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The Contributions of Primary and Secondary Memory to Working Memory Capacity: An Individual Differences Analysis of Immediate Free Recall

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The present study tested the dual-component model of working memory capacity (WMC) by examining estimates of primary memory and secondary memory from an immediate free recall task. Participants completed multiple measures of WMC and general intellectual ability as well as multiple trials of an immediate free recall task. It was demonstrated that there are 2 sources of variance (primary memory and secondary memory) in immediate free recall and that, further, these 2 sources of variance accounted for independent variation in WMC. Together, these results are consistent with a dual-component model of WMC reflecting individual differences in maintenance in primary memory and in retrieval from secondary memory. Theoretical implications for working memory and dual-component models of free recall are discussed.

Keywords: working memory, primary memory, secondary memory, immediate free recall

Working memory is usually referred to as a general purpose system that is responsible for the active maintenance of task- or goal-relevant information while simultaneously processing or acting on other information (Baddeley, 2007). Given the need of such a general purpose system for a wide variety of activities—including problem solving, reading, coordination and planning, and basic intellectual functioning more broadly—recent work has been devoted to measuring the capacity of working memory and investigating individual differences in working memory capacity (WMC). Beginning with Daneman and Carpenter (1980), most researchers have utilized complex working memory span tasks in which to-be-remembered (TBR) items are interspersed with some processing activity. For instance, in the reading span task participants attempt to remember words or letters while reading and comprehending sentences (Daneman & Carpenter, 1980). These tasks can be contrasted with simple memory span tasks in which TBR items are presented without any additional processing activities. The complex span tasks nicely capture the idea that the dynamics of processing and storage are needed to fully understand the essence of working memory and tap its capacity. Furthermore, these tasks can be used to estimate an individual's WMC and examine the correlation between this capacity and other important cognitive abilities.

Due to the popularity of complex span tasks and the fact that they provide good estimates of WMC, a number of theories have been proposed to account for performance on these tasks and to explain working memory more broadly. For instance, many original accounts of complex span tasks emphasized the notion that resources have to be shared between processing and storage activities and thus the capacity of working memory is the amount of total resources that individuals have at their disposal (e.g., Daneman & Carpenter, 1980). Individuals with more resources can effectively deal with the processing task while continuing to maintain activation of the TBR items, which leads to better performance than in the case of individuals with fewer resources. Alternatively, it is possible that the complex span tasks do not index overall resource-sharing abilities but rather that the processing task displaces items from working memory, and thus a rapid switching mechanism is needed to refresh items before they are lost due to time-based forgetting processes such as decay (Towse, Hitch, & Hutton, 1998). According to this task-switching view, individual differences in WMC, as measured by complex span tasks, are due in part to differences in people's ability to rapidly switch items in and out of working memory. The faster one can complete the processing activity and switch attention back to decaying representations, the better overall performance will be. Thus, processing and storage tasks index working memory because they induce a need to switch between processing and storage rather than sharing resources between the two. Recently, Barrouillet and colleagues (e.g., Barrouillet, Bernardin, Portrat, Vergauew, & Camos, 2007) have suggested that a combination of these two views provides the best account of the dynamics of processing and storage in complex span tasks. In their time-based resource-sharing model, they assumed that there is a finite amount of resources that are shared between processing and storage and that during the processing task, TBR items decay. Thus, the ability to share resources and the ability to switch between processing and storage jointly determine the capacity of working memory. As such, this model suggests that individual differences in WMC arise due to both resource-sharing and task-switching abilities. In all three models, the key to understanding working memory and individual differences in WMC relies on an understanding of the dynamics of processing and storage in complex span tasks.

Recently, we proposed an alternative account of working memory and individual differences in WMC (Unsworth & Engle, 2007a). In this view, working memory comprises two functionally

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different components that individuals may differ on. The first component is needed to actively maintain information over the short term. In keeping with James (1890), we have referred to this component as primary memory (PM), although it is conceptually similar to Cowan's (2001) focus of attention and more generally similar to the notion of active goal maintenance in the face of distraction (Engle & Kane, 2004). The second component is needed to retrieve information that could not be actively maintained in PM due to a large number of incoming target items or irrelevant distractors. Also in line with James (1890), we have referred to this component as secondary memory (SM) and have suggested that retrieval from SM relies on a cue-dependent search mechanism (Shiffrin, 1970). On the basis of this account, our interpretation of complex span performance is slightly different from that in previous models. In our account, items are first held in PM but are quickly displaced due to the need to engage in the processing activity. At recall, the majority of items are then recalled from SM via a strategic search. This same basic account also explains performance in simple span tasks. When list lengths are small (roughly four items or less), items are held in PM, and at recall they are simply unloaded. When list lengths are longer (more than four or five items), items will initially be held in PM, but as the number of incoming items increases beyond an individual's capacity, some items will be displaced into SM, and retrieving them will require a strategic search at recall. This view accounts for both simple and complex span tasks without postulating a special role for processing and storage activities. That is, processing and storage together are not needed to measure WMC or to understand working memory more broadly. Rather, storage-only tasks can do as good of a job as more complex span tasks (Unsworth & Engle, 2007b).

