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Simple and complex memory spans and their relation to fluid abilities: Evidence from list-length effects ☆

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Abstract

Complex (working memory) span tasks have generally shown larger and more consistent correlations with higher-order cognition than have simple (or short-term memory) span tasks. The relation between verbal complex and simple verbal span tasks to fluid abilities as a function of list-length was examined. The results suggest that the simple span-fluid abilities correlation changes as a function of list-length, but that the complex span-fluid abilities correlation remains constant across list-lengths from lists as short as two items. Furthermore, regression and factor analytic results suggested that the longest simple span list-lengths and all of the complex span list-lengths had both unique and shared variability in predicting fluid abilities, but that estimates of primary memory did not uniquely predict fluid abilities. It is suggested that complex spans, generally, predict higher-order cognition to a greater extent than do simple spans because complex spans require retrieval of items that have been displaced from primary memory due to the processing component of these tasks. Items in simple spans will also be displaced from primary memory but only after primary memory has become overloaded.

Keywords: Memory span; Fluid abilities; Individual differences; List-length

"We cannot possibly have a good theory of the processes involved in remembering, either in a short-term or a long-term sense, unless we have procedures for assessing the status and change of such processes within individuals." (Melton, 1967, p. 249).

Researchers interested in both experimental and differential psychology have long argued for the need to include individual differences in theory construction (Cohen, 1994; Cronbach, 1957; Melton, 1967; Underwood, 1975). As the above quote from Melton suggests, theories of memory processes (and cognition in general) need to attempt to account for individual differences in the ability to carry out the processes specified in the theory. Although interest in individual differences in cognitive processes has waxed and waned over the years, one area that has seen fairly continual interest is that of immediate memory processes that underlay memory span tasks. In these tasks, participants are presented with to-be-remembered items (such as letters, digits, or words) which they have to recall in the correct serial order. Since their inception (e.g., Jacobs, 1887) these tasks have interested

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researchers concerned both with basic memory processes and with the potential use of these tasks in determining individual differences in higher-order cognition (see Blankenship, 1938; Dempster, 1981, for reviews). Indeed, these tasks have long been a part of psychometric batteries of intelligence (e.g., Terman, 1916). Simple span tasks have been used extensively over the last 100 years in an attempt to gain a better understanding of memory processes and individual differences therein. Recently, interest has shifted to modified versions of these tasks known as complex span tasks. Complex span tasks, like simple span tasks, require participants to recall a set of items in their correct serial order. However, complex span tasks differ from simple span tasks in that some form of processing activity is interleaved between the to-be-remembered items. These tasks came about in order to test a more dynamic memory system based on the Baddeley and Hitch (1974) model.

Over the last 20 years research has examined the predictive utility of both types of tasks in predicting higher-order cognition. Generally, the verbal complex span tasks have been shown to predict measures of higher-order cognition to a greater extent than verbal simple span measures (Ackerman, Beier, & Boyle, 2005; Engle, Tuholski, Laughlin, & Conway, 1999). The explanation for the larger correlation between complex spans and higher-order cognition remains unresolved. Some researchers have argued that complex spans require simultaneous storage and processing, whereas simple spans simply require storage (Daneman & Carpenter, 1980). Thus, the larger correlation is due to the fact that complex spans better capture the storage and processing dynamics of the working memory system than do simple spans. Other researchers suggest that complex spans require the use of attention control to a greater extent than do simple spans (Engle et al., 1999). Thus, the reason for the larger correlation is due to the fact that both complex spans and tasks of higher-order cognition require the ability to control attention.

The goal of the present paper was to examine the relations between verbal complex and simple spans with fluid abilities. We briefly present a model of working memory and show how this framework can be used to interpret differences and similarities between complex and simple spans. Next, we present some relevant data demonstrating how this simple model can account for results based on list-length effects in both complex and simple spans. In short, we argue that the extent to which a span task will correlate with higher-order cognition is based in part on the extent to which retrieval from secondary memory is required (although see Conway & Engle, 1994).

