (β = .28, p = .012) and AC × SM (β = –.30, p = .010) interactions were obtained. A separate hierarchical regression analysis of these same variables confirmed that the joint contribution of the two interaction terms (entered in step 2) was signficant, ΔR^2 = .11, p = .007.

The second model tested was the same as the first, except that running span partial recall was used to index PM (see Table 10, Model 2). This model significantly accounted for 22% of the variance in simple strategy use, $F(5, 74) = 4.12$, p = .002. Consistent with Model 1, there were significant simple effects of antisaccade (β = .36, p = .002) and operation span (β = –.36, p = .003), but not running span partial recall (β = –.17, p = .138). There was also a significant AC × SM interaction (β = –.27, p = .023). However, unlike Model 1, no AC × PM interaction was obtained (β = .15, p = .172). Removing the non-significant interaction did not change these results. Hierarchical regression indicated that the joint contribution of the two interaction terms (entered in step 2) was not signficant, ΔR^2 = .06, p = .052.

The third model tested was the same as the previous two models, except immediate free recall was used to index PM (see Table 10, Model 3). This model significantly accounted for 24% of the variance in simple strategy use, $F(5, 74) = 4.70$, p = .001. Consistent with Models 1 and 2, there were significant simple effects of antisaccade (β = .26, p = .021) and operation span (β = –.37, p = .002), but not immediate free recall (β = –.01, p = .904). Consistent with Model 1, significant AC × PM (β = .28, p = .016) and AC × SM (β = –.29, p = .013) interactions were obtained. Hierarchical regression confirmed that the joint contribution of the two interaction effects (entered in step 2) was signficant, ΔR^2 = .10, p = .009.

In sum, moderation analyses revealed that (a) AC moderated the relationship between PM and simple strategy use when PM was indexed by running span whole recall (Model 1) and immediate free recall (Model 3), but not running span partial recall (Model 2), and (b) AC moderated the relationship between SM and simple strategy use regardless of which variable was used to index PM. These findings suggest that running span whole recall and immediate free recall provided more reliable estimates of PM than running span partial recall in the hypothesized model. Thus, Model 2 will not be analyzed further.

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)	.31	2.77	**.007**	.08
	Running span *whole recall* (PM)	.12	1.10	.275	.01
	Operation span (SM)	–.39	–3.40	**.001**	.12
	AC × PM	.28	2.59	**.012**	.07
	AC × SM	–.30	–2.65	**.010**	.07
2	Antisaccade (AC)	.36	3.16	**.002**	.11
	Running span *partial recall* (PM)	–.17	–1.50	.138	.02
	Operation span (SM)	–.36	–3.04	**.003**	.10
	AC × PM	.15	1.38	.172	.02
	AC × SM	–.27	–2.32	**.023**	.06
3	Antisaccade (AC)	.26	2.36	**.021**	.06
	Immediate free recall (PM)	–.01	–0.12	.904	.00
	Operation span (SM)	–.37	–3.21	**.002**	.11
	AC × PM	.28	2.48	**.016**	.06
	AC × SM	–.29	–2.56	**.013**	.07

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

$n = 80$.

Simple Slope Analyses. The significant interactions found in Models 1 and 3 were further examined using simple slope analyses (see Aiken & West, 1991; Cohen et al., 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 the moderator (i.e., 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, respectively). Tests determined whether each conditional relationship depicted differed statistically from zero. To facilitate comparisons between Models 1 and 3, the results are grouped by the focal predictor.

First, the interaction between AC and PM was examined. Specifically, the relationship between simple strategy use and PM—as indexed by either running span whole recall (Model 1) or immediate free recall (Model 3)—was tested when AC was one standard deviation above and below the mean. As shown in Figure 5, these tests revealed strikingly similar results. For individuals higher in AC, PM was significantly positively associated with simple strategy use in Model 1 ($\beta = .41$, $t(74) = 2.45$, $p = .016$, $sr^2 = .06$) and Model 3 ($\beta = .24$, $t(74) = 2.10$, $p = .039$, $sr^2 = .04$). For lower AC individuals, the relationship between PM and simple strategy use was not statistically different from zero in either model [Model 1: $\beta = -.17$, $t(74) = -1.23$, $p = .221$; Model 3: $\beta = -.27$, $t(74) = -1.50$, $p = .136$].

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 positive association found between PM (as 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.

