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The Relationships of Working Memory, Secondary Memory, and General Fluid Intelligence: Working Memory Is Special

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Recent efforts have been made to elucidate the commonly observed link between working memory and reasoning ability. The results have been inconsistent, with some work suggesting that the emphasis placed on retrieval from secondary memory by working memory tests is the driving force behind this association (Mogle, Lovett, Stawski, & Sliwinski, 2008), whereas other research suggests retrieval from secondary memory is only partly responsible for the observed link between working memory and reasoning (Unsworth & Engle, 2006, 2007). In the present study, we investigated the relationship between processing speed, working memory, secondary memory, primary memory, and fluid intelligence. Although our findings show that all constructs are significantly correlated with fluid intelligence, working memory—but not secondary memory—accounts for significant unique variance in fluid intelligence. Our data support predictions made by Unsworth and Engle (2006, 2007) and suggest that the combined need for maintenance and retrieval processes present in working memory tests makes them special in their prediction of higher order cognition.

Keywords: working memory, fluid intelligence, secondary memory, primary memory

Research examining individual differences in working memory function has led to numerous discoveries about how the human memory system operates. These insights hold important theoretical and practical utilities. Theoretically based research has revealed that working memory is a system that operates via a dynamic interaction between memory and executive attention processes (Cowan, 1995), allowing individuals to maintain task goals in the face of interference (Conway, Cowan, & Bunting, 2001; Kane & Engle, 2000), to update memory contents to meet current demands (Friedman et al., 2006), and to integrate distinct memory elements to form novel relationships (Oberauer, Süß, Wilhelm, & Wittman, 2008). Working memory research has also yielded results with far-reaching practical implications. For example, working memory dysfunction is highly sensitive to the presence of various psychoneurological disorders, such as schizophrenia (Barch, 2003), Parkinson's disease (Altgassen, Phillips, Kopp, & Kliegel, 2007), and Alzheimer's dementia (Collette, Van der Linden, & Salmon, 1999). Additionally, laboratory working memory tests can be used to identify individuals who have genetic risk factors for developing Alzheimer's dementia (Rosen, Bergeson, Putnam, Harwell, & Sunderland, 2002).

The widespread predictive utility of the working memory construct makes it a powerful tool for both scientists and practitioners. One of the most reliable demonstrations of the predictive power of working memory is its ability to account for variation in higher order cognitive functioning, such as fluid intelligence (Engle, Tuholski, Laughlin, & Conway, 1999; Friedman et al., 2006; Kane et al., 2004; Shelton, Elliott, Hill, Calamia, & Gouvier, 2009). Understanding the nature of this relationship is critical in determining why working memory is especially useful in predicting how well people can reason and adapt to an increasingly complex environment. Recent work, spearheaded by Unsworth and Engle (2006, 2007), has focused on the possibility that the key element linking working memory and fluid intelligence is the combination of active maintenance in primary memory and retrieval from secondary memory. Unsworth and Engle have argued that traditional working memory tasks (complex span tasks comprising both storage and processing demands) force people to actively maintain memoranda until they engage in the processing component of the task, at which point the memoranda must be displaced to secondary memory (see also McCabe, 2008). When it is time to retrieve the items, individuals must conduct a controlled search of the contents of secondary memory. One study revealed that participants who performed in the highest quartile on working memory tasks recalled more actual items and fewer erroneous items in a delayed free recall test, and they produced faster retrieval rates (Unsworth, 2007). These findings suggest that people who perform well on working memory tests could better constrain their search set and more effectively retrieve items from secondary memory. This ability would also be useful for the novel problem-solving component inherent to tests of fluid intelligence. For example, when trying to decide which pattern segment will best complete a

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matrix design (e.g., Raven's Advanced Progressive Matrices; Raven, Raven, & Court, 1998), it is necessary to maintain separate pieces of the design to determine how they fit together. As the designs increase with complexity, it becomes more difficult to hold these items in the limited space of primary memory, leading to some of the items being displaced into secondary memory. Ultimately, pertinent items must be retrieved from secondary memory to determine which option will best solve these complex problems.

Several recent studies have demonstrated that the link between working memory and fluid intelligence is, at least partly, driven by the shared need for retrieving information from secondary memory. Unsworth and Engle (2006) addressed this issue by examining how recall performance for lists of varying lengths in simple span (e.g., digit span) and complex span (e.g., operation span) tasks predicted variation in fluid intelligence. Engaging in the processing component of complex span tests purportedly requires participants to move the to-be-remembered items to secondary memory, whereas only the longer list lengths (e.g., >4 items) of simple span tasks require this process once the items have exceeded the capacity of primary memory. However, items from the shorter list lengths (e.g., <4 items) can be maintained in primary memory if participants are not required to engage in any secondary task. Unsworth and Engle found that individual differences in the number of items that people could recall from complex span tests (across all list lengths) and the longer list lengths of simple span tests predicted a significant amount of unique and shared variance in fluid intelligence; however, the number of items recalled from shorter simple span lists was not a good predictor of the criterion variable. These data suggest that simple span tests are good predictors of fluid intelligence only if the longer list lengths are isolated, whereas performance on complex span tasks is a good predictor of fluid intelligence regardless of list length. The authors concluded that the dual emphasis on processes underlying both primary and secondary memory in working memory tasks is the driving force behind their strong association with higher order cognition.

