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Individual differences in the delayed execution of prospective memories

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Working memory processes play a critical role in actively maintaining, rehearsing, and retrieving goal-relevant information during cognitively engaging tasks. In the current study, we examined individual differences in prospective memory between young adults with high versus low working memory capacity (WMC) when they had to momentarily delay their intentions for either 6 or 42 s. In Experiments 1 and 2, high-WMC individuals performed significantly better at both delay intervals than did low-WMC individuals under standard ongoing task conditions. In Experiment 2, we included an interrupting task during the longer delay that decreased performance in the low-WMC relative to the high-WMC individuals. These results suggest that prospective memory performance is generally impaired across all retention intervals in low-WMC individuals, and that high-WMC individuals may be better able to retrieve the intention from long-term memory even when attention is interrupted by intervening activities.

Keywords: Prospective memory; Working memory.

Event-based prospective memory (PM) refers to the ability to remember to perform an action in the future by relying on environmental cues to trigger the retrieval of intended action from long-term memory. Research investigating event-based PM suggests that people engage a variety of cognitive processes to support cue detection depending on the nature of the ongoing task and the types of cues that they expect to encounter (McDaniel & Einstein, 2000). However, much less research has addressed the cognitive mechanisms responsible for briefly delaying a target behaviour *after* an intention has been retrieved. For example, upon walking past a patient's room a physician may remember that the patient's laboratory results need to be picked up. However, before doing so

the physician must first attend to another patient that needs immediate attention. Thus, picking up the results must be delayed until after the immediate issue has been resolved. PM researchers have labelled this type of situation a *delayed-execute* PM (McDaniel, Einstein, Stout, & Morgan, 2003).

Relative to the typical PM paradigm in which intentions are fulfilled immediately upon retrieval of the intended action (referred to as a *retrieve-execute* PM task; Einstein, McDaniel, Manzi, Cochran, & Baker, 2000), little work has investigated the processes involved in fulfilling delayed-execute prospective memories despite the fact that many everyday PM tasks may involve delayed fulfilment (Kvavilashvili & Fisher, 2007). Previous

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research has implicated working memory processes as being essential to the ability to fulfil these delayed intentions (e.g., Einstein, McDaniel, Williford, Pagan, & Dismukes, 2003; Kelly, Hertzog, Hayes, & Smith, 2013; Kliegel & Jäger, 2006; McDaniel et al., 2003). However, this hypothesis has primarily been supported by comparing performance between older and younger adults. Furthermore, research has yielded inconsistent correlations between working memory and delayed–execute PM performance (e.g., Einstein et al., 2000). Thus, the current study sought to further investigate the role of working memory in fulfilling briefly delayed intentions in healthy, young adults.

Delayed–execute PM

In a typical delayed–execute paradigm, salient event-based cues (such as a red screen or an uppercase word) are associated with an intended action (a special key press) and embedded within different ongoing tasks. Using salient cues ensures that nearly all participants will notice the target event and retrieve the intended action (e.g., Einstein et al., 2000). In this respect, delayed–execute tasks are similar to the typical retrieve–execute tasks. However, in delayed–execute tasks a delay is introduced that prevents participants from performing the action for a short period of time. Generally, participants are required to delay their response until the current task is completed and must execute the intended action upon the start of a new task. To determine the rate of forgetting on delayed–execute intentions, cues can appear at different intervals preceding the end of a task. Previous research has demonstrated that when the intended action can be executed immediately, PM performance is generally high, but when a delay as short as 5 or 10 s is introduced, PM performance declines significantly (Einstein et al., 2000). However, longer delays (e.g., 15, 40 s) do not impair PM performance (McDaniel, Einstein, Graham, & Rall, 2004).

Decrements to performance have even been evidenced when the delay period is unfilled (McDaniel et al., 2003), suggesting that the

ongoing task processing is not necessarily the primary cause of forgetting (although filled delays and secondary task demands generally affect performance to a greater degree; Einstein et al., 2003; Kliegel & Jäger, 2006; McDaniel et al., 2004). Rather, these findings suggest that if the intention is not executed relatively immediately it may decay from focal awareness without some sort of refreshing process (Einstein et al., 2003), and this process is naturally disrupted by ongoing or secondary task demands. Thus, the difficulty in fulfilling delayed relative to immediate intentions may be due to a greater amount of self-initiated retrieval processes (Craik, 1986) necessary to retrieve the intended action from long-term memory at the beginning of a new ongoing task relative to the typical retrieve–execute PM tasks that may trigger retrieval of the intended action relatively automatically and that can be executed immediately (Einstein & McDaniel, 2005). To the degree that self-initiated retrieval is a capacity-consuming process (Unsworth, 2009), this suggests that individuals with poorer working memory abilities should be particularly affected by delays and secondary task demands.

Working memory capacity

Working memory is broadly defined as a general-purpose system responsible for actively maintaining task-relevant information in the face of internal or external distractions (Baddeley, 2007; Engle & Kane, 2004; Kane, Bleckley, Conway, & Engle, 2001). Active maintenance of task-relevant information involves the ability to direct attention in a flexible manner (Conway & Kane, 2001; Norman & Shallice, 1986). Unsworth and Engle's (2007) dual-component model of working memory suggests that, in addition to the controlled attention necessary for actively maintaining task-relevant information, controlled retrieval of momentarily displaced information also contributes to individual differences in working memory. Thus, individuals high in working memory capacity (WMC) are not only better able to actively maintain information in the focus of attention, but they can also more efficiently retrieve information that has

momentarily been displaced due to distraction (Brewer & Unsworth, 2012; Unsworth & Brewer, 2009; Unsworth & Engle, 2007). Presumably, lower order mechanisms such as the ability to actively maintain or sustain attention on task-relevant information, as well as the ability to retrieve task-relevant information that has been momentarily displaced by interference, underlie the relation between WMC and other important psychological constructs (Unsworth & Spillers, 2010). In previous work, we have argued that one such important construct is PM (Brewer, Knight, Unsworth, & Marsh, 2010; Unsworth, Brewer, & Spillers, 2012).