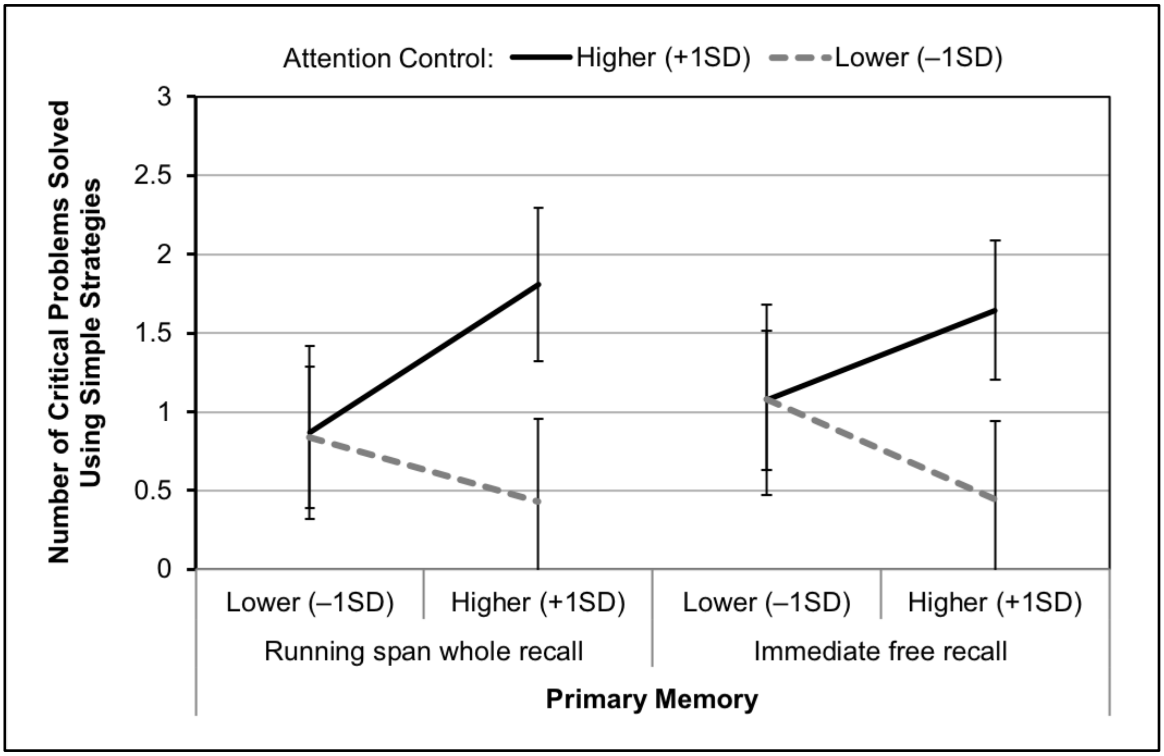

Figure 5. Number of critical problems solved using simple strategies as a function of individual differences in attention control and primary memory as indexed by running span whole recall (Model 1; left) and immediate free recall (Model 3; right) in Study 2. Error bars represent 95% confidence intervals.

Next, the interaction between AC and SM was examined using the method described above. Again, results were similar across models. As shown in Figure 6, SM was significantly negatively associated with simple strategy use for individuals higher in

AC in Model 1 ($\beta = -.69$, $t(74) = -3.73$, $p < .001$, $sr^2 = .14$) and Model 2 ($\beta = -.65$, $t(74) = -3.57$, $p < .001$, $sr^2 = .13$). For lower AC individuals, the relationship between SM and simple strategy use was not statistically different from zero in either model [Model 1: $\beta = -.09$, $t(74) = -0.74$, $p = .460$; Model 3: $\beta = -.28$, $t(74) = -1.51$, $p = .136$].

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, again, reveal a possible boundary condition for this relationship. Specifically, the current findings suggest that SM relies on AC to constrain breaking mental set.