A provocative study published by Mogle, Lovett, Stawski, and Sliwinski (2008) extended this line of inquiry. In their study, a large sample of undergraduates completed three measures of working memory (complex span tests), primary memory (simple span tests), secondary memory (cued recall and recognition of supraspan lists, and story recognition), processing speed, and one fluid intelligence test (Raven's Advanced Progressive Matrices). Participants completed these tests in one of three testing conditions: via the Internet, unsupervised computer testing, or supervised computer testing. They used structural equation modeling techniques to analyze the data, reporting an unexpected trend. Controlling for working memory variability did not diminish the relationship between secondary memory and fluid intelligence; however, controlling for secondary memory variability did diminish the relationship between working memory and fluid intelligence. In fact, the working memory construct no longer accounted for any unique variance in fluid intelligence. The authors interpreted their data as support for the argument that the relationship between working memory and fluid intelligence was driven by individual differences in the ability to retrieve information from secondary memory. Mogle et al. concluded by posing the following proposition, "if the relationship between these tasks and fluid intelligence is not due to any unique features of complex span tasks, it may prove more fruitful to determine which secondary memory processes relate to fluid intelligence" (p. 1076).

In the present study, we sought replication and extension of Mogle et al.'s (2008) findings with the advantage of using a controlled laboratory design. Participants completed a battery of cognitive tests that were used to represent the constructs of working memory, secondary memory, primary memory, fluid intelligence, and processing speed. An important strength of the present study was the way in which we operationalized working memory and secondary memory. We utilized a combination of laboratory-based working memory tests (two complex span tests and the N-back task)—which allowed for a broader assessment of this multifaceted construct (for a discussion of this issue, see Oberauer et al., 2008)—as well as neuropsychological tests that have been shown to have strong psychometric properties (Wechsler, 1997a) to assess secondary memory. Our goal was to investigate the robustness of the finding that secondary memory is the driving force behind the predictive power of working memory. To foreshadow our results, we found that working memory, rather than secondary memory, was special in its ability to predict higher order cognition.

Method

Participants

There were 172 undergraduate students (mean age = 20.55 years, *SD* = 3.74; 43 men) retained in the final sample. They participated either for extra credit or partial fulfillment of course credit in psychology courses.

Materials

Portions of this data set were reported in Shelton et al.'s (2009) study. The previous study focused on the relationship between laboratory and clinical tests of working memory in their prediction of fluid intelligence. Please see this reference for a more complete description of the working memory and fluid intelligence tasks.

Working memory tests. Participants completed three traditional laboratory working memory tests: the automated operation span (Ospan; Unsworth, Heitz, Schrock, & Engle, 2005), the listening span (Lspan; Cowan et al., 2003), and the N-back task (Shelton, Metzger, & Elliott, 2007). In the Ospan task, participants viewed a series of intermixed letters and math problems. First, they were told to respond to the veracity of the presented math solution, which remained on the screen for a set amount of time (participants' mean response time during the practice trials plus 2.5 standard deviations). Next, a letter appeared on the screen for 800 ms, and they were told to remember the series of letters until a later point. Their score consisted of the total number of items they recalled in perfectly recalled trials. In the Lspan task, participants heard sentences read aloud over headphones, and they had to determine the veracity of each sentence. The decision phase was not timed, but an experimenter was present to encourage participants to move forward to the next trial. Participants were told to remember the last word in each sentence for later recall. Their score reflected the total number of items correctly recalled from trials that were performed perfectly. The N-back task consisted of a list of items presented individually at a rate of one item per second, and at the end of each list, participants were asked to recall the last item in the list—the one presented 1-back, 2-back, or 3-back in the list. Only performance in the 2-back and 3-back positions was used to index working memory function. Their score was determined by the average number of items correctly recalled in the 2-back and 3-back positions.

Primary memory. The last word and 1-back positions of the N-back task constituted our index of primary memory.[1] Participants' scores were the average number of items recalled correctly in the last word and 1-back positions.