WMC and delayed–execute PM

Working memory processes have been implicated in both retrieve–execute (Breneiser & McDaniel, 2006; Brewer et al., 2010; Smith & Bayen, 2005) and delayed–execute PM (Einstein et al., 2000; Kliegel & Jäger, 2006; McDaniel et al., 2003). Two possible mechanisms have been proposed to underlie successful fulfilment of delayed–execute prospective memories. The *active maintenance view* (Einstein et al., 2003) posits that participants countermand temporal limits of working memory by adopting strategies to periodically activate the intended action during the retention interval by occasionally rehearsing or retrieving the intended action from long-term memory (Einstein & McDaniel, 2008). An alternative mechanism that may support fulfilment of delayed–execute prospective memories is reliance on long-term memory capabilities and *plan reformulation*, such that upon initial retrieval of the intention, participants may reconceptualize the task by noting that the new demand is to press the key at the beginning of the next task (McDaniel et al., 2003). Previous research suggests that individuals may rely on different processes to support intention fulfilment depending on the nature of the ongoing task and the capability of the individual. For example, dividing attention during *presentation* of the cue may interfere with one’s ability to reformulate the intention (McDaniel et al., 2003), whereas divided attention *throughout* the delay may disrupt

maintenance or refreshing of the intention (Einstein et al., 2003). Together, these findings suggest that multiple mechanisms support fulfilment of delayed–execute prospective memories. Thus, the current study sought to explore these alternative hypotheses using an individual differences approach.

The current study

In the current study we examined the role of working memory in the delayed execution of prospective memories. We defined groups of low- and high-WMC participants based on a standard working memory assessment and had them complete a delayed–execute PM task. In Experiment 1, participants performed a series of ongoing tasks with the intention to respond with a special key press after a red screen appeared during one of the tasks, but not until that task ended, and a new one began. For half the cues, there was only a 6-s delay between retrieval and execution, whereas for the other half there was a 42-s delay. In Experiment 2, we replicated this procedure and also included a 42-s delay with an interrupting task. Overall, these experiments speak to the role of working memory in delayed–execute PM and mitigating the consequences of interruption. Given that high-WMC individuals are better able to actively maintain task-relevant information in the face of distraction and retrieve representations from long-term memory that have been momentarily displaced from primary memory due to distraction (e.g., the ongoing task; Unsworth & Engle, 2007), we expected better performance for high- than for low-WMC individuals across delays and interruptions.

EXPERIMENT 1

Method

Participants

Undergraduate students from the University of Georgia volunteered in exchange for partial credit toward an introductory psychology course research

requirement. A total of 139 participants completed the WMC span tasks and were included in the overall analyses in Experiment 1. All participants first performed the three complex-span tasks before performing the delayed–execute experiment. For the secondary analyses, only participants falling in the upper (individuals with high working memory abilities) and lower (individuals with low working memory abilities) quartiles of the composite distribution were selected for inclusion. There were 35 high-WMC individuals (z -composite = 0.73, $SD = 0.04$) and 35 low-WMC individuals (z -composite, $M = -0.96$, $SD = 0.08$). We additionally collected control data from 35 undergraduate students in an introductory psychology course at Arizona State University that did not perform the WMC screening and served as a control group for baseline comparisons of delayed–execute response time analyses (i.e., PM costs). These participants were given instructions for the ongoing task but were never given any PM instructions.

WMC screening. *Operation span.* Participants solved a series of maths operations while trying to remember a set of unrelated letters (F, H, J, K, L, N, P, Q, R, S, T, Y). Participants were required to solve a maths operation and judge whether their answer matched either a correct or an incorrect alternative—for example, “ $(1 \times 2) + 1 = 3$?”. After solving the operation and making their judgement, they were presented with a letter for 1 s. Participants were given feedback about the accuracy of their maths operations, and they had to maintain their performance level above 85%. Immediately after the letter was presented, the next operation was presented. Three trials of each letter list-length (3–7) were presented, with the order of list-length varying randomly. At recall, participants attempted to recall letters from the current set in the correct order by clicking on the appropriate letters (see Unsworth, Heitz, Schrock, & Engle, 2005). Participants received three sets (of list-length two) of practice. For all of the span measures, items were scored if the item was correct in the correct position. The score was the proportion of correct items recalled in the correct position.

Comprehension span. Participants were required to read sentences while trying to remember the same set of unrelated letters as that in the operation span task. For this task, participants read a sentence and determined whether the sentence made sense or not (e.g., “The prosecutor’s dish was lost because it was not based on fact.?”). Half of the sentences made sense while the other half did not. Nonsense sentences were made by simply changing one word (e.g., “dish” from “case”) from an otherwise normal sentence. Participants were required to read the sentence and to indicate whether it made sense or not. After participants gave their response they were presented with a letter for 1 s. At recall, participants were asked to recall letters from the current set in the correct order by clicking on the appropriate letters. There were three trials of each list-length, with list-length ranging from 3–7. Participants received practice on all components of the comprehension span task before beginning. The same scoring procedure as that for operation span was used.