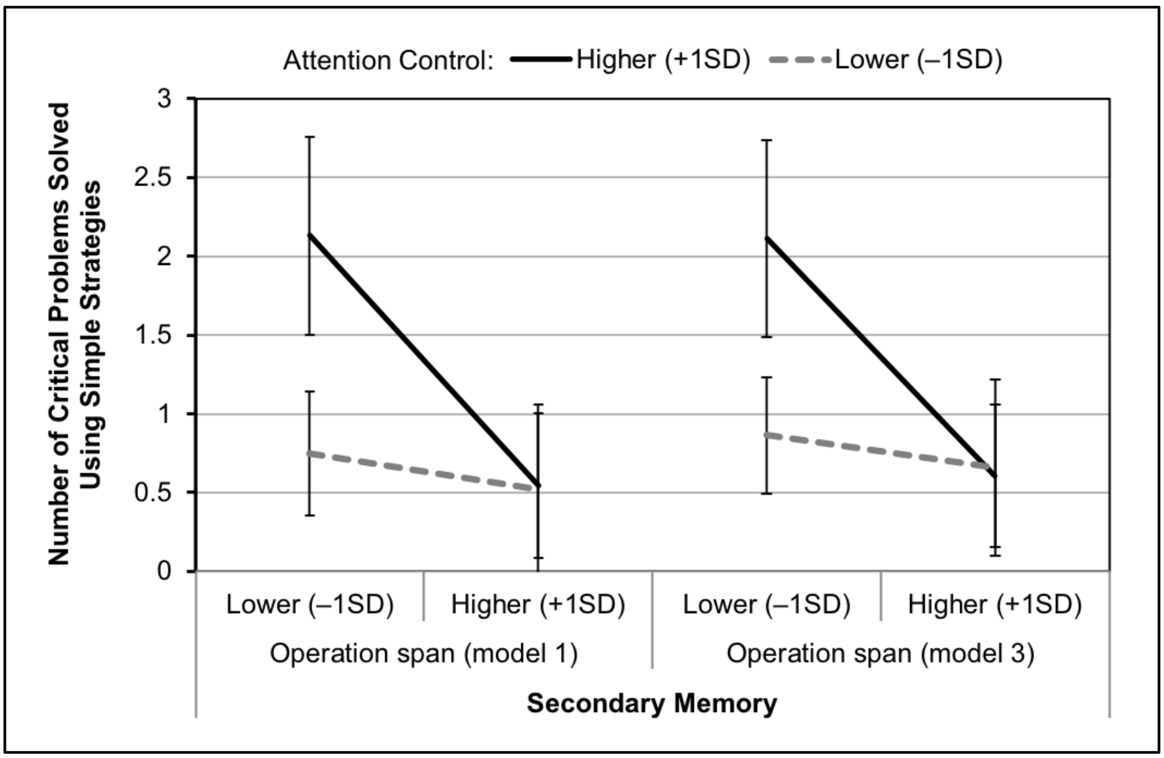

Figure 6. Number of critical problems solved using simple strategies as a function of individual differences in attention control and secondary memory for Model 1 (PM indexed by running span whole recall; left) and Model 3 (PM indexed by immediate free recall; right) in Study 2. Error bars represent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

In sum, simple slope analyses revealed that (a) individuals higher in both AC and PM demonstrated greater flexibility on critical problems, whereas (b) individuals higher in AC but lower in SM demonstrated greater flexibility on critical problems. Furthermore, these results were the same regardless of whether PM was indexed by running span whole recall or immediate free recall. Thus, running span whole recall and immediate free recall provided comparable estimates of PM in the hypothesized model.

Conclusions

Study 2 offered additional support for the theory of functional opponency in WMC, proposed in Study 1. Furthermore, Study 2 provided initial support for the novel hypothesis that AC moderates the relationships between breaking mental set and both PM and SM. By using a larger sample in Study 2, a greater number of individuals established mental set and thus were included in the analysis of breaking mental set. This allowed for a more thorough examination of the relationship between AC and breaking mental set than was possible in Study 1. Additionally, Study 2 demonstrated that some measures of PM had greater predictive utility in the hypothesized model than others. As predicted, PM measures without distractors (i.e., running span whole recall and immediate free recall) evidenced the expected conditional positive relationship with breaking mental set, whereas a PM measure with distractors (i.e., running span partial recall) did not.

One possibility is that the observed patterns of results are specific to the water jug task. Specifically, the version of the water jug task used in Studies 1 and 2 required participants to discover the complex strategy to solve the first three problems without assistance. Breaking mental set could only be examined for those individuals who solved all three set problems and were thus deemed to have initially established mental set.

Thus, analysis of the key variable of interest (i.e., breaking mental set) was restricted to those individuals who demonstrated a related but distinct ability (i.e., the ability to discover the complex strategy). Less than 50% of participants in Studies 1 and 2 correctly solved the first three problems, drastically limiting the critical sample. There is no prior research indicating that the ability to break mental set is contingent upon the ability to independently establish it (Wiley, 1998). Study 3 addresses this limitation by using a modified version of the water jug task, designed to retain a higher proportion of participants in the critical sample.

CHAPTER IV

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. In Study 2, this hypothesis was tested using the same version of the water jug task used in Study 1, but with a larger sample. In the current study, this hypothesis was tested using a modified version of the water jug task, designed to control for individual differences in the ability to discover the complex strategy by providing all participants the answer to the first three problems. Specifically, all participants were instructed on the complex strategy, and required to demonstrate basic comprehension by completing a worked example set problem before proceeding to the experimental problems (see Figure 7). 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 the primary variable of interest (breaking mental set on the critical problems).

It was hypothesized that the conditional relationships between breaking mental set and both PM and SM would be found regardless of whether individuals discovered the complex strategy independently (Study 2) or by learning the complex strategy by example (Study 3).

Study 3 also tested the novel hypothesis 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 (DeCaro, 2018; DeCaro et al., 2016; Wiley et al., 2011). On the standard water jug task (Studies 1 and 2), discovering the complex strategy needed to solve the set problems (and thus establish mental set) may rely on the ability to form an initial mental representation of the water jug problems. On the modified water jug task, providing a worked example of the complex strategy was expected to decrease reliance on the ability to form an initial problem representation (and thus AC) for establishing mental set. Consequently, the modified water jug task was expected to increase reliance on SM for correctly executing the complex strategy as it was demonstrated in the worked example. Finally, if AC supports (suboptimal) retrieval of the complex strategy via SM on the critical problems (Study 2), it may also support (optimal) retrieval of this same strategy on the set problems in the modified water jug task (Duncan, Schramm, Thompson, & Dumontheil, 2012; Sakai, 2008). Therefore, it was predicted 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.