Given that this dual-component model of working memory is based on dual-component models of free recall (e.g., Atkinson & Shiffrin, 1971), we have argued that immediate free recall should be an excellent measure of WMC and that understanding performance on immediate free recall should aid in our understanding of working memory (Unsworth & Engle, 2007a). Initial evidence for this view came from our prior work demonstrating that (a) immediate free recall loaded as well as complex span tasks on a WMC factor, (b) high- and low-WMC individuals showed differences on both PM and SM estimates extracted from immediate free recall, (c) high- and low-WMC individuals demonstrated differences at nearly all serial positions in immediate free recall, and (d) separate PM and SM factors could be extracted from complex spans, simple spans, and immediate free recall (Unsworth & Engle, 2007a, 2007b). Thus, we suggested that WMC was partially determined by both PM and SM, with high-WMC individuals generally being better able to maintain information in PM and retrieve information from SM than are low-WMC individuals. Recently Mogle, Lovett, Stawski, and Sliwinski (2008) have argued that SM is the key component to WMC and WMC's relation to higher order cognition and have suggested that understanding PM is not necessary for a fuller understanding of WMC. In contrast, we have argued that both components are needed for a fuller understanding of WMC.

Despite this initial evidence, a direct test of the notion that WMC is jointly determined by PM and SM is wanting. In particular, our previous work has been limited by the fact that in one study only high- and low-WMC individuals were examined, and thus it was not possible to fully examine how PM and SM contribute to WMC (Unsworth & Engle, 2007a). We demonstrated that high-WMC individuals had higher PM and SM estimates than did low-WMC individuals, but this does not necessarily suggest that PM and SM contribute unique variance to WMC. Furthermore, given that the study examined only high- and low-WMC individuals, it is possible that the effect sizes shown in that study were biased due to the use of extreme groups (Conway et al., 2005). An examination of the full range of participants is needed to better demonstrate these effects. In another study, we reanalyzed data from Engle, Tuholski, Laughlin, and Conway (1999), who did collect measures for a full range of participants (Unsworth & Engle, 2007b). An examination of the simple correlations between estimates of PM and SM extracted from immediate free recall and WMC suggested that both PM and SM were correlated with complex and simple spans but were not correlated with each other (Unsworth & Engle, 2007b). However, like the results of the above study examining extreme groups, these results are problematic given that PM tended to have weaker correlations with both complex and simple spans and no estimate of reliability was obtained from the Engle et al. (1999) study. Thus, differences in the simple correlations could have arisen from differences in the reliability of the measures.

In the current study, we aimed to test the notion that PM and SM jointly contribute to WMC by alleviating some of the weaknesses of the previous studies. We did this by testing a full range of participants on multiple measures of WMC, multiple measures of general intellectual ability (g), and multiple trials of immediate free recall. For the immediate free recall measure we extracted PM and SM components from each trial on the basis of Tulving and Colotla (1970) in order to gauge the reliability of each. Additionally, we examined the serial position functions for each trial to determine the reliability of performance for each serial. Assuming that the last serial positions (recency) provide an index of PM and the early serial positions (prerecency) provide an index of SM, we should be able to test the dual-component model with serial position effects in line with the PM and SM estimates. By this we are not suggesting that individual variation in WMC is completely reducible to variation in PM and SM. Rather, we are suggesting that variations in PM and SM are two important sources of variance in WMC and part of the reason WMC predicts higher order cognition so well. Given the multifaceted nature of WMC, additional sources of variance could be due to updating and binding operations as well as individual differences in strategy usage on the complex span tasks.