Symmetry span. Participants were required to recall sequences of red squares within a matrix while performing a symmetry judgement task. In the symmetry judgement task, participants were shown an 8×8 matrix in which some squares were filled in black and were to decide whether the design was symmetrical about its vertical axis. The pattern was symmetrical on half of the trials. Immediately after determining the pattern’s symmetry, participants were presented with a 4×4 matrix in which one of the cells was filled in red for 650 ms. At recall, participants recalled the sequence of red-square locations in the preceding displays in the order they appeared by clicking on the cells of an empty matrix. There were three trials of each list-length ranging from 2 to 5 for a total possible of 42. The same scoring procedure as that for operation span was used.

Composite score. In Experiment 1, the complex-span tasks were significantly interrelated (all correlations $> .361$, $ps < .001$). Thus, z -transforming each score and averaging them together created a

composite measure, and quartiles were computed from the averaged distribution of the measure.

Delayed–execute task. *Materials and procedure.* Participants were instructed that they were going to be taking part in an experiment with multiple ongoing activities that would occur in different blocks. Participants were first given instructions for the four ongoing tasks, in which participants were to: (Task 1) decide whether or not a string of letters formed a valid English word; (Task 2) indicate whether a stimulus consisted of one or two syllables; (Task 3) decide whether a stimulus depicted something living or nonliving; (Task 4) decide whether or not the first and last letters of a stimulus were presented in alphabetical order. Participants were shown examples of each kind of task and were given the opportunity to ask any questions. Responses were made with the “F” and “J” keys for each kind of task, and a heading appeared above the stimulus to indicate the nature of the ongoing task and which key to press. For example, the heading “ONE or TWO” would indicate to the participant that they were to perform the syllable rating task and that they were to respond with “F” to one-syllable and “J” to two-syllable words.

After receiving instructions for the ongoing tasks, participants in the experimental condition were then given the PM instructions. They were told that during some of the trials, a red screen would appear on the computer screen for 1 s, and when this occurred they were to press the slash key (/) on the keyboard, but not until the current task ended, and a new one began. After the experimenter summarized the instructions, and participants acknowledged to the experimenter that they understood all of the instructions, they were allowed to proceed with the task. After receiving instructions for the PM task, participants were asked to assess how well they would do at remembering to respond with the slash key for both the short and long delays.

Each ongoing task lasted 1 min, with 20 trials per task presented for 3 s each with items randomly assigned to each trial. Each of the ongoing tasks was presented eight times, resulting in a total of 32 min of ongoing task trials. The eight presentations of the ongoing task were determined

pseudorandomly such that each of the four tasks was presented once within a “block” (i.e., four different ongoing tasks), and the next block would present the four tasks in a different order. After the item and task order was determined, presentation was identical for each participant. The signal to form an intention (red screen) over a delay occurred during Tasks 3, 6, 11, 15, 18, 21, 26, and 30. Four cues occurred for each delay length (6 s and 42 s), with two of each type presented in both the first and the second halves of the experiment. After receiving instructions for the ongoing tasks or making assessments for PM performance, participants in the control and experimental groups, respectively, were given a brief practice phase to become familiar with the procedure that included one trial in which a red screen appeared during the ongoing tasks. The experimenter then reiterated the instructions, and the participants began the experiment.

Results

Prospective memory

To examine the effect of delay on PM performance across the entire distribution of participants, the proportion of successfully fulfilled delayed intentions (short vs. long) was submitted to a repeated measures analysis of variance (ANOVA). This analysis failed to reveal an effect of delay on PM performance, $F(1, 138) < 1$. Similarly, when the composite working memory span score was entered as a covariate into the model using an analysis of covariance (ANCOVA), there was no effect of delay, $F(1, 137) < 1$. However, the ANCOVA revealed a main effect of span score, $F(1, 137) = 6.8$, $p < .05$, $\eta_p^2 = .047$, as well as a significant interaction of delay and span score, $F(1, 137) = 4.86$, $p < .05$, $\eta_p^2 = .034$. To gain leverage on the interaction of delay and span score, we investigated participants failing in the upper (high WMC) and lower (low WMC) quartiles of the overall distribution of WMC span scores.

The proportion of successfully executed delayed intentions was submitted to a 2 (delay: short vs. long) \times 2 (WMC: high vs. low) mixed-factorial ANOVA (see Figure 1). This analysis revealed

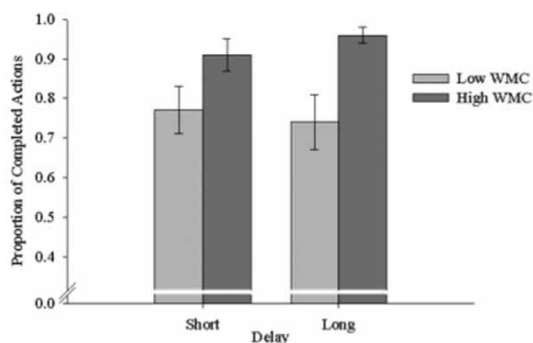


Figure 1. Proportion of successfully fulfilled delayed intentions for Experiment 1. WMC = working memory capacity. Error bars reflect standard errors.

that performance was better for high-WMC participants than for the low-WMC participants, $F(1, 68) = 7.85$, $p < .01$, $\eta_p^2 = .104$, but there was no effect of delay, $F(1, 68) < 1$. There was also a significant interaction of WMC and delay, $F(1, 68) = 5.06$, $p < .05$, $\eta_p^2 = .069$. This interaction reflects that while high-WMC individuals outperformed low-WMC individuals at both short and long delays, $t(68) = 2.01$, $p < .05$, $d = 0.48$, and $t(68) = 3.32$, $p < .01$, $d = 0.79$, respectively, performance for low-WMC individuals numerically (but not significantly) decreased with

longer delays, $t(34) = 1.15$, $p = .26$, $d = 0.2$, whereas performance for high-WMC individuals actually increased with longer delays, $t(34) = 2.10$, $p < .05$, $d = 0.39$. Thus, high-WMC individuals performed better at both delays than low-WMC individuals and actually showed improved performance with longer delays.