Processing speed tests. Digit Symbol Coding (Weschler Adult Intelligence Scale—Third Edition [WAIS–III]; Wechsler, 1997a) involved the participant copying symbols that have been paired with numbers. A key with the symbol/number pairs was presented for the entire test at the top of the page containing the stimuli. The raw score reflected the number of symbols drawn beneath the presented number in 120 s. In the second WAIS–III subtest, Symbol Search, the participant visually scanned for two target symbols embedded within a search group of five symbols. They were instructed to mark "yes" or "no" to indicate whether a target symbol was found in the search group. The raw score for Symbol Search was determined by the number of correct responses obtained in 120 s minus the number of incorrect responses.

Fluid intelligence tests. On the WAIS–III Block Design subtest, the participant used bicolored blocks to replicate a visually presented design. Scoring was based on both the correct replication of the design and how quickly the individual completed the task. WAIS–III Matrix Reasoning involved asking the participant to complete a picture or pattern by choosing the missing part from potential solutions. The task was not timed, and scores reflected the number of correct solutions made. Participants also completed the Raven's Advanced Progressive Matrices. In this task, participants viewed incomplete matrix patterns and were told to choose which option best completed the pattern. Individual scores reflected the total number of items responded to correctly in the task.

Secondary memory tests. The following subtests of the Weschler Memory Scale—Third Edition (WMS–III; Wechsler, 1997b) were used as indicators of secondary memory and were administered to participants according to the protocol described in the test manual. Raw score data were utilized for all analyses. Three of the four subtests composing the Immediate Memory Index of the WMS–III were used to index secondary memory. The Faces I subtest was not used in further analyses, as exploratory model testing revealed that it loaded poorly on the secondary memory factor. In Logical Memory I, the participant was presented with a short story and was asked to immediately repeat back what he or she remembered. The participant was instructed to use the same words read by the examiner, if possible, and to start at the beginning of the story. Logical Memory I consisted of two stories. The first story was presented once, and the second story was presented twice. Learning and recall for story material was assessed after each presentation, but only the first recall scores from the two stories were averaged to constitute scores on this test. Verbal Paired Associates I was used to assess the ability of the participant to learn unrelated word pairs. The participant was initially presented with eight pairs of unrelated words at the rate of one pair every 3 s; he or she was then given the first word of each pair and asked to recall the second word. This was repeated for four trials always using the same list of word pairs. The total number of correctly recalled word pairs formed the total score. In Family Pictures I, the participant was shown four different scenes (for 10 s each) involving four different family members and was asked to remember as much as he or she could about each scene. The participant was then asked to name a character from the scenes, to provide the character's location, and to describe what the character was doing in the scene. Scores were calculated according to the protocol outlined in the WMS–III manual (Wechsler, 1997b).

Procedure

Participants completed all of the tests as part of a larger battery in two sessions that lasted 2 hr each and that occurred approximately 1 week apart. All of the laboratory tests were administered to participants at individual computer stations. The WAIS–III and the WMS–III were administered by trained personnel according to manual protocols. The informed consent process took place at the beginning of the first session, and debriefing occurred at the end of the second session.

Results

The goal of the analyses was to examine the relationships among the measures and constructs of processing speed, primary memory, working memory, secondary memory, and fluid intelligence. This goal was approached in several steps. First, the variables were each examined for the presence of outliers. Only four variables—out of the possible 1,914—revealed values greater than 3.5 standard deviations above or below the mean of the respective variable. The results did not change when these values were replaced with the mean ± 3.5 standard deviations; thus, the raw values were used in the following analyses. As presented in Tables 1 and 2, descriptive statistics and correlations were examined. No extreme values were observed in the skewness and kurtosis indices (Kline, 2005), suggesting univariate normality can be assumed. Next, a measurement model was tested to examine the underlying structure of the multiple indicators used to assess the four latent constructs (processing speed, working memory, secondary memory, and fluid intelligence) and the observed measure of primary memory; to achieve this, we used AMOS 7 (Arbuckle, 2006). It was proposed that each of the different indicators would load onto one of the four latent factors and that each of the latent factors would be distinguishable (i.e., multicollinearity would not exist). Finally, a nested series of models was compared to evaluate the relative contributions of the different measures and constructs (i.e., processing speed, primary memory, working memory, and secondary memory) to the prediction of fluid intelligence (for a similar approach, see Mogle et al., 2008).

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[1] Digit span forward scores were available in this data set, and we attempted to use this as an index of primary memory; however, several statistical analyses revealed that these scores were highly related to our working memory measures and could not be statistically separated from these measures. The primary memory N-back index did separate nicely from the other memory measures without creating problems for the model and represented a theoretically sound index of primary memory. The zero-order correlation between the last item and 1-back positions used to create this index was .35 ($p < .001$).