Memory spans, the capacity of primary memory, and retrieval from secondary memory

We view working memory as consisting of a subset of activated long-term memory units, some of which are highly active and are in primary memory. This conceptualization is similar to Cowan's model of the focus of attention (1995), with Craik's early work distinguishing between primary and secondary memory (e.g., Craik, 1971; Craik & Levy, 1976), to the episodic buffer postulated by Baddeley (2000), and the direct access region in Oberauer's model (2002). However, our view is probably most consistent with the activation buffer in the neurocomputational model advanced by Davelaar, Usher and colleagues (Davelaar & Usher, 2002; Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005; Haarmann & Usher, 2001; Usher & Cohen, 1999).

In our view, primary memory is qualitatively and functionally distinct from secondary memory. Primary memory serves to maintain a distinct number of separate representations active for on-going processing. Consistent with prior work, primary memory is thought to have an upper bound of approximately four items (e.g., Broadbent, 1975; Cowan, 2001); when more than four items are present, items currently within primary memory are probabilistically displaced and must be recalled from secondary memory. Similar to the activation buffer model proposed by Davelaar et al. (2005) the capacity limit is due to the fact that only about four items can be distinctly maintained (see Usher, Cohen, Haarmann, & Horn, 2001, for a discussion). Note that this view of primary memory is not simply a buffer limited to four slots, but rather is a more dynamic system that can change due to task demands. There may be times when it is optimal for primary memory to hold less than its maximal limit, such as when trying to maintain only one item in the presence of distracting stimuli, in which case primary memory is restricted to only one item or goal representation (see Heitz & Engle, 2005; Usher & Cohen, 1999). However, in many memory tasks such as immediate serial and free recall, it is optimal to keep the size of primary memory at its maximum in order to maintain as many distinct items as possible. This is because, at recall, items that are in primary memory are simply output and recall is nearly perfect. Items that are displaced from primary memory, however, must be recalled from secondary memory. Items are displaced from primary memory via incoming information (i.e., new items) or via the disengagement of attention from the maintained items. In the former case, some items are maintained in primary memory while others are displaced (e.g., Davelaar et al., 2005). In the latter case, all items are displaced from primary memory due to the removal of attention.

Once items are displaced from primary memory, they must be retrieved from secondary memory. Thus, it is assumed for simplicity that all items that are not currently in primary memory must be retrieved from secondary memory. We assume that retrieval from secondary memory requires a cue-dependent search process (e.g., Shiffrin, 1970). The key to the search process is the ability to delimit the search process to only the relevant items. Cues (e.g., temporal, contextual, categorical, etc.) are used to effectively delimit the search set. Retrieval from secondary memory is fraught with potential problems such as proactive interference (PI) and thus, it is optimal to try and maintain as many items in primary memory as possible to ensure a higher probability of recall.

Within this simple framework, we can now begin to examine some of the potential differences and similarities between complex and simple span tasks. First, let us begin with a basic description of complex span tasks. In these tasks, to-be-remembered items are interleaved with some form of distracting task such as solving math operations or reading sentences. For example, an operation is first presented followed by a word and then another operation-word string until recall is required. Thus, as with the continuous distractor paradigm (Bjork & Whitten, 1974), items are presented and held within primary memory, but are quickly displaced due to the need to switch attention to the processing of the operations. Hence, items in complex span tasks must, generally, be retrieved from secondary memory. We say generally because there is typically no operation following the last word, so it is likely that it remains in primary memory at recall.

Simple spans, on the other hand, are more of a combination of both unloading from primary memory and retrieval from secondary memory (Craik, 1971; Watkins, 1977). Because there is no intervening activity to displace items from primary memory, items are either recalled from primary memory or from secondary memory depending on the number of items and on the way items are displaced from primary memory. That is, performance on short list-lengths will be primarily determined by unloading from primary memory. Only at longer list-lengths will retrieval from secondary memory be required. Thus, the similarity between complex and simple spans is that items must be recalled both from primary memory and from secondary memory. The main difference is that the majority of items in complex spans are displaced from primary memory and must be retrieved from secondary memory, whereas for simple spans many items can be recalled from primary memory. Therefore, in order to understand the correlation between complex span tasks and higher-order cognition, we have to consider the possibility that these tasks require the ability to successfully retrieve items from secondary memory.

By this rationale, complex spans correlate with measures of higher-order cognition because they require greater retrieval from secondary memory than simple spans. Support for this position comes from previous work which demonstrated that estimates of secondary memory from an immediate free recall task loaded highly on a latent variable made up of the working memory span tasks (Engle et al., 1999). Furthermore, this factor was highly related to fluid abilities.