Cost analyses

We first examined response latencies for trials during blocks in which no red screen was presented (collapsed across all ongoing tasks) to determine whether there were differences in processing speed between the high- and low-WMC individuals relative to a control group that received no PM instructions. Only correct response latencies within 2.5 standard deviations of a given participant's mean were included in the analysis (and all subsequent analyses; Brewer, 2011). This analysis revealed no overall differences in latencies between the three groups, $F(2, 102) = 1.26$, $p = .30$, $\eta_p^2 = .024$. To examine the cost of delaying the execution of the target action, we examined response latencies on trials that occurred prior to and following cue presentation for each group across delays. The data are summarized in the upper half of Table 1.

Table 1. Mean response latencies for trials prior to and following cue presentation and after the interrupting task for low- and high-WMC and control groups in Experiments 1 and 2

Experiment and group	Short + long delay ^a (2 trials)		Long delay ^b (remaining)		Long delay ^c (interruption)		
	Precue	Postcue	Precue	Postcue	Precue	Postcue	Postinterruption
Experiment 1							
Low WMC	1173 (204)	1499 (192)	1191 (28)	1132 (30)			
High WMC	1100 (158)	1429 (219)	1168 (28)	1063 (30)			
Control	1178 (204)	1176 (171)	1203 (28)	1103 (30)			
Experiment 2							
Low WMC	1333 (242)	1621 (258)	1506 (197)	1402 (243)	1102 (204)	1331 (201)	1396 (209)
High WMC	1201 (198)	1548 (261)	1374 (186)	1318 (141)	1024 (139)	1266 (182)	1390 (215)
Control	1231 (160)	1221 (210)	1401 (179)	1341 (205)	1071 (211)	1077 (177)	1402 (209)

Note: WMC = working memory capacity. Standard deviations are in parentheses.

^aResponse latencies for the two trials immediately prior to and following cue presentation, collapsed across short and long delays.

^bResponse latencies for the six trials prior to and 12 trials that following cue presentation (after excluding the first two trials) for the long delay. ^cResponse latencies for the four trials prior to and following cue presentation (but before the interruption task) and response latencies for the six trials following the interruption task.

Because only two trials occurred after cue presentation in the short delay, we restricted our analyses to the two trials preceding and following the cue in both the short and long delays. We submitted mean reaction times to a 2 (delay: short vs. long) \times 2 (trial type: preceding cue vs. following cue) \times 3 (group: high vs. low vs. control) mixed-factorial ANOVA. This analysis revealed an effect of group, $F(2, 102) = 8.01, p < .01, \eta_p^2 = .136$, an effect of delay, $F(1, 102) = 74.16, p < .001, \eta_p^2 = .421$, and an effect of trial type, $F(1, 102) = 131.16, p < .001, \eta_p^2 = .563$. The only significant interaction occurred between group and trial type, $F(2, 102) = 33.33, p < .001, \eta_p^2 = .395$ (all other F s $< 1.96, p$ s $> .16$). This interaction reflects that while both the high- and low-WMC groups exhibited significant slowing following cue presentation, $t(34) = 10.54, p < .001, d = 1.72$, and $t(34) = 8.25, p < .001, d = 1.64$, respectively, the control group did not, $t(34) < 1$. Thus, despite no differences in latencies prior to cue presentation, immediately after cue presentation both high- and low-WMC individuals showed cost to ongoing task performance.

To examine whether participants exhibited slowing following cue presentation for the remainder of the trials during the long delay, we also compared latencies for the six trials occurring prior to cue presentation with those for the 12 trials that followed cue presentation (after excluding the first two trials)¹ by submitting mean response latencies to a 2 (trial type: preceding cue vs. following cue) \times 2 (group: high vs. low vs. control) mixed-factorial ANOVA. This analysis revealed an effect of trial type, $F(1, 102) = 39.50, p < .001, \eta_p^2 = .279$, with faster latencies following cue

presentation. However, there was neither an effect of group, nor an interaction of trial type and group, F s $< 1.11, p$ s $> .34$. Thus, participants actually responded more quickly following the presentation of a cue, but this did not differ between groups.²

Predictions

Prior to beginning the experiment, participants were asked to assess (predict) the proportion of times they would remember to make their PM response upon the end of the short and long delays. We submitted mean predictions for each delay to a 2 (delay: short vs. long) \times 2 (WMC: high vs. low) mixed-factorial ANOVA. This analysis revealed an effect of delay, $F(1, 68) = 5.84, p < .05, \eta_p^2 = .079$, and an effect of WMC, $F(1, 68) = 4.57, p < .05, \eta_p^2 = .063$. These effects were qualified by a significant interaction of delay and WMC, $F(1, 68) = 5.58, p < .05, \eta_p^2 = .076$, indicating that while predictions for high-WMC individuals were more confident overall, predictions for the long delay were lower than those for the short delay for high-WMC individuals, $t(34) = 5.19, p < .001, d = 0.468$, but not for low-WMC individuals, $t(34) < 1$.