Overall, the goals of the study were (a) to test the notion that immediate free recall (a storage-only task) measures processes largely similar to those of complex span tasks; that is, immediate free recall should be as reliable as the complex spans, should correlate with the complex span tasks as well as the complex span tasks do with themselves, and should load on the same factor as do the complex spans and with the same magnitude; (b) to test the notion that there are two sources of variance in immediate free recall (PM and SM), on the basis of estimates of PM and SM and serial position functions, consistent with a dual-component model; (c) to test the notion that these two sources of variance (PM and SM) in immediate free recall account for independent variance in WMC; and (d) to examine the extent to which the shared variance between WMC and g is due to shared variance with PM and SM.

Method

Participants

A total of 135 students between the ages of 18 and 35 years were recruited from the University of Georgia. Each student was tested individually in a laboratory session lasting approximately two hours and received course credit for participating.

Materials and Procedure

After signing informed consent, all participants completed operation span, symmetry span, reading span, verbal analogies, number series, and immediate free recall tasks. All tasks were administered in that order (see Unsworth, Redick, Heitz, Broadway, & Engle, 2009, for full task descriptions).

Measures

Operation span (Ospan) task. This task involved solving a series of math operations while trying to remember a set of unrelated letters. Participants were required to solve a math operation, and after solving it they were presented with a letter for 1 s on their computer screen. Immediately after the letter was shown, the next math operation appeared for them to solve, and so on. At the end of the set, participants had to recall the letters from the set in the correct order by clicking on the appropriate letters. For all of the span measures, an item was scored if it was both correct and in the correct position. The total score was therefore the number of correct items in the correct position.

Symmetry span task. Here participants recalled sequences of red squares within a matrix while performing a symmetry-judgment task. In the symmetry-judgment task, participants were shown an 8 $\times$ 8 matrix with some squares filled in black. They had to decide whether the design was symmetrical with respect to its vertical axis. The pattern was symmetrical half of the time. Immediately after determining whether the pattern was symmetrical, participants were presented with a 4 $\times$ 4 matrix with one of the cells filled in red for 650 ms, followed by the next symmetry-judgment task to answer, and so on. At the end of the set, participants had to recall the sequence of red-square locations in the preceding displays in the order in which they appeared by clicking on the cells of an empty matrix. The same scoring procedure as in the Ospan task was used.

Reading span task. For this task, participants read sentences while trying to remember a set of unrelated letters. They would read a sentence and then determine whether the sentence made sense. Half of the sentences made sense, whereas the other half did not. Nonsense sentences were made by simply changing one word in an otherwise normal sentence. After participants gave their response to a sentence, they were presented with a letter for 1 s, and this was immediately followed by the next sentence to read, and so on. At the end of the set, participants had to recall the letters from the set in the correct order by clicking on the appropriate letters. The same scoring procedure as in the Ospan task was used.

Immediate free recall task. In this task, participants were given 10 lists of 10 words each. All words were common nouns that were presented for 1 s each. At test, participants were cued with the presence of *???* to begin recalling the words from the current list. They could remember in any order they wished. Participants had 30 s to recall the words. A participant's total score was the number of items recalled correctly. We also computed, in addition to the total score, estimates of PM and SM for each trial on the basis of Tulving and Colotla's (1970) method. In this method, the number of words between a given word's presentation and recall was tallied. If there were seven or fewer words intervening between presentation and recall of a given word, the word was considered to be recalled from PM. If more than seven words intervened, then the word was considered to be recalled from SM. This method suggests that items in PM are those items that are recalled first, with only a minimal amount of interference from input and output events (Watkins, 1974). Importantly, this method does not suggest that all recency items are recalled from PM, rather only those recency items that are recalled first. It is entirely possible that participants will recall a recency item after many other items have been recalled, in which case that item would be considered to be recalled from SM. Prior work has suggested that this method provides fairly valid estimates of PM and SM (Watkins, 1974).

Verbal analogies task. In this task, participants read an incomplete analogy and were required to select the one word out of five possible words that best completed it. After doing one practice item, participants had 5 min to complete 18 test items. A participant's score was the total number of items solved correctly.

Number series task. In this task, participants saw a series of numbers and were required to determine what the next number in the series should be. That is, the series followed some unstated rule that participants were required to figure out in order to determine what the next number in the series should be. They selected their answer out of five possible numbers that were presented. Participants had 4.5 min to complete 15 test items. A participant's score was the total number of items solved correctly.

SAT test. We also obtained, in addition to the above measures, each individual's SAT scores (both quantitative and verbal scores) via self-report.

Results and Discussion

Descriptive statistics and correlations for the memory and ability measures are shown in Table 1. As can be seen in the table, most measures had generally acceptable values of internal consistency and were approximately normally distributed, with values of skewness and kurtosis under the generally accepted values.