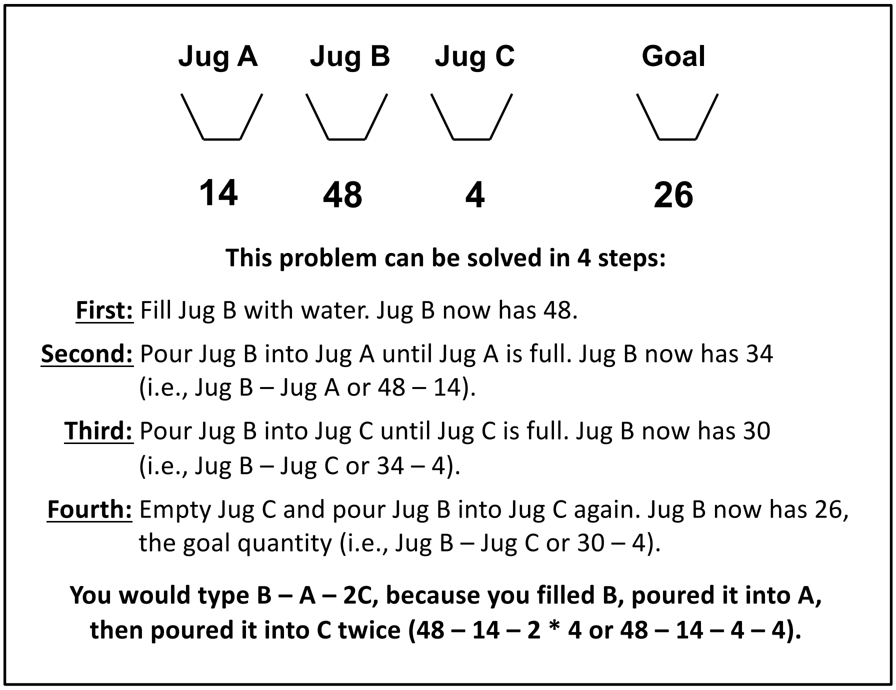

Figure 7. Worked example set problem used in Study 3.

Method

Participants

One hundred eighty-two undergraduate students (108 females, 74 males; M_{age} = 20 years, *SD* = 3.5) 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 and 2. Nineteen additional participants were removed for (a) committing more than 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 greater than 3 SDs from scale means; *n* = 11).

Procedure and Tasks

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

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 (Figure 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.

Results and Discussion

Variables and Analyses

Operational definitions of individual differences in AC, PM, and SM were the same as in Study 1, except that running span whole recall was used to index PM (see Study 2). Dependent variables, derived from the modified water jug task, were the same as in Studies 1 and 2. Again, performance on the critical problems was examined only for individuals who established mental set (i.e., correctly solved all three set problems; n = 124).

Moderation analyses were conducted using the same approach as in Study 2, except that only 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 in either model.

Set Problems

Descriptive statistics and intercorrelations 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, $r(180) = -.22$, $p = .003$), consistent with Studies 1 and 2.

Table 11

Descriptive statistics and intercorrelations among key variables ***for all participants*** *in Study 3.*

			Correlations (*r*)		
Measure	Mean	*SD*	1	2	3
1. Antisaccade	00.79	00.13	—		
2. RunSpan whole recall	17.63	04.42	.26**	—	
3. Operation span	58.63	11.57	.18*	.27**	—
4. Set problems solved	02.50	00.86	.08	.58	.17*

N = 182. *p < .05, **p < .01.

Moderation Analysis. Next, it was 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). This model significantly accounted for 7% of the variance in simple strategy use, $F(5, 176) = 2.66$, $p = .024$ (see Table 12). There was a significant simple effect of operation span (β = .19, $p = .016$). There was also a positive but not significant simple effect of antisaccade (β = .15, $p = .052$). No simple effect of running span whole recall was found (β = –.07, $p = .416$), and no antisaccade × running span whole recall interaction was obtained (β = –.02, $p = .842$). As predicted, a significant antisaccade × operation span interaction was found (β = .18, $p = .022$). Removing the non-significant interaction from the model did not change these results.

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)	.15	1.96	.052	.02
Running span whole recall (PM)	–.07	–0.81	.416	.00
Operation span (SM)	.19	2.44	**.016**	.03
AC × PM	–.02	–0.20	.842	.00
AC × SM	.18	2.31	**.022**	.03

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

Simple Slope Analysis. The significant AC × SM interaction was further examined by testing simple slopes. As shown in Figure 8, for individuals higher in AC, SM was significantly positively associated with the number of set problems solved (β = .36, $t(176) = 3.10$, $p = .002$, $sr^2 = .05$). For lower AC individuals, the relationship between SM and the number of set problems solved was not statistically different from zero (β = .02, $t(176) = 0.23$, $p = .815$). These results indicate that individuals higher in

SM were more likely to 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.