Simple spans show lower, and less consistent, correlations with higher-order cognition because they require less retrieval from secondary memory. That is, due to the way simple span tasks are typically administered and scored, variability generally only comes from the shortest list-lengths and hence, primary memory. According to the framework outlined here, by increasing list-length the number of items in primary memory should remain fairly constant, but the number of items that are recalled from secondary memory should grow. Thus, if what is important for the correlation with higher-order cognition is the ability to retrieve from secondary memory, then the correlation between simple spans and higher-order cognition should increase as list-length increases. However, because complex spans already require recall from secondary memory, even at small list-lengths, an increase in list-length will not necessarily lead to an increase in the correlation with higher-cognition.

In addition to predicting that list-length effects will affect the correlation between complex and simple spans with higher-order cognition differently, this framework also predicts differences in probability of recall as a function of list-length. Specifically, the probability of recall should be a joint function of recalling from both primary and secondary memory. Consistent with search models (e.g., Shiffrin, 1970), list-length effects occur because the size of the search set in secondary memory increases with list-length. For example, in a list-length of five in a simple span task, the probability of recalling an item from primary memory is practically 1.0. If we assume that four items are recalled from primary memory (Broadbent, 1975; Cowan, 2001), this means that one item has to be recalled from secondary memory. Thus, the probability of recall for a list-length of five in a simple span should be quite high. For complex span tasks, however, the probability of recall for a list-length of five should be drastically lower. Assuming that one item is recalled from primary memory, then the other four items must be recalled from secondary memory. Therefore, the model predicts that complex spans should show steeper list-length effects than simple spans. However, correcting for the number of items recalled from secondary memory in both should lead to equivalent list-length effects.

The present investigation examined these predictions by analyzing list-length effects in two verbal complex and two verbal simple span tasks. In addition, in order to examine the correlational predictions, we used three fluid abilities measures as our measures of higher-order cognition. In line with Underwood (1975) and others (Cohen, 1994; Cronbach, 1957; Melton, 1967) we have attempted to examine aspects of our framework by examining individual differences in the theoretical processes underlying these tasks.

Method

Participants

The data analyzed in the current study were from a large correlation-based study with 235 adults between the ages of 18–35 that has been published previously (i.e., Kane et al., 2004). Participants were both college students and community volunteers from a combination of three universities and metropolitan areas (see Kane et al., 2004, for more details). None of the analyses reported in this paper were reported in the Kane et al. (2004) study.

Tasks

Participants completed a number of complex span, simple span, and fluid abilities measures. However, for the current purposes, we only analyzed data from two of the more popular complex span tasks (operation and reading span), two corresponding verbal simple span tasks (word and letter span), and three measures of fluid abilities.

Operation span (Ospan)

Participants solved a series of math operations while trying to remember a set of unrelated words. Participants saw one operation-word string at a time. For each trial participants were required to solve the operation and read the word aloud. Immediately after the participant read the word, the next operation-word string was presented. Three trials of each list-length (2–5) were presented, with the order of list-length varying randomly. At recall, words from the current set were written in the correct order. To ensure that participants were not trading off between solving the operations and remembering the words, an 85% accuracy criterion on the operations was required. Participants received three sets (of list-length two) of practice.

For all of the span measures, items were scored if the item was correct and in the correct serial position. The score was the proportion of correct items in the correct serial position.

Reading span (Rspan)

Participants were required to read sentences while trying to remember a set of unrelated letters (B, F, H, J, L, M, Q, R, and X). For this task, participants read a sentence and determined whether the sentence made sense (e.g., “The prosecutor’s dish was lost because it was not based on fact. ? M”). Half of the sentences were 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. There were 10 – 15 words in each sentence. Participants were required to read the sentence aloud and to indicate whether it made sense or not by saying either “yes” or “no”. After participants gave their response they said the letter aloud. At recall, participants wrote down the letters from the current set in the correct order. There were three trials of each set-size with list length ranging from 2 to 5. The same scoring procedure as Ospan was used.