Immediate free recall was found to be as reliable as the complex span tasks. The complex span tasks were found to correlate with one another and with immediate free recall with a similar magnitude (see Table 1). In order to examine this more thoroughly, we submitted the three complex span tasks, the four general ability measures, and the immediate free recall task to a confirmatory factor analysis. In this analysis, the three complex span measures and immediate free recall were specified to load on the same WMC factor, and the four general ability measures were specified to load on another factor. These two factors were allowed to correlate. If immediate free recall measures processes that are largely similar to those measured by the three complex span tasks, then it should load on the WMC factor with a magnitude similar to that of the WMC factor that the three complex span tasks load on, and this factor should be related to g. The fit of the model was

Table 1
Means, Standard Deviations, Estimates of Reliability, and Correlations for All Measures

Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1. Ospan	—																					
2. Symspan	.20	—																				
3. Rspan	.52	.28	—																			
4. NS	.10	.18	.13	—																		
5. Ang	.14	.09	.18	.19	—																	
6. VSAT	.25	.06	.23	.20	.42	—																
7. QSAT	.28	.19	.15	.35	.23	.44	—															
8. IFR	.41	.13	.39	.07	.19	.26	.16	—														
9. PM1	.24	.21	.29	.13	.11	.07	.05	.39	—													
10. PM2	.25	.19	.28	.16	.14	.11	.06	.36	.95	—												
11. SM1	.33	.08	.42	.04	.16	.29	.09	.65	.09	.07	—											
12. SM2	.27	.01	.21	−.02	.12	.23	.12	.81	−.13	−.13	.56	—										
13. S1	.21	−.03	.18	−.08	.09	.23	.07	.45	−.20	−.18	.43	.61	—									
14. S2	.21	−.02	.28	−.04	.08	.17	.01	.68	.09	.05	.56	.71	.50	—								
15. S3	.26	.03	.21	−.03	.12	.23	.09	.67	.08	.07	.49	.68	.54	.55	—							
16. S4	.26	.01	.22	.09	.16	.22	.16	.68	.07	.04	.53	.73	.43	.59	.65	—						
17. S5	.18	.00	.24	.07	.01	.13	−.06	.67	.21	.18	.56	.57	.40	.59	.48	.48	—					
18. S6	.38	.04	.30	.07	.08	.14	.24	.63	.24	.23	.36	.53	.28	.30	.34	.38	.43	—				
19. S7	.23	.05	.19	.16	.04	.14	.11	.67	.44	.39	.39	.44	.12	.27	.31	.38	.41	.50	—			
20. S8	.23	.16	.28	.16	.19	.08	.10	.57	.51	.45	.21	.28	−.02	.16	.21	.20	.19	.29	.52	—		
21. S9	.25	.24	.16	.02	.12	.08	.17	.42	.53	.51	.18	.07	−.22	−.01	.00	−.03	.02	.13	.32	.52	—	
22. S10	.01	.17	.13	.03	.15	.01	.12	.25	.37	.27	.07	−.04	−.24	−.01	−.13	−.07	−.15	.01	.10	.34	.54	—
M	61.83	30.41	59.90	9.61	11.47	601	623	6.09	2.87	2.88	3.44	3.39	0.77	0.68	0.57	0.52	0.46	0.48	0.48	0.60	0.68	0.76
SD	8.84	6.50	10.63	2.30	2.80	77.00	78.00	1.12	0.76	0.80	1.21	1.25	0.16	0.22	0.20	0.19	0.21	0.20	0.20	0.18	0.21	0.21
Reliability	0.79	0.80	0.75	0.70	0.68			0.85	0.62	0.64	0.76	0.78	0.40	0.61	0.50	0.40	0.53	0.51	0.42	0.42	0.57	0.65
Skewness	−0.96	−0.63	−1.38	0.19	−0.31	0.10	0.21	0.29	−0.02	0.01	0.64	0.41	−0.45	−0.30	−0.17	0.03	0.20	0.08	0.17	−0.21	−0.53	−1.17
Kurtosis	0.64	0.15	3.00	−0.85	0.20	−0.08	−0.33	−0.68	−0.16	−0.22	0.52	−0.61	−0.24	−0.70	−0.35	−0.09	−0.53	−0.77	−0.52	0.11	−0.06	1.44

Note. Correlations >.16 are significant at the $p < .05$ level. Ospan = operation span; Symspan = symmetry span; Rspan = reading span; NS = number series; Ang = verbal analogies; VSAT = verbal SAT; QSAT = quantitative SAT; IFR = immediate free recall; PM1 and PM2 = primary memory parcels based on the average of the first five and second five lists of words, respectively, for the IFR task; SM1 and SM2 = secondary memory parcels based on the average of the first five and second five lists of words, respectively, for the IFR task; S in S1–S10 = serial position.