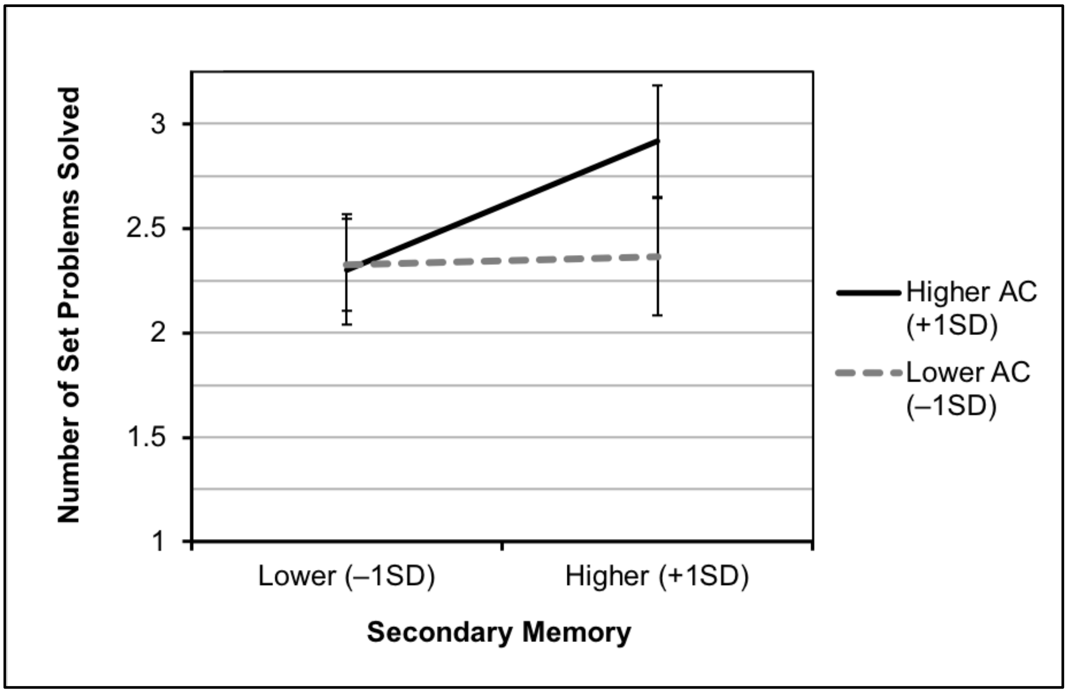

Figure 8. Number of set problems solved as a function of individual differences in secondary memory and attention control (AC) in Study 3. Error bars represent 95% confidence intervals.

Critical Problems

Descriptive statistics and intercorrelations 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. Of the 182 total participants, 124 (69%) solved all three set problems and were thereby deemed to have established mental set. The modification made to the water jug task thus had the intended effect of increasing the proportion of participants who solved all three set problems (by over 20%). 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 simpler (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 simpler strategies, the faster were mean response times for critical problems correctly solved (regardless of which strategy was used) (M = 18.30 sec, SD = 12.50 sec, $r(98) = -.20$, p = .044).[3]

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[3] 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 (see Beilock & DeCaro, 2007).

Table 13

Descriptive statistics and intercorrelations among key variables ***for individuals who established mental set*** *in Study 3.*

			Correlations (*r*)		
Measure	Mean	*SD*	1	2	3
1. Antisaccade	00.80	00.13	—		
2. RunSpan whole recall	17.69	04.43	.27**	—	
3. Operation span	59.75	10.80	.32**	.30**	—
4. Critical problems solved using simple strategies	00.60	01.02	.22*	.14	–.13

n = 124. *$p < .05$, **$p < .01$.

Moderation Analyses. The principal research question for Study 3 was whether AC moderates the effects of PM and SM for critical problem flexibility on the modified water jug task. To test this question, 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, $F(5, 118) = 4.96$, $p < .001$ (see Table 14).

There were significant simple effects of antisaccade ($\beta = .24$, $p = .013$), operation span ($\beta = -.40$, $p < .001$), and running span whole recall ($\beta = .27$, $p = .008$). Of note, no simple effect of running span whole recall was observed in Study 2, suggesting that the more comprehensive sample used in Study 3 contributed to this result. Significant antisaccade × running span whole recall ($\beta = .21$, $p = .028$) and antisaccade × operation span ($\beta = -.25$, $p = .013$) interactions were obtained. Hierarchical regression confirmed that the joint contribution of the two interaction effects (terms entered in step 2) was signficant, $\Delta R^2 = .06$, $p = .017$.

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)	.24	2.54	**.013**	.04
Running span whole recall (PM)	.27	2.71	**.008**	.05
Operation span (SM)	–.40	–3.92	**.000**	.11
AC × PM	.21	2.23	**.028**	.03
AC × SM	–.25	–2.51	**.013**	.04

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

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). The plots for both interaction effects are shown in Figure 9.