Word span (Wspan)

Participants recalled one- and two-syllable nouns presented for 1 s each. Participants were required to read the word allowed when it appeared. Participants received three trials of each list-length (2–7). No word appeared more than once and list-lengths were presented randomly. At recall, words from the current trial were written in the correct order. Words were scored correct only if they were in the correct serial position.

Letter span (Lspan)

Participants recalled letters presented for 1 s each. Participants were required to read the letters allowed as they appeared. Letters were drawn from a fixed pool of 9 letters (B, F, H, J, L, M, Q, R, and X). Letters repeated across trials, but not within trials with list-lengths presented randomly. There were three trials of each list-length (2–8). At recall, letters from the current trial were written in the correct order.

Raven

Raven Advanced Progressive matrices (Raven, Raven, & Court, 1998) is a measure of abstract reasoning. The test consists of 36 items presented in ascending order of difficulty (i.e., easiest–hardest). Each item consists of a display of 3 × 3 matrices of geometric patterns with the bottom right pattern missing. The task for the participant is to select among eight alternatives, the one that correctly completes the overall series of patterns. Participants had 10 min to complete the 18 odd-numbered items. A participant’s score was the total number of correct solutions.

WASI matrix reasoning

Each item presented a pattern of novel, colored figures, and most were arranged in a matrix with one figure missing. Nine items presented 2 × 2 matrices, 2 items presented 3 × 3 matrices, 2 items presented a missing piece from a continuous wallpaper-like design, and 1 item presented a missing piece from a linear sequence of 5 figures. Participants selected the one of five figures that would best complete the pattern. Participants had 7 min to complete 14 items that increased in difficulty. The items were 14, 16, 18, 20, 22, 24, 26, 28, 30, 31, 32, 33, 34, and 35 from the WASI test (The Psychological Corporation, 1999).

Beta III

Each item presented a pattern of 3 novel, black-and-white figures arranged in a 2 × 2 matrix with one figure missing. Participants selected the one of five figures that would best complete the pattern. Participants had 10 min to complete 20 test items that increased in difficulty. The items were the 20 final items (numbers 6–25) of the BETA III test (Kellogg & Morton, 1999).

Results

The results are divided into three sections, the first section deals with the probability of correct recall as a function of list-length. The second section deals with correlational results of complex and simple spans with fluid abilities as a function of list-length. Finally, the third section examines individual estimates of primary memory and their unique and shared effects in predicting fluid abilities. For all analyses, the two complex spans were combined, the two simple spans were combined, and the three fluid abilities measures were combined to form single composites.[1]

List-length and probability of recall

For both complex and simple spans, the probability correct is based on the number of items recalled in the correct serial position. We first examined the effect of list-length on both complex and simple spans for list-lengths 2–5. As shown in Fig. 1, the probability of correct recall was much lower for the complex spans than for the simple spans ($M = .62$, $SE = .004$, $M = .93$, $SE = .004$, respectively), $F(1,696) = 4518.97, p < .01$, partial $\eta^2 = .95$. Additionally, the effect of list-length suggests that probability of recall decreases with increases of list-length, $F(3,696) = 1752.64$, $p < .01$, partial $\eta^2 = .88$. Crucially, the drop in probability correct was steeper for the complex spans than for the simple spans, $F(3,696) = 518.75, p < .01$, partial $\eta^2 = .69$.

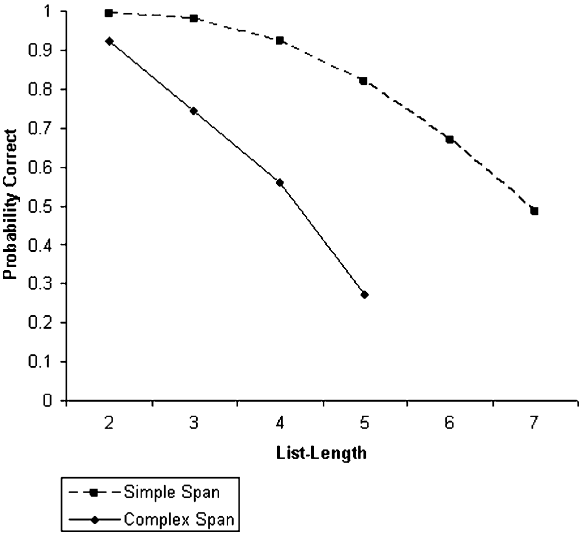

Fig. 1. Probability correct as a function of list-length and memory span task. Error bars represent one standard error of the mean.