good, $\chi^2(19) = 21.18$, $p > .32$, root-mean-square error of approximation (RMSEA) = .03, standardized root-mean-square residual (SRMR) = .05, nonnormed fit index (NNFI) = .99, comparative fit index (CFI) = .99, Akaike's information criterion (AIC) = 55.18.[1] As can be seen in Figure 1, immediate free recall loaded as highly on the WMC factor as did the complex span tasks, and the WMC and g factors were correlated at a magnitude similar to what had been found previously (e.g., Engle et al., 1999). We also tested an alternative model in which immediate free recall loaded on the g factor rather than the WMC factor. However, the fit of this model was not nearly as good as that of the prior model, $\chi^2(19) = 37.93$, $p < .05$, RMSEA = .09, SRMR = .08, NNFI = .87, CFI = .91, AIC = 71.93. Thus, at least within the current data, together these results provide important evidence that immediate free recall (a storage-only task) taps processes similar to those for the complex span tasks replicating previous work (Unsworth & Engle, 2007a).

Next we examined the extent to which PM and SM estimates from immediate free recall would account for separate variance in WMC via structural equation modeling (SEM). First, two separate parcels for PM and SM were created from the first five lists and the second five lists from immediate free recall. That is, one PM parcel (PM1) was created by averaging PM estimates from the first five lists, and a second PM parcel (PM2) was created by averaging PM estimates from the last five lists. The same was done for SM, creating two SM parcels (SM1 and SM2). Correlations are shown in Table 1. For the SEM, we created a PM factor by having the two PM parcels load together and an SM factor by having the two SM parcels load together. These factors were allowed to correlate and were specified to jointly predict a WMC latent variable composed of the three complex span tasks. The fit of the model was good,

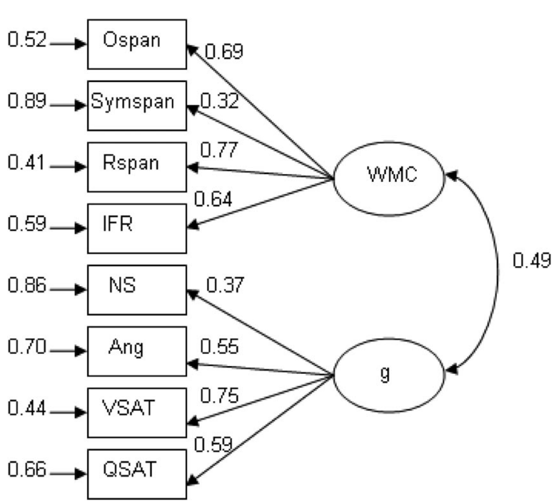

Figure 1. Confirmatory factor analysis for working memory capacity (WMC) and general intellectual ability (g). The path connecting the latent variables (circles) to each other represents the correlation between the constructs, the numbers from the latent variables to the manifest variables (squares) represent the loadings of each task onto the latent variable, and numbers appearing next to each manifest variable represent error variance associated with each task. All paths are significant at the $p < .05$ level. Ospan = operation span; Symspan = symmetry span; Rspan = reading span; IFR = immediate free recall; NS = number series; Ang = verbal analogies; VSAT = verbal SAT; QSAT = quantitative SAT.

$\chi^2(11) = 14.55$, $p > .20$, RMSEA = .05, SRMR = .06, NNFI = .98, CFI = .99, AIC = 48.55.[2] As can be seen in Figure 2, the PM and SM estimates loaded substantially on their respective factors, and these two factors were not correlated. Note also that both the PM and SM estimates were generally reliable, although the SM estimates seemed to be slightly more reliable than the PM estimates. Critically, each factor accounted for unique variance in WMC. This provides important evidence for the notion that both PM and SM contribute independently to WMC.

The next set of analyses examined the dual-component model by determining serial position effects in immediate free recall. As noted previously, if we assume that recency items generally reflect recall from PM and prerecency items reflect recall from SM, then it should be possible to form a PM factor based on recency items and an SM factor based on prerecency items. As with the previous analysis, these two factors should not be correlated and should both contribute to WMC. Therefore, we submitted all of the serial positions to an exploratory factor analysis with promax rotation to determine whether two factors were viable and what serial positions would load on each factor. As shown in Table 2, the factor analysis yielded two factors (Factor 1 eigenvalue = 3.72, Factor 2 eigenvalue = 2.22) accounting for 49.66% of the variance. The scree plot also suggested the presence of two factors. The first factor consisted of the first seven serial positions, and the second factor consisted of the last five serial positions. Additionally these two factors were weakly correlated ($r = .14$).