As predicted, results were the same as in Study 2. For individuals higher in AC, PM was significantly positively associated with simple strategy use ($\beta = .44$, $t(118) = 3.07$, $p = .003$, $sr^2 = .07$). For lower AC individuals, the relationship between PM and simple strategy use was not statistically different from zero in either model ($\beta = .09$, $t(118) = 0.86$, $p = .389$). These findings indicate that 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 ($\beta = -.62$, $t(118) = -3.87$, $p < .001$, $sr^2 = .10$). For lower AC individuals, the relationship between SM and simple strategy use was not statistically different from zero (β = −.19, $t(74) = -1.82$, $p = .071$). These findings indicate that individuals lower in SM were more likely to break mental set if they were also higher in AC.

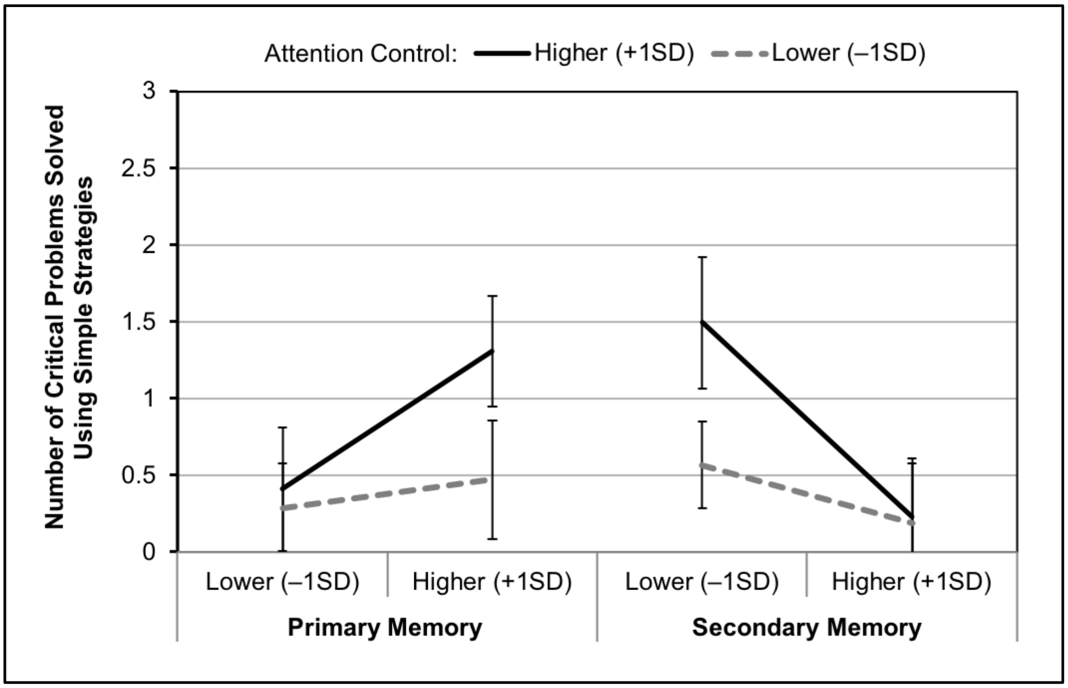

Figure 9. Number of critical problems solved using simple strategies as a function of individual differences in primary memory and attention control (left), and secondary memory and attention control (right) for individuals who established mental set in Study 3. Error bars represent 95% confidence intervals.

Taken together, these findings suggest that AC both supports and constrains functionally opponent processes associated with different WMC mechanisms. Specifically, in Study 3 neither the positive relationship between breaking mental set and PM, nor the negative relationship between breaking mental set and SM, was entirely dependent on higher levels of AC, as indicated by the significant simple effects.

Conclusions

Study 3 supported the hypothesis that AC moderates the relationships between PM and SM and breaking mental set on the modified water jug task, replicating Study 2. Taken together, these findings indicate that the predicted pattern of results did not depend on whether individuals discovered the complex strategy freely (Study 2) or by example (Study 3). These findings also suggest that the hypothesized model may generalize to other mental set phenomena outside the laboratory (see Ricks et al., 2007).

By demonstrating the predicted relationships between PM and SM and breaking mental set at varying levels of AC, Study 3 also supported a more generalized application of the theory of functional opponency in WMC. Furthermore, Study 3 provided initial support for the novel hypothesis that AC moderates the relationship between SM and establishing mental set. Specifically, Study 3 demonstrated 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).

CHAPTER V

GENERAL DISCUSSION

Although cognitive flexibility is sometimes considered a hallmark of high WMC, high WMs also persist in using suboptimal strategies (e.g., Beilock & DeCaro, 2007; Fischer & Holt, 2017; Richmond et al., 2015). To address this apparent inconsistency in the literature, the present research adopted a multifaceted view of WMC (Shipstead et al., 2014; see also Unsworth et al., 2014) to advance a novel theory of functional opponency in which different WMC mechanisms interact in ways that both support and constrain cognitive flexibility.