Table 1
Descriptive Statistics for All Measures

Measure	*M*	*SD*	Range	Skew	Kurtosis
Processing speed					
Symbol Search	41.09	6.80	39	−0.09	0.57
Digit Symbol Coding	88.25	13.27	75	−0.00	0.62
Primary memory					
Primary memory N-back	8.73	1.15	6.50	−1.41	3.13
Working memory					
Operation span	44.15	15.54	68	−0.03	−0.52
Listening span	29.77	12.22	67	1.075	1.63
Working memory N-back	4.15	2.07	9.50	0.19	−0.67
Secondary memory					
Story recall	13.86	3.24	15.5	−0.11	−0.64
Verbal Paired Associates I	22.97	5.95	28	−1.04	0.98
Family Pictures I	51.36	7.44	40	−1.31	2.10
Fluid intelligence					
Raven's Advanced Progressive Matrices	25.50	4.04	19	−0.22	0.04
Block Design	45.79	10.94	52	−0.10	−0.67
Matrix Reasoning	19.89	2.92	17	−0.94	1.72

Note. $N = 172$ for all measures. Raw scores were used for the measures from the Weschler Adult Intelligence Scale—Third Edition (WAIS–III; processing speed) and the Weschler Memory Scale—Third Edition (WMS–III; secondary memory). The N-back task was divided into two components: The primary memory N-back measure includes the average of the raw scores for Lags 0 and 1, whereas the working memory N-back measure includes the average of the raw scores for Lags 2 and 3. Story recall represents the average of the total number of items recalled from the first two stories in the WMS–III Logical Memory I subtest. Verbal Paired Associates I represents the total score from the four recall trials of the WMS–III. Fluid intelligence was represented by a combination of measures from the WAIS–III (in which raw scores were used) and the Raven's Advanced Progressive Matrices (in which the total score was used).

Three measures of model fit were calculated: chi-square, comparative fit index (CFI), and root mean square error of approximation (RMSEA). A nonsignificant chi-square indicates good model fit; however, chi-square is sensitive to sample size. A *CFI* value of .95 or higher and a *RMSEA* value of .06 or lower are indicative of good model fit (Hu & Bentler, 1999).

Model fit for the measurement model was good (see Figure 1), $\chi^2(46, N = 172) = 61.0$, $p = .068$, $CFI = .958$, $RMSEA = .044$. Each of the different indicators loaded well on their respective latent constructs. Standardized factor loadings ranged between .40 and .72,[2] and all paths from the observed variables to the latent constructs were significant at $p < .01$. Additionally, fluid intelligence was significantly correlated with processing speed ($r = .26$), primary memory N-back ($r = .37$), working memory ($r = .71$), and secondary memory ($r = .57$).

In addition to demonstrating that processing speed, primary memory, working memory, and secondary memory were all correlated with fluid intelligence, we were specifically interested in examining how these different constructs relate to the explanation of variance in fluid intelligence (i.e., how much unique variance does each of these three constructs explain in terms of fluid intelligence). Following the technique used by Mogle et al. (2008), a series of four, nested structural equation models were compared to test the changes in the model fits when different paths in the model were set to zero (see Figure 2). In the first model, the paths from working memory and secondary memory to fluid intelligence were constrained to zero, and as shown in Figure 2A, model fit was poor. The secondary memory path was constrained in Model 2 (see Figure 2B), the working memory path was constrained in Model 3 (see Figure 2C), and Model 4 allowed all of the predictors to contribute—such that processing speed, primary memory, working memory, and secondary memory were set to predict fluid intelligence (see Figure 2D). Inspection of Figure 2 reveals that Model 2 and Model 4 had very similar fit statistics. Indeed, constraining the secondary memory path in Model 2 did not result in a significant drop in model fit compared with Model 4, $\chi^2(1, N = 172) = 1.7$, $p > .05$. This clearly demonstrates that working memory is contributing special and unique variance in the prediction of fluid intelligence, above and beyond secondary memory. The only instance in which a model (Model 3) showed a significant path for secondary memory was when working memory did not contribute to the prediction of fluid intelligence. Thus, our results contradict those of Mogle et al. (2008).

Discussion

In the present study, we addressed an important question: Is working memory special? These data suggest that the answer is yes. The results of the structural equation modeling analyses revealed that working memory was a unique predictor of fluid intelligence, whereas secondary memory was not a unique predictor of the criterion construct. These results are inconsistent with the

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[2] The standardized factor loading for Symbol Search was greater than one, representing a Heywood case that could have been driven by having only two indicators on the processing speed construct (Kline, 2005). We took two approaches to addressing this issue. First, we constrained this parameter value to one and tested the measurement model as well as the nested structural models (see Figures 1 and 2). Second, we removed Symbol Search from the processing speed construct, which left one observed variable representing processing speed (Digit Symbol Coding). No notable differences were observed in the fit of the measurement model or nested structural models relative to when Symbol Search was retained in the model.