In the final SEM, we examined, on the basis of the results from the exploratory factor analysis, separate PM and SM latent variables based on serial position and how each of these latent variables would account for variance in WMC. We specified an SM latent variable in which the first seven serial positions loaded onto a single factor and a PM latent variable in which the last five serial positions loaded onto a single factor. Note that on the basis of the exploratory factor analysis, Serial Positions 6 and 7 were allowed to load on both the PM and the SM factors. This cross-loading is

[1] The chi-square statistic reflects whether there is a significant difference between the observed and reproduced covariance matrices. Therefore, nonsignificant values are desirable. We also report the RMSEA, which is an index of model misfit due to model misspecification, and the SRMR, which reflects the average squared deviation between the observed and reproduced covariances. In addition, the NNFI and the CFI both compare the fit of the specified model to a baseline null model. The NNFI—and CFI values greater than .90 and RMSEA and SRMR values less than .08—are indicative of acceptable fit. Finally, the AIC examines the relative fit between models in which the model with the smallest AIC is preferred.

[2] We also examined several alternative models for the relations among WMC, PM, and SM. Specifically, we tested an alternative model in which the three complex span tasks, the two estimates of PM, and the two estimates of SM all loaded on a unitary factor. Unfortunately, given the near-zero correlation between PM and SM, this model could not converge. We also tested 2 two-factor models in which one factor was composed of the complex span tasks and the PM estimates and the other factor was composed of only the SM estimates. In the other model, we specified one factor as being composed of the complex span tasks and the SM estimates and the other factor as being composed of the PM estimates. In both models the factors were allowed to correlate. Both of these two-factor models fit the data significantly worse than did the three-factor model presented in the current article (both $\Delta\chi^2$s > 38, $ps < .01$). Thus, the three-factor model was retained as the preferred model.

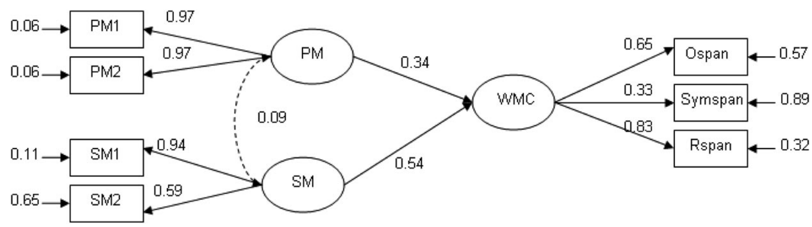

Figure 2. Structural equation model for primary memory (PM) and secondary memory (SM) estimates from immediate free recall (IFR) predicting working memory capacity (WMC). The numbers from the latent variables (circles) to the manifest variables (squares) represent the loadings of each task onto the latent variable, and numbers appearing next to each manifest variable represent error variance associated with each task. Single-headed arrows connecting latent variables to each other represent standardized path coefficients indicating the unique contribution of the latent variable. Double-headed arrows connecting the memory factors represent the correlations among the factors. Solid lines are significant at the $p < .05$ level, and dotted lines are not significant at the $p < .05$ level. PM1 and PM2 = PM parcels based on the average of the first five and second five lists of words, respectively, for the IFR task; SM1 and SM2 = SM parcels based on the average of the first five and second five lists of words, respectively, for the IFR task; Ospan = operation span; Symspan = symmetry span; Rspan = reading span.

likely due to the fact that individuals differed in the capacity of PM, with some individuals having a capacity of three items and others having a capacity of four items. As with the previous SEM, both PM and SM were allowed to correlate, and both were specified to predict WMC. The fit of the model was acceptable, $\chi^2(60) = 118.78$, $p < .01$, RMSEA = .08, SRMR = .08, NNFI = .91, CFI = .93, AIC = 180.78. Note that the fit of this model could have been improved if several of the serial position error variances had been allowed to correlate. However, for simplicity's sake we decided to present only the initial, noncorrelated error model. As can be seen in Figure 3, the first seven serial positions loaded significantly on the SM factor, whereas the last five serial positions loaded significantly on the PM factor. These two factors were not correlated, and both accounted for unique variance in WMC. Thus, again both PM and SM were shown to contribute to WMC.