Across three studies, individual differences in three WMC mechanisms (AC, PM, and SM) differentially predicted performance on Luchins's (1942) water jug task. Study 1 offered initial support for the 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 added further support to the proposed theory by replicating the pattern of results from Study 1, while also demonstrating the role AC plays in moderating these effects. Study 3 strongly supported the proposed theory by demonstrating that the same pattern of results observed in Study 2 can be obtained using a less restrictive methodology (i.e., by directly providing participants the complex strategy needed to solve the set problems and establish mental set).

A negative relationship between WMC and breaking mental set on the water jug task was found in a previous study in which WMC (as measured by complex span tasks) was treated as a unitary construct (Beilock & DeCaro, 2007), consistent with the influential "executive attention" view of WMC (Engle, 2002; cf. Engle, 2018). One goal of the present research was to determine whether this negative association could be explained by one or more WMC mechanisms. Results from each study indicated that higher SM was associated with lower likelihood of breaking mental set, supporting the hypothesis that greater ability to efficiently retrieve previously used strategies hinders breaking mental set (Harrison et al., 2015; Verguts & De Boeck, 2002). These results suggest that the finding from Beilock and DeCaro (2007) may have been driven by SM.

A common contention in creativity research is that negative associations between WMC and problem-solving are driven by AC (see Wiley & Jarosz, 2012, for a review). Specifically, AC helps constrain focal attention to relevant information and restrain inappropriate thoughts and responses (e.g., Kane & Engle, 2003; McVay & Kane, 2012). In problem situations where the solution path suggested by prior knowledge or experience is inappropriate, high WMs may overlook remote alternatives by virtue of having higher AC (Ansburg & Hill, 2003; Rerko & Oberauer, 2013; Vartanian, 2009; Wegbreit, Suzuki, Grabowecky, Kounios, & Beeman, 2012; Zabelina & Robinson, 2010). In contrast, the present research indicates that SM plays an important role in limiting the discovery of new solutions by facilitating the retrieval of those that have worked in the past. The multifaceted view of WMC and the proposed theory of function opponency may offer new insights into the nature these phenomena.

Positive associations with WMC are extremely common in the literature (e.g., Beier & Oswald, 2012). However, the positive association found between PM and breaking mental set in the present research is noteworthy for two major reasons. First, these findings provide novel evidence that greater ability to disengage from no-longer-relevant information via PM enables individuals to break mental set (Shipstead et al., 2014). Second, Study 2 demonstrated that disengagement is not uniquely tapped by the running span task. Rather, when running span trial types were examined separately, whole recall trials, and not partial recall trials, were positively associated with breaking mental set. Furthermore, the same pattern of results was found using immediate free recall, a more common measure of PM (Unsworth et al., 2010). These findings suggest that greater absolute capacity (i.e., the maximum amount of information that can be maintained in the focus of attention; Cowan et al., 2005), apart from the influence of factors that contribute to effective WM maintenance (i.e., in the presence of distractors; Poole & Kane, 2009), facilitates breaking mental set (Oberauer et al., 2007; cf. Shipstead et al., 2016). Future studies may benefit from examining running span performance as a function of trial type, as whole recall and partial recall scores may demonstrate different patterns of association with other outcomes.

An important question raised by the present research concerns the role of AC in the hypothesized model. In Studies 1 and 2, AC was found to be positively associated with success on the set problems, and thus important for establishing mental set. However, AC was also found to moderate the relationships between PM and SM and breaking mental set. Specifically, in Studies 2 and 3, higher AC supported both the positive relationship between PM and breaking mental set and the negative relationship between SM and breaking mental set. Additionally, in Study 3, when the complex strategy needed to solve the set problems was provided to participants, AC was no longer associated with establishing mental set. Rather, higher AC was found to support a positive relationship between SM and establishing mental set—the inverse of the relationship higher AC supported between SM and breaking mental set.

Taken together, these findings suggest that AC plays an important role in balancing trade-offs between flexibility and stability that are driven by individual differences in PM and SM. A possible explanation for the unique role of AC in the hypothesized model is that all tasks likely require some degree of goal maintenance and thus benefit from higher AC (Engle, 2018). If cognitive stability and flexibility subserve functionally opposing "computational goals" (Badre & Wagner, 2006; see also Hazy, Frank, & O'Reilly, 2007), and AC is an essential component of effective goal pursuit, then AC may support processes that further either of these goals. Specifically, the current findings supported the hypothesis that AC would support PM by limiting attentional capture during disengagement, when intrusions from SM are more likely, furthering the goal of flexibility (e.g., Dreisbach & Wenke, 2011; Mayr et al., 2014). These same findings also supported the hypothesis that AC would also support SM by facilitating the identification of seemingly relevant retrieval cues, furthering the goal of stability (e.g., Hills et al., 2010; Lilienthal et al., 2015; Schilling et al., 2014). Future studies may benefit from testing AC as a possible moderator for both new and established WMC effects (e.g., Sattizahn et al. 2016). However, further research is needed to develop a better understanding of the interplay of WMC mechanisms. In particular, the present research suggests that research examining intra-individual differences in WMC mechanisms may offer further insights in the diverse nature of cognitive abilities (see Braver, Cole, & Yarkoni, 2010).