Table 2
Correlations Among All Measures

Measure	1	2	3	4	5	6	7	8	9	10	11	12
1. Symbol Search	*.77*											
2. Digit Symbol Coding	.51**	*.84*										
3. Primary memory N-back	−.03	.11	*.62*									
4. Operation span	.08	.10	.36**	*.77*								
5. Listening span	.05	−.04	.30**	.54**	*.74*							
6. Working memory N-back	.05	.13	.35**	.32**	.41**	*.77*						
7. Story recall	.02	.00	.15*	.24**	.31**	.30**	*.64*					
8. Verbal Paired Associates I	.05	.11	.17*	.07	.07	.16*	.25**	*.86*				
9. Family Pictures I	.15	.07	.08	.06	.17*	.13	.28**	.22**	*.72*			
10. Raven's Advanced Progressive Matrices	.06	.09	.22**	.29**	.33**	.38**	.20**	.07	.20**	*.75*		
11. Block Design	.27**	.11	.29**	.29**	.31**	.34**	.15*	.17*	.28**	.41**	*.75*	
12. Matrix Reasoning	.14	.12	.19*	.18**	.26**	.32**	.20**	.18*	.21**	.40**	.40**	*.65*

Note. Italicized numbers on the diagonal represent Cronbach's alpha measures of internal consistency, reported from the raw data, with the exception of the two measures of processing speed. As these were speeded measures, test–retest stability coefficients were used instead. These values are reported from the normed values available in the Weschler Adult Intelligence Scale—Third Edition: Technical Manual, across the normative sample.
* $p < .05$. ** $p < .01$.

findings of Mogle et al. (2008), which suggested that working memory was not a significant predictor of fluid intelligence once individual differences in secondary memory were controlled for. There are several possibilities for why these differences emerged.

One potential explanation for the discrepant findings stems from differences in the way in which the constructs were operationalized in the two studies. In the present study, all of the secondary memory tasks utilized recall measures, whereas two of the three secondary memory measures used in Mogle et al.'s (2008) study required recognition rather than recall. It is possible that the driving force behind secondary memory and fluid intelligence in Mogle et al.'s study is an overlap between the discrimination process required by the recognition tasks and the need to make a decision between potential solutions in the Raven's Advanced Progressive Matrices. This is, of course, speculative and runs counter to the argument that recognition tests should be less related to higher order cognition than recall tests because external cues are available to assist the retrieval process (for a discussion on this topic, see Unsworth & Engle, 2007).

A potentially more important difference between the present study and Mogle et al.'s (2008) study is the way in which working memory was assessed. As noted by Mogle et al., one potential limitation of their study is that participants had partial control over the pacing of the working memory tasks (self-paced) as opposed to using tests in which task administration parameters (e.g., item presentation rate, time allowed to respond to processing component) were controlled (experimenter-paced). Friedman and Miyake (2004) demonstrated that experimenter-paced tasks were more correlated with higher order cognition than self-paced tasks. They argued that the reason for the superior predictive utility of experimenter-paced working memory tasks was that participants have to actively maintain the incoming information rather than taking additional time to implement various strategies, as is afforded by self-paced tests. In the present study, two of the three working memory tasks were experimenter-paced (Ospan and N-back), whereas only the Lspan task was self-paced. Additionally, in Mogle et al.'s study, the working memory construct was defined by three complex span tasks, whereas in the present study, we assessed working memory using two complex span tasks as well as the N-back task. Oberauer et al. (2008) concluded that working memory was a multifaceted construct, and defining it in this way led to superior prediction of reasoning ability (see also Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002). Oberauer et al. further argued that latent constructs of working memory should be more broadly defined using a variety of different tasks. Thus, the heterogeneity of the working memory construct in the present study could have contributed to its superior prediction of fluid intelligence.

Previous research has been mixed regarding the construct validity of the N-back task as a measure of working memory; however, the key difference in these studies was that a recognition version of the N-back task did not correlate well with complex span tasks (Kane, Conway, Miura, & Colflesh, 2007), whereas a recall version of the N-back task—like the one used in the present study—was shown to be significantly correlated with complex span tasks (Shelton et al., 2009, 2007). The inclusion of the N-back task strengthened the present study in several ways. First, this task encouraged participants to quickly shift items in and out of the focus of attention. Researchers using the N-back task have identified the focus-switching mechanism as a distinct working memory control process (Verhaeghen & Basak, 2005). The focus-switching mechanism that is presumably tapped by the N-back task could contribute to its strong relationship with fluid intelligence. Future research is needed to investigate this possibility. In addition, the results of the present study suggest that another advantage of the N-back task is that an estimate of primary memory (or information present in the focus of attention) can be easily extracted from the performance index.