In the final set of analyses, we utilized variance partitioning to examine whether the shared variance between WMC and g that has been found previously was due to shared variance with PM and SM. Researchers use variance partitioning to attempt to allocate the overall R^2 of a particular criterion variable (here g) into portions that are shared and unique to a set of predictor variables (here WMC, PM, and SM). We carried out a series of regression analyses to obtain R^2 values from different combinations of the predictor variables in order to partition the variance (see Table 3). For each variable entering into the regression, the factor correlations for WMC, g, PM, and SM were used. For instance, in the first regression WMC, PM, and SM were entered as predictors of g. As can be seen in Figure 4, the results suggested that 21% of the variance in g was accounted for. Next, this variance was broken down into unique and shared components (see Chuah & Maybery, 1999, for more details). Specifically, 11% of the variance was shared between WMC and SM, 3% was shared between WMC and PM, and there was no shared variance between all three components or between PM and SM. Finally, both WMC (5%) and SM (2%) accounted for unique variance in g.[3] This suggests that the majority of the variance shared between WMC and g is due to shared variance with PM and SM. At the same time, WMC accounted for unique variance in g independently of PM or SM. This suggests that part of the relation between WMC and g is likely due to something other than PM or SM and may be due to updating and binding operations that are needed in complex span tasks. It is also possible that this unique variance is due to the fact that WMC represented a true latent variable (based on multiple tasks), whereas PM and SM were based on parcels from the same task, and thus PM and SM were assessed more narrowly than was WMC. Furthermore, this issue of the breadth of assessment likely also accounts for the relatively low amount of variance accounted for in intelligence in the current study. Broader measures of PM and SM, along with WMC, would likely account for substantially more variance in intelligence.

Table 2
Exploratory Factor Analysis for Serial Positions in Immediate Free Recall

	Factor		
Measure	1	2	h^2
S1	.66	−.30	.47
S2	.73	—	.53
S3	.76	—	.58
S4	.76	—	.58
S5	.70	—	.50
S6	.50	.22	.33
S7	.44	.46	.47
S8	—	.69	.55
S9	—	.80	.63
S10	−.22	.58	.34

Note. Dashes indicate factor loadings <.15. S in S1–S10 = serial position; h^2 = communality estimate.

[3] One potential problem with this type of analysis is that it is possible to compute negative variances (potentially due to suppression effects), and thus the results should not always be interpreted as proportions of variance. There were no negative variance values in the current study, so this issue was not a problem for the current analyses.

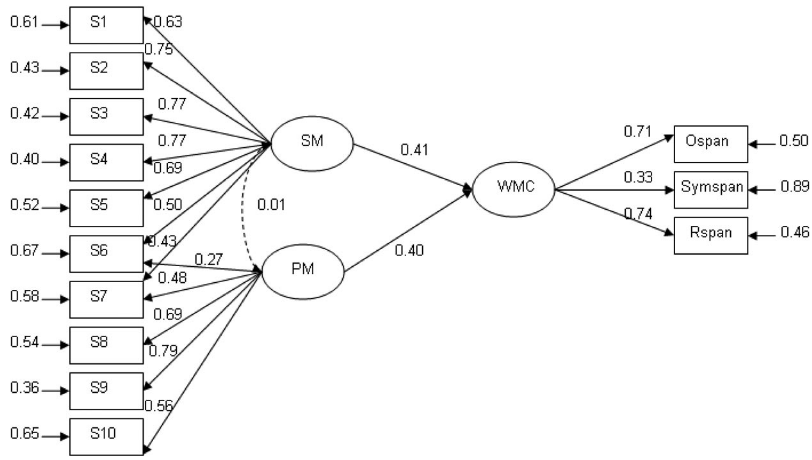

Figure 3. Structural equation model for primary memory (PM) and secondary memory (SM) based on serial position (S1–S10) in immediate free recall predicting working memory capacity (WMC). The numbers from the latent variables (circles) to the manifest variables (squares) represent the loadings of each task onto the latent variable, and numbers appearing next to each manifest variable represent error variance associated with each task. Single-headed arrows connecting latent variables to each other represent standardized path coefficients indicating the unique contribution of the latent variable. Double-headed arrows connecting the memory factors represent the correlations among the factors. Solid lines are significant at the $p < .05$ level, and dotted lines are not significant at the $p < .05$ level. Ospan = operation span; Symspan = symmetry span; Rspan = reading span.