Discussion

Consistent with previous research, the results from Experiment 1 suggest that maintaining intentions even for very brief durations can be difficult and that increasing the length of the interval between initial retrieval and execution does not decrease performance in a college-aged sample. Similar to previous findings comparing younger and older adults

¹ Eliminating the first two trials during the long delay (in which slowing occurred) did not affect the results in either Experiment 1 or Experiment 2. Similarly, equating trials by comparing the six trials before and the six trials after the cue also did not affect the results. Response latencies did not differ for either the high- or the low-WMC groups relative to the control group over the remaining 36 s during the long delay (all p s $> .05$).

² We also matched ongoing tasks that either did or did not include a PM cue and compared latencies for the trials following the cue to those for the same trial positions of the matching ongoing task that did not present a cue. For example, a cue appeared in the 11th ongoing task (syllable rating task) on the 6th trial (i.e., long delay). Thus, we took the average performance for Trials 6 through 20 in the 11th ongoing task that presented a cue and compared it to the same trials during the 14th ongoing task (syllable rating task) that did not present a cue. This procedure was done for each delay length and was averaged across all trials for both tasks with and without cues. In both Experiments 1 and 2, the results tell a similar story as the between-subjects comparisons with the control group (i.e., there was slowing immediately after the cue appeared relative to the same trials in which no cue appeared, but there was no slowing for the remainder of the delay).

(e.g., Einstein et al., 2000), high-WMC individuals outperformed low-WMC individuals even when the delay between retrieval and execution was as short as 6 s. Contrary to previous findings, however, performance actually increased during the longer delay for high-WMC individuals. One possibility is that with multiple intervening trials between the cue and response, high-WMC individuals may have increased their frequency of thinking about the intention (Hicks, Marsh, & Russell, 2000; McCabe, 2008), resulting in greater performance with longer delays; however, the latency analyses in the current study suggest that this hypothesis may not be the case. Interestingly, predictions for high-WMC individuals were actually lower for the long delay than for the short delay, suggesting that high-WMC individuals may have been aware of the fleeting nature of prospective memories and that remembering to respond after a longer delay may be more difficult. Thus, high-WMC individuals may have engaged in compensatory strategies to ensure successful intention fulfilment that resulted in increased PM performance over the longer delay (see Einstein & McDaniel, 2008, for a similar argument).

Response latencies for high- and low-WMC groups, but not the control group, were significantly slower immediately after cue presentation for both short and long delays. This result suggests that the interference to ongoing task performance was probably due to retrieval of the intended action rather than irritation or distraction from the presentation of the red screen. However, there was no overall cost associated with cue presentation throughout the duration of the long delay, which suggests that participants were not allocating additional resources towards actively maintaining the intended action in working memory throughout the delay. Rather, these results suggest that participants may have tried to reformulate the goal (e.g., “the new demand is to press the key at the beginning of the next task”) upon initial retrieval, resulting in cost to ongoing task performance, and high-WMC individuals were better able to retrieve this new intention from long-term memory upon the beginning of the next task.

EXPERIMENT 2

Method

In Experiment 2 we replicated the delayed–execute procedure from Experiment 1 with a 6- and 42-s delay, but also included an additional within-subjects condition where an interruption (“GO TO FOLDER”) was administered during the long delay to examine whether including an interrupting task would differentially affect high- and low-working-memory individuals. This interruption occurred roughly halfway between cue presentation and the end of the ongoing task.

Participants

Undergraduate students from the University of Georgia volunteered in exchange for partial credit toward an introductory psychology course research requirement. A total of 135 participants completed the WMC span tasks and were included in the overall analyses in Experiment 2. All participants first performed the three complex-span tasks before beginning the delayed–execute experiment. In the secondary analyses based on the upper and lower quartiles of the WMC distribution, participants were 30 high-WMC individuals (z -composite, $M = 0.96$, $SD = 0.07$) and 30 low-WMC individuals (z -composite = -1.24 , $SD = 0.13$). We additionally collected control data from 30 undergraduate students at Arizona State University that received partial credit toward an introductory psychology course research requirement.

Composite score

In Experiment 2, the complex-span tasks were significantly interrelated (all correlations $> .355$, $ps < .001$). Thus, z -transforming each score and averaging them together created a composite measure, and quartiles were computed from the averaged distribution of the measure.

Delayed–execute task with interruptions

The same procedure was used as that in Experiment 1 with only one major change. In Experiment 2, participants were informed that on

some trials, a message would appear on the screen displaying the instruction to “GO TO FOLDER”. Whenever this message occurred, they were to stop performing the ongoing task, open the folder located beside the keyboard, and begin doing multiplication problems by hand. They were to continue performing this task as long as the “GO TO FOLDER” remained on the screen. Thus, participants performed multiplication problems while also having to monitor the computer screen to determine whether they needed to resume the ongoing task. Critically, the red screen always appeared before the “GO TO FOLDER” screen appeared. Participants in the experimental condition were informed that the “GO TO FOLDER” screen did *not* count as “starting a new task”, and that they should only press the slash key upon starting a new *computer* task (participants in the control condition were not given these additional instructions since they did not form a PM intention).