Based on the model outlined previously, this large difference in the probability of recall for complex and simple spans as a function of list-length is to be expected because more items must be recalled from secondary memory in complex than simple spans. However, if we attempt to equate the number of items recalled from secondary memory for the two types of span tasks, will the difference in list-length disappear? As noted previously, our argument is that for complex spans, the number of items recalled from secondary memory starts out at one for list-length two and increases to four for list-length five. For simple spans, no items are recalled from secondary memory until list-length five where at least one item is theoretically recalled from secondary memory. This number increases to three for list-length seven. Therefore, we examined list-length effects for the two types of span tasks depending on the number of items the model predicts are recalled from secondary memory. We examined list-lengths 2–4 for complex spans, and 5–7 for the simple spans. If the list-length differences observed are due to differences in the number of items being recalled from secondary memory, then by excluding those list-lengths where items are only recalled from primary memory should result in no differences between the two types of span tasks. The results are shown in Fig. 2, and are quite close to the prediction. Specifically, the list-length effects for the two spans were nearly identical, both showing steep list-length effects, $F(2, 464) = 1369.84$, $p < .01$, partial $\eta^2 = .86$. The interaction did, however, reach significance, $F(2,464) = 3.79, p < .05$, partial $\eta^2 = .02$. Note, however, that this interaction is accounting for only 2% of the variance, which is much smaller than the previous interaction which accounted for 69% of the variance. Thus, "equating" for the number of items recalled from secondary memory reduced the size of differential list-length effect substantially.

Span-gF correlations as a function of list-length

To examine the differential effect of list-length on the memory span-gF correlations, we combined the

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[1] For the memory span measures, the composites were a simple average of probability correct for the two complex span tasks and probability correct for the two simple span measures. The gF composite was a factor composite of the three reasoning tasks. Additionally, note that the same pattern of results were obtained when examining each task individually as examining the composites. For clarity only the results from the composite measures are reported.

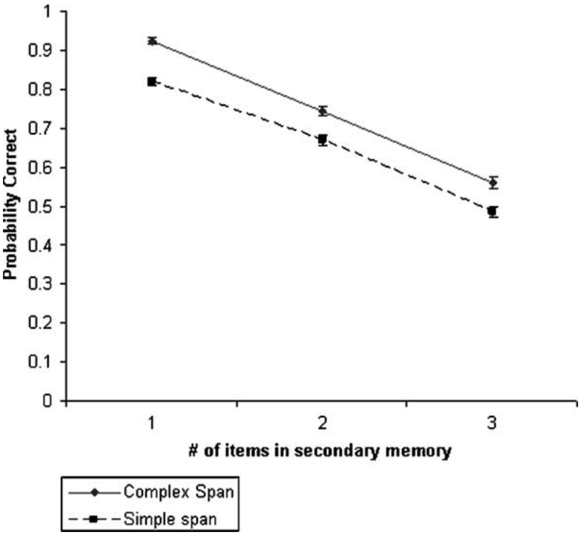

Fig. 2. Probability correct as a function of number of items in secondary memory and memory span task. Error bars represent one standard error of the mean.

three gF measures into a single factor composite. We first examined the correlation between the complex spans and gF as function of list-length. As shown in Fig. 3, the correlation between the complex spans and gF is fairly constant across the different list-lengths with an average correlation of .41 (see Appendix A for more details). For the simple spans, a quite different pattern emerges. As shown in Fig. 4, the correlation between simple spans and gF increases as list-length increases, reaching the same level as the complex spans only at list-lengths four and above. Note, that for simple spans, the standard deviation increases as list-length increases (see Appendix A). Thus, the low correlations observed at the lowest list-lengths are due to the fact that there is little variability. However, this is exactly the point. The fact that the standard deviation and correlations are small until about list-length four suggests that there are few individual differences present until list-length four, and when individual differences do appear, they are related to higher-order cognition.