General Discussion

The current study tested the dual-component model of WMC by examining estimates of PM and SM from immediate free recall. According to the dual-component model, both the ability to maintain information in PM and the ability to retrieve information from SM are important components of WMC. To test this notion, we used latent WMC and g factors to examine PM and SM components derived from immediate free recall. It was found that both PM and SM accounted for unique variance in WMC and were not correlated to one another. Furthermore, an examination of the serial position functions revealed that two factors accounted for serial position functions in immediate free recall, with the first factor consisting of the first seven serial positions and the second factor consisting of the last five serial positions. Both serial position factors accounted for unique variance in WMC and were not correlated to one another. Thus, the results of an examination of either estimates of PM and SM or serial position functions suggest that there are two independent sources of variance in immediate free recall and that both sources of variance contribute to WMC. These results provide important evidence for the dual-component model of WMC and for dual-component models of recall more generally.

In terms of theories of WMC, the current results suggest that immediate free recall, which is a storage-only task, measures processes largely similar to those for complex span tasks. This contrasts with processing and storage models of working memory that suggest (a) WMC is determined by a dynamic tradeoff between processing and storage in which resources are shared be-

Table 3
R^2 Values for Regression Analyses Predicting g From Various Predictor Variables

Predictor variables	R^2	F
WMC, PM, and SM	.21	11.87
WMC and PM	.19	15.85
WMC and SM	.21	17.80
PM and SM	.16	12.10
WMC	.19	31.93
PM	.03	3.96
SM	.13	19.80

Note. All R^2 values are significant at $p < .05$. g = general intellectual ability; WMC = working memory capacity; PM = primary memory; SM = secondary memory.

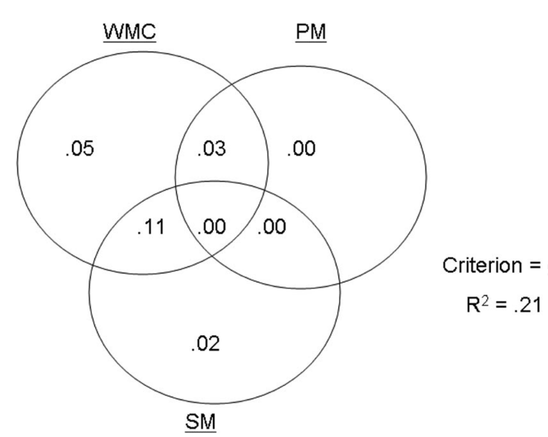

Figure 4. Venn diagrams indicating the shared and unique variance accounted for in general intellectual ability (g) by working memory capacity (WMC), primary memory (PM), and secondary memory (SM). Numbers are based on regressions from Table 3.

tween the two (Daneman & Carpenter, 1980), (b) attention must be switched between the two before the TBR items are forgotten (Towse et al., 1998), or (c) it is some combination of shared resources and time-based forgetting (Barrouillet et al., 2007). Rather, the current results are more in line with other working memory models that do not rely exclusively on processing and storage activities. In these models, WMC appears to be determined by the size of the focus of attention (Cowan, 2001), general storage abilities (Colom, Rebollo, Abad, & Shih, 2006), or the ability to set up and maintain temporary bindings within a region of direct access (Oberauer, 2005). In terms of our dual-component model, we have suggested that the PM component is similar to Cowan's (2001) focus of attention and to Oberauer's (2005) direct access region (Unsworth & Engle, 2007a). Thus, these models are much in line with the current results and our account of them. The only difference is that we suggest that a second component (SM) is needed to fully account for the results. Conversely, Mogle et al. (2008) recently suggested that examining only SM was necessary to understand WMC and its relation to higher order cognition. Clearly, the current results are at odds with this claim, because both PM and SM contributed to WMC.

The current results also have implications for dual-component models of memory and free recall more generally. Recently a number of researchers have reinvigorated the debate between single- and dual-component models of free recall (Brown, Neath, & Chater, 2007; Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005; Sederberg, Howard, & Kahana, 2008), with some arguing for two components (Davelaar et al., 2005) whereas others suggest that a single mechanism underlies performance (Brown et al., 2007; Sederberg et al., 2008). Given that two independent sources of variance (one associated with recency items and one associated with prerecency items) account for serial position functions in immediate free recall, the results are clearly in line with dual-component models of free recall. It is not clear how single-component models of free recall would account for these different sources of variance, given that a single mechanism is thought to underlie performance for all serial positions. Thus, the current results provide further evidence for dual-component models of free recall, but they do so in a novel way by examining individual differences. Incorporating individual differences into explicit computational models of free recall should help elucidate the mechanisms that drive performance on these tasks and help explain other constructs such as working memory.

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