The interruption task occurred four trials after the cue appeared during the long delay, remained on the screen for 12 s, and was followed by six ongoing task trials before the start of the new ongoing task. Thus, the overall time between cue presentation and the start of a new ongoing task (42 s) was identical for the long delay and long delay with interruption conditions. In Experiment 2, each of the ongoing tasks was presented nine times for a total of 36 minutes. The nine presentations of the ongoing task were determined pseudorandomly such that each of the four tasks was presented once within a “block” (i.e., four different ongoing tasks), and the next block would present the four tasks in a different order. After the item and task order was determined, presentation was identical for each participant. The signal to form an intention (red screen) over a delay occurred during Tasks 3, 6, 11, 15, 18, 21, 26, 30, and 34. Three cues occurred for each delay length (6 s, 42 s, and 42 s with interruption), with one of each type presented in each third of the experiment. After participants completed the same practice phase as that in Experiment 1, the experimenter then reiterated the instructions, and the participants began the experiment.

Results

Prospective memory

To examine the effect of delay on PM performance across the entire distribution of participants, the proportion of successfully fulfilled delayed intentions (short vs. long vs. long interruption) was submitted to a repeated measures ANOVA. This analysis revealed an effect of delay on PM performance, $F(2, 118) = 22.82, p < .001, \eta_p^2 = .162$. When the composite working memory span score was entered as a covariate into the model, the ANCOVA revealed an effect of delay, $F(2, 117) = 23.30, p < .001, \eta_p^2 = .166$, but no effect of span score, $F(1, 117) = 1.39, p = .24, \eta_p^2 = .012$. However, there was a significant interaction of delay and span score, $F(2, 117) = 4.48, p < .05, \eta_p^2 = .037$. To further explore the interaction of delay and span score, we investigated participants falling in the upper (high WMC) and lower (low WMC) quartiles of the overall distribution of WMC span scores.

The proportion of successfully executed delayed intentions was submitted to a 3 (delay: short vs. long vs. long interruption) \times 2 (WMC: high vs. low) mixed-factorial ANOVA (see Figure 2). This analysis revealed that overall performance was better for high-WMC participants than for low-WMC participants, $F(1, 58) = 4.58, p < .05, \eta_p^2 = .073$. There was also an effect of delay,

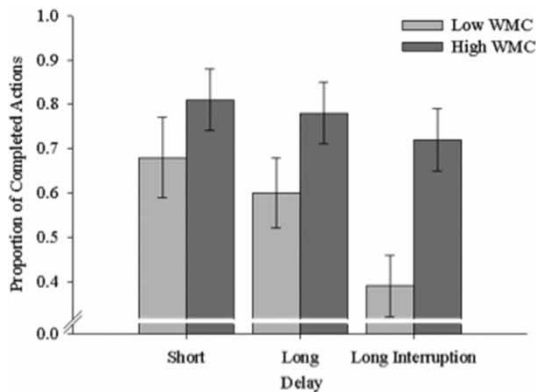


Figure 2. Proportion of successfully fulfilled delayed intentions for Experiment 2. WMC = working memory capacity. Error bars reflect standard errors.

$F(2, 58) = 20.00, p < .001, \eta_p^2 = .256$, indicating that performance tended to decrease across delays. However, this effect was qualified by an interaction between WMC and delay, $F(2, 58) = 5.85, p < .01, \eta_p^2 = .092$. This interaction reflects that for low- but not high-WMC individuals, performance declined across delays. Follow-up comparisons revealed that for low-WMC individuals, performance was better for short than for long delays, $t(29) = 2.25, p < .05, d = 0.42$, and better for long delays than for long delays with an interruption, $t(29) = 3.47, p < .05, d = 0.64$. For high-WMC individuals, performance did not differ between short and long delays, $t(29) = 1.84, p = .18, d = 0.25$, or for long with or without an interruption, $t(29) = 1.72, p = .1, d = 0.32$. However, performance was better for short delays than for long delays with an interruption, $t(29) = 2.8, p < .01, d = 0.5$. Thus, these results suggest that performance was generally impaired for low-WMC relative to high-WMC individuals, and interruptions dramatically attenuated performance for low-WMC individuals.

Cost analyses

Overall, there were no differences in latencies between the high-WMC, low-WMC, and control groups for ongoing task trials during blocks in which no red screen appeared, $F(2, 87) = 2.29, p = .11, \eta_p^2 = .05$. As with Experiment 1, we examined response latencies on trials following cue presentation for high- and low-WMC individuals compared to the same trials for the control group that had no PM intention. The data are summarized in the lower half of Table 1.

We first examined the two trials that occurred immediately prior to and after cue presentation for the short and long delays by submitting mean reaction times to a 2 (delay: short vs. long) \times 2 (trial type: preceding cue vs. following cue) \times 3 (group: high vs. low vs. control) mixed-factorial ANOVA. Two low-WMC individuals were inaccurate on two trials following the cue during the long delay and were therefore not included in the analyses. The analysis revealed an effect of group, $F(2, 85) = 12.39, p < .001, \eta_p^2 = .226$, an effect

of delay, $F(1, 85) = 10.81, p < .01, \eta_p^2 = .113$, and an effect of trial type, $F(1, 85) = 75.66, p < .001, \eta_p^2 = .471$. There was no interaction of group and delay and no three-way interaction, $F_s < 1$. However, there was an interaction of delay and trial type, $F(1, 85) = 19.53, p < .001, \eta_p^2 = .187$, indicating faster latencies in the long delay prior to but not following cue presentation. Of primary interest, however, was the interaction of group and trial type that replicated the results from Experiment 1, $F(2, 85) = 21.65, p < .001, \eta_p^2 = .337$. This interaction primarily reflects that while both high- and low-WMC groups slowed following cue presentation, $t(29) = 7.36, p < .001, d = 1.50$, and $t(27) = 7.56, p < .001, d = 1.15$, the control group did not, $t(29) < 1$. These results suggest that the intended action was retrieved after cue presentation for both high- and low-WMC individuals.