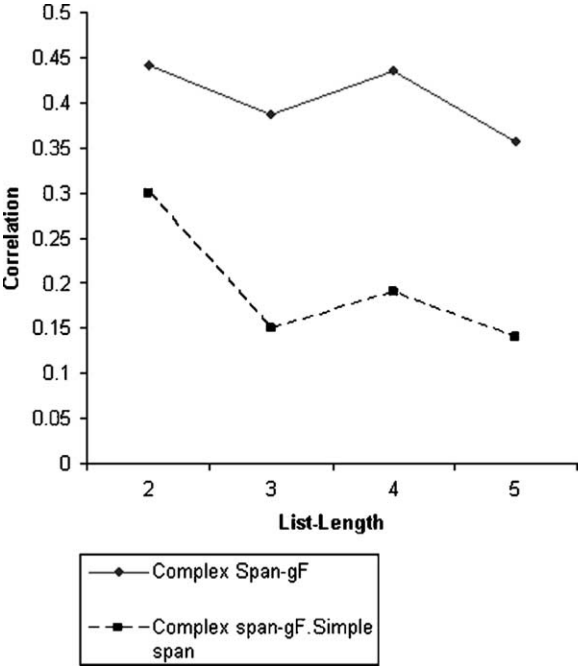

Fig. 3. Zero-order and partial correlations between complex span tasks and fluid abilities partialling out simple span performance as a function of list-length.

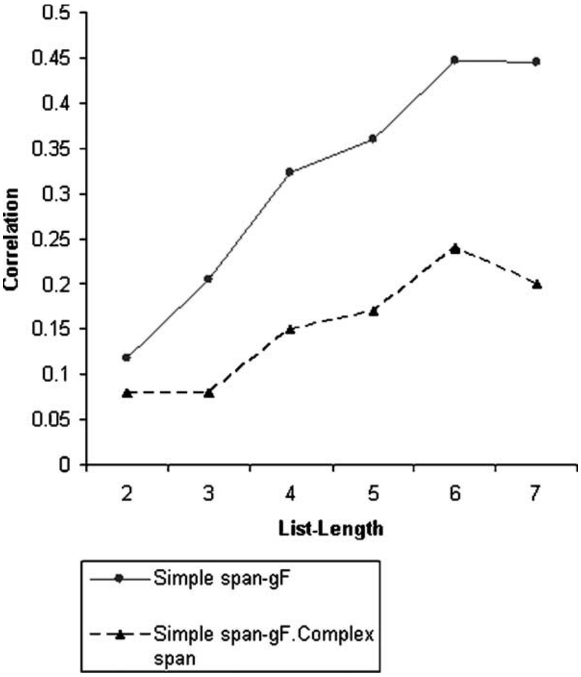

Fig. 4. Zero-order and partial correlations between simple span tasks and fluid abilities partialling out complex span performance as a function of list-length.

If the simple span-gF list-length correlations are due to the fact that longer list-lengths are tapping the same variability as the complex spans, then partialling out performance on complex spans should result in a decrease in the correlations. If, however, variability on the longest simple span list-lengths is unrelated to variability in the complex spans, then partialling out performance on the complex spans should not affect the correlations. The results support the former. As shown in Fig. 4, when performance on the complex spans is partialled out of the simple span-gF correlations, the correlations drop significantly. As shown in Fig. 3, the same is true for the complex spans. Partialling out performance on the simple spans from the complex span-gF list-length correlations results in the correlations all dropping substantially. Thus, the simple span-gF correlation is moderated by list-length and the simple span-gF correlations at the longer list-lengths share the same variability with the complex spans. That is, the variability in complex spans is related to the variability in the longest simple span list-lengths and this shared variability is related to performance on fluid abilities measures.