Although the recall version of the N-back task is a valid and useful measure of working memory, complex span tasks are the most widely used measures of working memory in laboratory-based studies and are considered by many to be the gold standard. The covert retrieval model proposed by McCabe (2008) provides an explanation for what is special about complex span tasks. According to this model, these tasks emphasize active maintenance and retrieval processes by allowing the opportunity for strategic activity during the processing stage. Specifically, many participants can complete the processing activity while also retrieving the

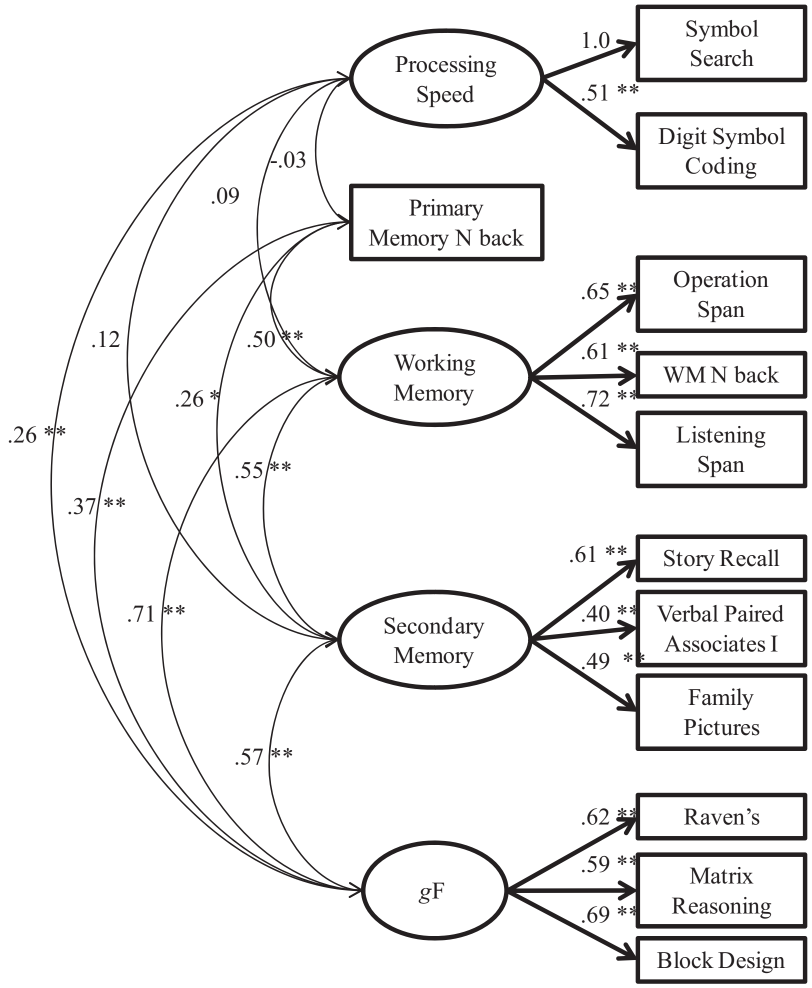

Figure 1. Measurement model depicting the path estimates for the constructs of processing speed, working memory, secondary memory, primary memory, and general fluid intelligence (*g*F). The rectangles indicate observed variables, whereas the ovals indicate latent constructs. The numbers on the double-headed arrows represent correlation coefficients. $^{*}p < .05$. $^{**}p < .01$.

to-be-remembered items. McCabe provided empirical support for these predictions by observing better recall of items from complex relative to simple span tasks on a delayed test. Superior memory for items from the complex span tasks was particularly evident for the initial list items presented, supporting the prediction that participants practice retrieving the presented items during each interleaved processing stage. The fact that delayed recall rates were higher for complex span tasks suggests that the processes underlying successful performance on these tests help to facilitate learning of the material (for a review on the benefit of repeated retrieval attempts for later retention, see Roediger & Karpicke, 2006). The way in which active maintenance and repeated retrieval attempts help to reinforce learning in working memory tests could be a key for why they are able to predict complex human behavior so well. Indeed, recent research has demonstrated that individual differences in associative learning predicted performance on a fluid intelligence test (Tamez, Myerson, & Hale, 2008).

One potential criticism of both Mogle et al.'s (2008) and the present study is that secondary memory was assessed with immediate memory tests. In previous research that used immediate recall tests, separate estimates of primary and secondary memory were both derived from the memory output (Craik, 1968; Unsworth & Engle, 2006). The assumption was that most memory tests requiring immediate retrieval, and that contain enough information to exceed the capacity limit of primary memory, will elicit items that are currently being maintained in both primary memory and secondary memory. We were able to further evaluate this issue in the present study because participants were retested on all of the measures used to assess secondary memory approximately 25–35 min after the immediate test (Wechsler, 1997b). The scores from the delayed tests were used to represent secondary memory in a structural model that was otherwise identical to Model 2D. This model provided good fit to the data and revealed a similar pattern as that observed in Model 2D: Working memory, but not secondary memory, was a unique predictor of fluid intelligence. Researchers should be cautious in choosing how to assess secondary memory to ensure that the purest possible measurement is achieved; however, in the present study, the same pattern of results