To examine whether participants exhibited slowing following cue presentation for the remainder of the trials during the long delay, we also compared latencies for trials occurring prior to cue presentation with the trials that followed the cue presentation (after excluding the first two trials) by submitting mean response latencies to a 2 (trial type: preceding cue vs. following cue) \times 2 (group: high vs. low vs. control) mixed-factorial ANOVA. The group effect was just above the conventional significance level, $F(2, 85) = 3.08, p = .05, \eta_p^2 = .068$, reflecting relatively slower latencies for the low-WMC group. There was also an effect of trial type, $F(1, 85) = 15.36, p < .001, \eta_p^2 = .153$, indicating faster latencies following cue presentation. However, there was no interaction of trial type and group, $F < 1$. Thus, participants actually responded more quickly following the presentation of a cue, but this did not differ across groups.

To examine cost in the long delay with an interruption (see right half of Table 1), we first compared latencies for the four trials immediately prior to and following cue presentation (but before the interruption task). Mean response latencies were submitted to a 2 (trial type: preceding cue vs. following cue) \times 3 (group: high vs. low vs. control) mixed-factorial ANOVA. This

analysis revealed a main effect of group, $F(2, 85) = 5.76, p < .01, \eta_p^2 = .153$, and an effect of trial type, $F(1, 85) = 59.35, p < .001, \eta_p^2 = .411$. Furthermore, there was a significant interaction of group and trial type, $F(2, 85) = 14.09, p < .001, \eta_p^2 = .249$. This interaction reflects that while both the high- and low-WMC groups slowed following cue presentation, $t(29) = 6.89, p < .001, d = 1.49$, and $t(27) = 7.13, p < .001, d = 0.89$, respectively, the control group did not, $t(29) < 1$. Thus, despite no latency differences prior to cue presentation, both high- and low-WMC exhibited cost to ongoing task performance following presentation of the cue, suggesting that these participants retrieved the intended action.³

Predictions

We submitted predictions for each delay to a 2 (delay: short vs. long) \times 2 (WMC: high vs. low) mixed-factorial ANOVA. This analysis revealed no effects of delay or WMC, and no interaction between the two, $F_s < 2.16, p_s > .14$.

Discussion

As with Experiment 1, the results from Experiment 2 demonstrate that there are important individual differences in the ability to successfully fulfil delayed intentions after being interrupted. Specifically, low-WMC individuals tended to do worse than high-WMC individuals across delay intervals and were particularly affected by an interrupting task. In contrast, high-WMC individuals showed little negative effects of including an interrupting task, although this interruption did slightly reduce performance relative to a short delay,

suggesting that high-WMC individuals are not impervious to disruption. Cost analyses revealed that response latencies for high- and low-WMC groups, but not the control group, were slower immediately after cue presentation for both short and long delays and before the interruption occurred during the long delay. However, there was no cost throughout the remainder of the ongoing task in the long delay. This result suggests that high- and low-WMC groups probably retrieved the intended action and may have reformulated the goal, thereby reducing cost throughout the remainder of the long delay.

The overall decrease in performance across experiments may be a result of different methodologies. The inclusion of the interruption task may have caused participants to alter their attentional allocation after the presentation of the cue in anticipation of an interruption rather than solely focusing on the ongoing task and fulfilment of the intended action. Alternatively, decreased performance may be an artefact of fewer cues in Experiment 2 than in Experiment 1. That is, if participants only failed to respond to one cue during the long delay, performance would be at 66% in Experiment 2 but 75% in Experiment 1. This may also explain why the numerical decrease in performance across delays for low-WMC individuals in Experiment 1 was statistically lower in Experiment 2. The fact that high-WMC individuals did not show increased performance in the long delay may reflect that these participants did not predict any greater difficulty in retrieving the intention in the long delay as in Experiment 1 and therefore did not engage compensatory strategies to increase performance. Overall, the decreased PM performance for low- relative to

³ We also examined latencies following cue presentation for the four trials occurring prior to and six trials following the interruption task. This analysis revealed a main effect of group, $F(2, 85) = 4.35, p < .05, \eta_p^2 = .093$, an effect of trial type, $F(1, 85) = 53.26, p < .001, \eta_p^2 = .385$, and an interaction of group and trial type, $F(2, 85) = 11.30, p < .001, \eta_p^2 = .210$. This interaction primarily reflects that while the control group exhibited a substantial increase in latencies following the interruption task, $t(29) = 8.28, p < .001, d = 1.68$, the high-WMC group showed a much smaller increase in latencies, $t(29) = 2.73, p < .01, d = 0.61$, and low-WMC participants did not show a statistically significant increase in latency after interruption, $t(27) = 1.80, p = .08, d = 0.32$. These results suggest that performing the interruption task and monitoring the computer screen for the resumption of the ongoing task simultaneously may have been sufficiently taxing to slow performance after the interruption for all groups. However, because high- and low-WMC groups were already performing the task slower than the control group due to retrieving the intention after cue presentation, the relative increase in latencies following the interruption was much more substantial for the control group.

high-WMC individuals converges with the results from Experiment 1 suggesting that they may have had difficulty in retrieving the intention from long-term memory upon completion of the ongoing task. Moreover, interruptions could have theoretically altered task context leading to more severe consequences for the low-WMC individuals. That is, exacerbated changes in task context further diminished low-WMC individuals' ability to refresh or retrieve the target action following the interrupting task.