As a further test of this notion, we submitted all of the simple and complex span list-lengths to an exploratory factor analysis. The purpose of exploratory factor analysis is to determine the underlying factor structure for a set of interrelated variables. Factor analysis is based on the assumption that a small number of underlying constructs account for the interrelationships among the observed variables. Thus, it provides an index of the number of underlying factors that purportedly underlie the relation among the variables and provides an indication of the strength with which each variable is associated with each factor. Therefore, in order to examine the factor structure of our variables we conducted principal factor analysis with promax rotation (oblique rotation) on all of the variables. As a criterion for factor extraction we used eigenvalues greater than one. As shown in Table 1, the factor analysis yielded three factors (factor 1 eigenvalue = 4.61, factor 2 eigenvalue = 1.18, factor 3 eigenvalue = 1.06) accounting for 54.44% of the variance. The first factor consists of the longest list-lengths for the simple spans, the second factor is all of the list-lengths for the complex spans, and the third factor is the smallest simple span list-lengths. Thus, it would seem that there is a clear division between the smallest and longest list-lengths for the simple spans but not for the complex spans. Additionally, as shown in Table 1, the correlation between the first and second factors is .67, whereas the other factor correlations are only about .39. This suggests that there is strong relationship between recall from the longest simple span list-lengths with recall from all of the complex span list-lengths and a much weaker relationship with recall from the smaller simple span list-lengths. These results suggest that the complex spans and the longest simple span list-lengths share a good deal of variability and this variability is highly related to fluid abilities.

Table 1
Exploratory factor analysis for all list-lengths for simple and complex spans

Measure	Factor			h^2
	1	2	3	
Com2		.420		.32
Com3		.654		.61
Com4		.871		.78
Com5		.933		.60
Sim2			.420	.17
Sim3			.544	.31
Sim4	.513		.256	.42
Sim5	.872			.66
Sim6	.811			.68
Sim7	.807			.78

	Correlations		
Factor	1	2	3
1.	—		
2.	.674	—	
3.	.391	.388	—

Note. Factor loadings less than .25 have been omitted.
Com, complex memory span tasks; Sim, simple memory span tasks. h^2, communality estimate.

Table 2
Simultaneous regression predicting gF

Variable	*B*	*t*	sr^2	R^2	*F*
SimLL2-3	.090	1.56	.01		
SimLL5-7	.293	4.03**	.05		
ComLLAll	.258	3.51**	.04	.278	29.50**

Note. $^{**}p < .01$. SimLL2-3, simple memory spans list-lengths 2–3; SimLL5-7, simple memory spans list-lengths 5–7; ComLLAll, all complex memory span list-lengths.

Next, we examined how these three factors would predict both unique and shared variance in gF. Therefore, we formed three composites, one consisting of simple span list-lengths 2–3, one of simple span list-lengths 5–7, and one consisting of all the complex span list-lengths.[2] These three composites were then submitted to a simultaneous regression predicting gF. As shown in Table 2, the results suggest that together the three composites predict 28% of the variance in gF. Of this 28%, roughly 5% is uniquely accounted for by simple span list-lengths 5–7 and 5% by all the complex span list-lengths, suggesting that the remaining 18% of variance is shared.

To get a better idea of the proportion of unique and shared variance among the variables, we utilized variance partitioning methods that have been used previously in similar studies (Chuah & Mayberry, 1999; Cowan et al., in press). Variance partitioning, or communality analysis, attempts to partition the overall R^2 of a particular criterion variable into portions that are shared and unique to a set of independent predictor variables (Pedhazur, 1997). A series of regression analyses was carried out to obtain R^2 values from different combinations of the predictor variables (see Table 3) in order to parti-

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[2] All of these composites were factor composites. Note that simple span list-length 4 was excluded from this analysis because it showed a pattern of cross-loadings on the two simple span factors. Adding list-length 4 to either composite did not drastically change the results.

Table 3
R^2 values for regression analyses predicting gF for various predictor variables

Predictor Variables	R^2	F
1. ComLLAll, SimLL2-3, SimLL5-7	.283	30.23
2. ComLLAll, SimLL2-3	.237	35.87
3. ComLLAll, SimLL5-7	.276	43.97
4. SimLL2-3, SimLL5-7	.239	36.32
5. ComLLAll	.229	68.74
6. SimLL2-3	.043	10.32
7. SimLL5-7	.225	67.21

Note. All R^2 values are significant at $p < .01$. SimLL2-3, simple memory spans list-lengths 2–3; SimLL5-7, simple memory spans list-lengths 5–7; ComLLAll, all complex memory span list-lengths.