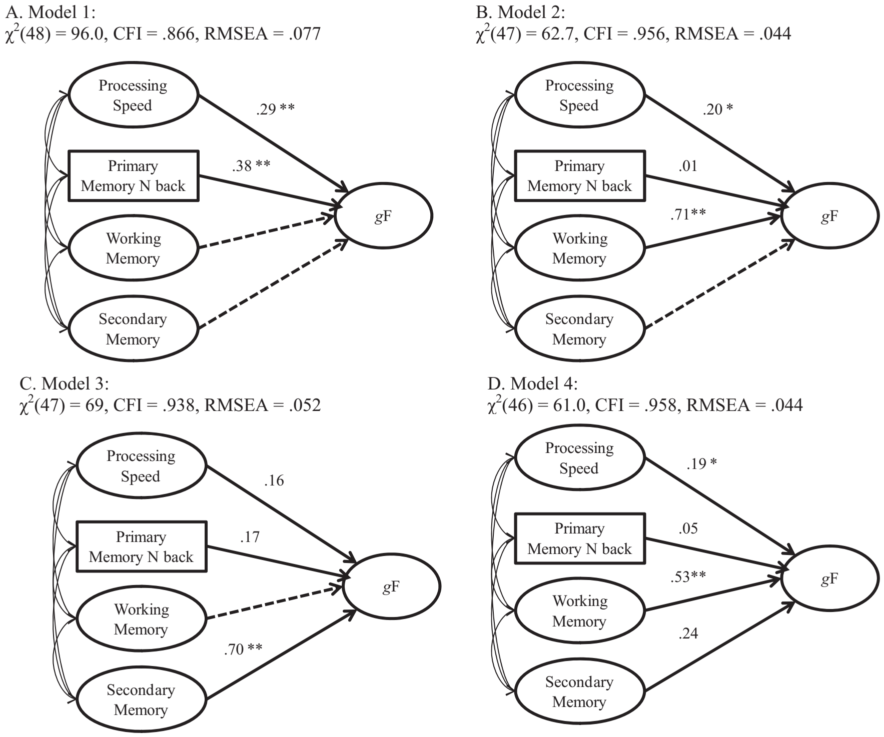

Figure 2. Model comparison using nested structural equation models to illustrate the importance of working memory in the prediction of general fluid intelligence (*g*F) when other paths in the model were constrained to zero. The rectangles indicate observed variables, whereas the ovals indicate latent constructs. The dashed lines indicate paths that were constrained to zero. CFI = comparative fit index; RMSEA = root mean square error of approximation. $^{*}\ p < .05$. $^{**}\ p < .01$.

emerged regardless of whether secondary memory was defined by immediate or delayed tests.

In sum, the present study demonstrates that although working memory, secondary memory, primary memory, and processing speed were all significantly related to fluid intelligence, individual differences in working memory, but not secondary memory, accounted for a significant amount of unique variance in fluid intelligence. There is converging evidence from a recent study that demonstrated that working memory accounted for unique variance in fluid intelligence after controlling for individual differences in secondary memory (Unsworth, Brewer, & Spillers, 2009). Both sets of data are in line with the argument that working memory tasks are special because they demand an interaction between active maintenance of items in primary memory and a controlled search of secondary memory (Unsworth & Engle, 2007). These results are, however, inconsistent with recent findings that suggest that secondary memory is the driving force behind the observed working memory–fluid intelligence link. Although secondary memory does not appear to be the primary determinant of fluid intelligence, we do not want to minimize the important contribution of retrieval processes to performance on fluid intelligence tests. Rather, we argue that future research should focus on how working memory tests, in particular, emphasize the specific processes that drive learning. This, in turn, will shed light on why working memory consistently predicts such a diverse set of human behaviors and does so better than competing constructs.

References

Altgassen, M., Phillips, L., Kopp, U., & Kliegel, M. (2007). Role of working memory components in planning performance in Parkinson's disease. *Neuropsychologia, 45,* 2393–2397.

Arbuckle, J. L. (2006). AMOS 7 [Computer software]. Chicago, IL: Smallwaters.

Barch, D. W. (2003). Cognition in schizophrenia: Does working memory work? *Current Directions in Psychological Science, 12,* 146–150.

Collette, F., Van der Linden, M., & Salmon, E. (1999). Phonological loop and central executive functioning in Alzheimer's disease. *Cortex, 35,* 57–72.

Conway, A. R. A., Cowan, N., & Bunting, M. F. (2001). The cocktail party phenomenon revisited: The importance of working memory capacity. *Psychonomic Bulletin & Review, 8,* 331–335.

Cowan, N. (1995). *Attention and memory: An integrated framework.* Oxford, England: Oxford University Press.