The multifaceted view of WMC provides new research opportunities for reexamining classic effects and long-standing assumptions (e.g., Martin et al., 2017; Sattizahn et al. 2016). Indeed, 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. Specifically, the theory of functional opponency in WMC cautions against simple low/high WM dichotomies, suggesting that characteristics of "high WMs" can lead to conflicting patterns of results. Cognitive flexibility and cognitive stability may not necessarily be opposite ends of a continuum; rather, multiple components of cognitive control may facilitate or hinder flexibility. A better understanding of how WMC mechanisms both independently and jointly support and constrain cognitive performance may further development of effective training regimens and intervention strategies to facilitate learning and problem solving across the lifespan (e.g., Ionescu, 2019; Redick, 2019; Zaehringer, Falquez, Schubert, Nees, & Barnow, 2018).

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RESEARCH INTERESTS

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- The intersection of cognitive control and cognitive flexibility
- Problem solving

PUBLICATIONS

Van Stockum, C. A. Jr., & DeCaro, M. S., (under review). When working memory mechanisms compete: Predicting cognitive flexibility versus mental set. *Manuscript submitted for publication*.

DeCaro, M. S., & **Van Stockum, C. A. Jr.** (2018). Ego depletion improves insight. *Thinking and Reasoning, 24*, 315–343. doi:10.1080/13546783.2017.1396253

DeCaro, M. S., **Van Stockum, C. A. Jr.**, & Wieth, M. (2017). The relationship between working memory and insight depends on moderators: Reply to Chuderski and Jastrzębski (2017). *Journal of Experimental Psychology: Learning, Memory, and Cognition, 43,* 2005–2010. doi:10.1037/xlm0000460

DeCaro, M. S., **Van Stockum, C. A. Jr.**, & Wieth, M. B. (2016). When working memory capacity hinders insight. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 42*, 39–49. doi:10.1037/xlm0000152

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CONFERENCE PROCEEDING PAPERS

Van Stockum, C. A. Jr., & DeCaro, M. S. (2013). The path less taken: When working memory capacity constrains insight. In M. Knauff, M. Pauen, N. Sebanz, & I. Wachsmuth (Eds.), *Proceedings of the 35th Annual Conference of the Cognitive Science Society* (pp. 3633–3638). Berlin, Germany: Cognitive Science Society.

PRESENTATIONS

Van Stockum, C. A. Jr., & DeCaro, M. S. (2016, November). Working memory mechanisms predict insight in opposite directions. Poster presented at the *Annual Meeting of the Psychonomic Society*, Boston, MA.

Van Stockum, C. A. Jr., & DeCaro, M. S. (2016, March). Working memory capacity mechanisms differentially predict flexibility versus mental set. Paper presented at *The Southern Society of Philosophy and Psychology*, Louisville, KY. **Griffith Memorial Award in Psychology**.

Van Stockum, C. A. Jr., & DeCaro, M. S. (2015, November). Different working memory components predict flexibility versus mental set. Poster presented at the *Annual Meeting of the Psychonomic Society*, Chicago, IL.

Van Stockum, C. A. Jr., & DeCaro, M. S. (2015, May). Enclothed cognition and controlled attention during insight problem-solving. Paper presented at the Annual Meeting of the Midwestern Psychological Association, Chicago, IL.

Van Stockum, C. A. Jr., & DeCaro, M. S. (2014, November). The upside of down-regulated self- control: Depletion enhances insight. Poster presented at the Annual Meeting of the Psychonomic Society, Long Beach, CA.

Van Stockum, C. A. Jr., & DeCaro, M. S. (2014b, May). Perceived exhaustion predicts mind wandering. Poster presented at the *4th annual Midwest Cognitive Science Conference*, Dayton, OH.

Edlin, J. M., **Van Stockum, C. A. Jr.**, DeCaro, M. S., & Lyle, K. B. (2014, May). Bilateral saccade execution can impair working memory. Poster presented at the *Midwest Cognitive Science Conference*, Dayton, OH.

Van Stockum, C. A. Jr., & DeCaro, M. S. (2014a, May). When less is more: attentional control hinders insight. Talk presented at the *University of Louisville Department of Psychological & Brain Sciences Ph.D. Program 50th Anniversary Reunion Celebration*, Louisville, KY.

Van Stockum, C. A. Jr., & DeCaro, M. S. (2013, August). The path less taken: When working memory capacity constrains insight. Poster presented at the *35th Annual Conference of the Cognitive Science Society*. Berlin, Germany.

SERVICE

Experimental Psychology Graduate Student Representative, 2013–2016

Ad hoc Journal Reviewer

The Journal of Problem Solving
Thinking & Reasoning

MEDIA COVERAGE

UofL Today Radio Show, March 2018
Harvard Business Review, August 2015