GENERAL DISCUSSION

The purpose of the current study was to examine how individual differences in working memory would relate to the delayed execution of prospective memories in college-aged sample. Using multiple complex-span tasks to measure working memory capacity, we found a clear relationship between working memory and PM abilities in two experiments. These results suggest that PM performance is generally impaired across all retention intervals in low- relative to high-WMC individuals, and that interruptions particularly impair low-WMC individuals. Theoretically, low-WMC individuals may be less likely to periodically refresh or reformulate the intention, and high-WMC individuals may be better able to flexibly control attention in the face of distraction and refresh or retrieve the intended action from long-term memory.

Secondary analyses suggest that high- and low-WMC individuals performed the task in a fundamentally similar manner (for similar results comparing younger and older adults see Kelly et al., 2013). Cost analyses revealed that slowing was restricted only to the first two trials after cue presentation in the short and long delays, but there was no slowing for the remainder of the delay. This suggests that the intention was initially retrieved and that rather than trying to actively maintain the intention throughout the delay, participants may have reformulated their intention and then relied on retrieval of the intention from long-term memory upon the conclusion of the ongoing task (Einstein et al., 2000; McDaniel et al., 2003).

This view could account for the initial cost immediately after intention retrieval, the lack of cost throughout the remainder of the delay, and the relatively high performance across experiments. However, because task switching requires attentional resources necessary to update task goals to match the new ongoing task instructions (Marsh, Hancock, & Hicks, 2002), low-WMC individuals may have had particular difficulty in retrieving the intention from long-term memory, especially when they were interrupted just prior to switching tasks. The enhanced performance for high- relative to low-WMC individuals may be due to their ability to generate more diagnostic temporal-contextual retrieval cues to retrieve intention at the beginning of the new task. However, it still might be the case that participants tried to actively maintain the intention during the ongoing task, but because the trials were experimenter paced, participants may have been able to sneak in rehearsals after their response but before the next ongoing task trial and were therefore undetected by the cost analyses.

Previous research has implicated an important role of individual differences in attentional control processes necessary for cue detection in standard PM tasks (e.g., Breneiser & McDaniel, 2006; Brewer et al., 2010; Marsh & Hicks, 1998; Smith & Bayen, 2005). The current study extends previous findings by suggesting that beyond attentional control, individual differences in controlled retrieval of momentarily displaced information is an important determinant of successful fulfillment of prospective memories. When execution of retrieved intentions must be delayed, controlled attention is necessary to allocate resources toward the ongoing task as well as to maintaining the intention in working memory. However, once this intention has been displaced from primary memory, it must be retrieved from secondary memory. This can be accomplished either by reformulating the intention upon initial retrieval such that the start of a new task serves as a cue to retrieve the new intention (McDaniel et al., 2003), or by periodically reactivating the intention during the ongoing task (Einstein et al., 2003). Regardless of the exact mechanisms, we suggest that the ability

to effectively reformulate and retrieve intentions from long-term memory underlies individual differences in the delayed execution of prospective memories. The dual-component model of WMC (Unsworth & Engle, 2007) specifies the relationship of attention and memory control processes with higher order cognitive processes and is most consistent with the current differences between low- and high-WMC individuals in PM performance. Future research should further explore the joint role of attention and memory in fulfilling both immediate and delayed intentions.

One potential criticism of the current study is that we did not directly assess performance for immediate retrieval of the intended action (i.e., retrieve–execute PM). However, given that previous research has found that older and younger adults do not differ in their ability to immediately execute the intended action when highly salient or focal cues are used (Einstein et al., 2000; Kelly et al., 2013; McDaniel et al., 2004), and that high- and low-WMC individuals show similar PM performance using focal cues (Breneiser & McDaniel, 2006; Brewer et al., 2010), we did not feel that this manipulation was necessary. Nonetheless, it is possible, albeit unlikely, that differences in the successful fulfilment of delayed intentions could be due to differences in the ability to initially retrieve the intended action. It should be noted that previous research using salient cues such as the ones used in the current study results in near-perfect performance when intentions can be fulfilled immediately, suggesting that high-WMC individuals are not impervious to forgetting over brief delays and interruptions. Future research could use a modified delayed–execute task that ensures that the intention is initially retrieved by having participants respond both immediately following the cue and at the start of a new ongoing task to better understand initial retrieval processes and the slowing that occurs on the following trials (see Kelly et al., 2013).

Beyond the theoretical significance of the current study, these results have important practical implications as well. In high-risk situations such as in the emergency room or aviation operations,

failures of delayed–execute prospective memories could have severe negative ramifications. To return to the previous example, a physician may be in the process of picking up important laboratory results when suddenly a new patient is rushed in that needs immediate attention. Failing to pick up the results after attending to the new patient could result in fatal consequences. The results from the current study suggest that in demanding situations that require attention to be devoted to several different ongoing tasks, suspending prospective memories over delays can have dramatic influences on eventual intention fulfilment. Furthermore, when attention is captured by some interruption to the ongoing activity, these suspended actions may be more likely to result in failures of execution regardless of an individual's working memory capacity. Critically, however, these failures were most apparent for low-WMC individuals, potentially due to their inability to maintain or retrieve the intended action even with delays as short as 6 s. Low-WMC individuals consistently showed impairment across delays relative to high-WMC individuals who showed little negative effects of delay or interruptions. Although there are probably other individual differences variables that contribute to PM performance, these findings suggest that in settings that require constant task switching and may include delays or interruptions before the appropriate intention can be fulfilled, low-WMC individuals may have particular issues in resolving competing demands.

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