Cowan, N., Towse, J. N., Hamilton, Z., Saults, J. S., Elliott, E. M., Lacey, J. F., . . . Hitch, G. J. (2003). Children's working memory processes: A response-timing analysis. *Journal of Experimental Psychology: General, 132,* 113–132.

Craik, F. I. M. (1968). Two components in free recall. *Journal of Verbal Learning and Verbal Behavior, 7,* 996–1004.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory, and general fluid intelligence: A latent variable approach. *Journal of Experimental Psychology: General, 128,* 309–331.

Friedman, N. P., & Miyake, A. (2004). The Reading Span Test and its predictive power for reading comprehension ability. *Journal of Memory and Language, 51,* 136–158.

Friedman, N. P., Miyake, A., Corley, R. P., Young, S. E., DeFries, J. C., & Hewitt, J. K. (2006). Not all executive functions are related to intelligence. *Psychological Science, 17,* 172–179.

Hu, L., & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling, 6,* 1–55.

Kane, M. J., Conway, A. R. A., Miura, T. K., & Colflesh, G. J. H. (2007). Working memory, attention control, and the N-back task: A question of construct validity. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33,* 615–622.

Kane, M. J., & Engle, R. W. (2000). WM capacity, proactive interference, and divided attention: Limits on long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26,* 336–358.

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. W. (2004). The generality of working memory capacity: A latent variable approach to verbal and visuospatial memory span and reasoning ability. *Journal of Experimental Psychology: General, 133,* 189–217.

Kline, R. B. (2005). *Principles and practice of structural equation modeling.* New York, NY: Guilford Press.

McCabe, D. P. (2008). The role of covert retrieval in working memory span tasks: Evidence from delayed recall tests. *Journal of Memory and Language, 58,* 480–494.

Mogle, J. A., Lovett, B. J., Stawski, R. S., & Sliwinski, M. J. (2008). What's so special about working memory? An examination of the relationships among working memory, secondary memory, and fluid intelligence. *Psychological Science, 19,* 1071–1077.

Oberauer, K., Süß, H. M., Wilhelm, O., & Wittman, W. W. (2008). Which working memory functions predict intelligence? *Intelligence, 36,* 641–652.

Raven, J., Raven, J. C., & Court, J. H. (1998). *Manual for Raven's Progressive Matrices and Vocabulary Scales.* Oxford, England: Oxford Psychologists Press.

Roediger, H. L., & Karpicke, J. D. (2006). The power of testing memory: Basic research and implications for educational practice. *Perspectives on Psychological Science, 1,* 181–210.

Rosen, V. M., Bergeson, J. L., Putnam, K., Harwell, A., & Sunderland, T. (2002). Working memory and apolipoprotein E: What's the connection? *Neuropsychologia, 40,* 2226–2233.

Shelton, J. T., Elliott, E. M., Hill, B. D., Calamia, M. R., & Gouvier, W. D. (2009). A comparison of laboratory and clinical working memory tests and their prediction of fluid intelligence. *Intelligence, 37,* 283–293.

Shelton, J. T., Metzger, R. L., & Elliott, E. M. (2007). Modified lag task as a measure of working memory. *Behavior Research Method, 39,* 482–493.

Süβ, H. M., Oberauer, K., Wittmann, W. W., Wilhelm, O., & Schulze, R. (2002). Working memory capacity explains reasoning ability—And a little bit more. *Intelligence, 30,* 261–288.

Tamez, E., Myerson, J., & Hale, S. (2008). Learning, working memory, and intelligence revisited. *Behavioural Processes, 78,* 240–245.

Unsworth, N. (2007). Individual differences in working memory capacity and episodic retrieval: Examining the dynamics of delayed and continuous distractor free recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33,* 1020–1034.

Unsworth, N., Brewer, G. A., & Spillers, G. J. (2009). There's more to the working memory capacity–fluid intelligence relationship than just secondary memory. *Psychonomic Bulletin & Review, 16,* 931–937.

Unsworth, N., & Engle, R. W. (2006). Simple and complex memory span and their relation to fluid abilities: Evidence from list-length effects. *Journal of Memory and Language, 54,* 68–80.

Unsworth, N., & Engle, R. W. (2007). The nature of individual differences in working memory capacity: Active maintenance in primary memory and controlled search from secondary memory. *Psychological Review, 114,* 104–132.

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

Verhaeghen, P., & Basak, C. (2005). Ageing and switching of the focus of attention in working memory: Results from a modified N-back task. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 58*(A), 134–154.

Wechsler, D. (1997a). *Weschler Adult Intelligence Scale—Third Edition: Technical manual.* San Antonio, TX: The Psychological Corporation.

Wechsler, D. (1997b). *Weschler Memory Scale—Third Edition: Administration and scoring manual.* San Antonio, TX: The Psychological Corporation.

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