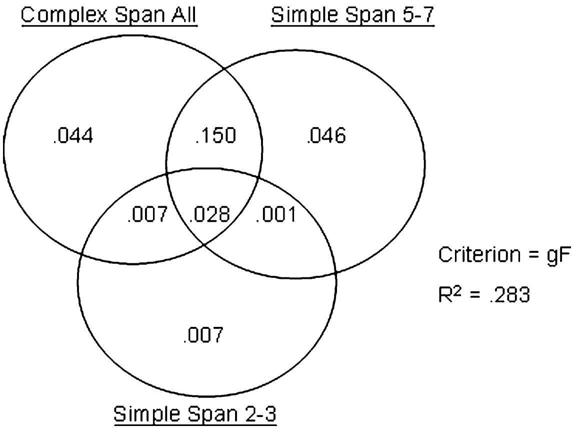

Fig. 5. Venn diagrams indicating the amount of variance accounted for in fluid abilities (gF) by all the complex span list-lengths, simple span list-length 5–7, and simple span list-lengths 2–3. Numbers are based on regressions from Table 3.

tion the variance. As shown in Fig. 5, the results suggest that of the 28.3% of the variance in fluid abilities accounted for by the three predictor variables, 15% is shared by the complex span all composite and the simple long composite and only, 2.8% is shared by all three predictors. The remaining variance being uniquely accounted for by all the complex span list-lengths (4.4%) and by the simple span long list-lengths (4.6%). Note that the shortest simple span list-lengths did not uniquely predict gF, nor did they relate highly to the other composites.[3] Thus, it would seem that not only do the longest simple list-lengths correlate highly with all the complex span list-lengths, but also they share a good deal of variance in predicting gF, with each also uniquely predicting a small amount of variance in gF.

Individual differences in the size of primary memory, supraspan recall, and fluid abilities

One problem with the above results that could limit their interpretability is the fact that the lowest simple span list-lengths do not have very much variability which would affect the magnitude of their relation with other variables. Indeed, as shown in Table 1, simple span list-length 2 has a communality estimate of only .17. This suggests that only 17% of the variance in simple span list-length 2 is accounted for by the extracted factors. In order to rectify this issues, we attempted to obtain estimates of primary memory that would result in adequate variability and would also be theoretically meaningful. To do this, we relied on reviews by Broadbent (1975) and Cowan (2001) which suggested that one way to effectively estimate the size of primary memory for each individual is to determine the point at which each individual can no longer obtain perfect recall in the simple span tasks. Broadbent (see also, Cowan, 2001) argued that when primary memory was estimated based on the point at which perfect recall ceases, that the estimates were around 3–4 items.

Heeding Broadbent and Cowan's suggestion, we estimated the size of primary memory for each individual based on the point at which perfect recall was no longer obtained for both word span and letter span. Participants were only included in the analyses if they gave unambiguous estimates for both word and letter span. By unambiguous we mean that performance was perfect up to a specific list-length, after which it was less than perfect. For instance, participants whose probability correct recall was 1.0, 1.0, 1.0, .80, .56, and .33 (for list-lengths 2–7) were given a primary memory estimate of 4.0. Participants whose probability correct recall was .67, 1.0, .92, .80, .39, and .67 (for list-lengths 2–7) were not retained for the subsequent analyses. This resulted in 161 participants who gave unambiguous estimates for both word and letter span. The resulting estimates were 3.77 ($SD = .92$) and 4.18 ($SD = 1.15$) for word and letter span, respectively, $t(160) = -4.76$, $p < .01$. The two estimates were also moderately correlated, $r(161) = .46$, $p < .01$. Therefore, the two estimates were averaged to form a single primary memory estimate to be used in subsequent analyses.[4]

Next, we examined how these estimates of primary memory would relate to the longest simple span list-lengths, all of the complex span list-lengths, and gF. The

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[3] Note that due to low variability in simple span list-lengths 2 and 3, these list-lengths have very low correlations with all of the other measures and thus do not add variability in predicting gF.

[4] High complex spans' estimate of primary memory was larger than low complex spans' ($M = 4.57$, $SD = .88$ and $M = 3.44$, $SD = .81$, respectively), $t(79) = -6.05$, $p < .01$.

Table 4
Zero-order correlations between composite variables and primary memory estimates

Variable	1	2	3	4
1. gF	—			
2. PM	.31	—		
3. ComAll	.47	.49	—	
4. Sim5-7	.47	.75	.64	—

Note. All correlations are significant at $p < .01$. gF, fluid abilities composite; PM, individual estimates of primary memory; ComAll, composite of all of the complex memory span list-lengths; Sim5-7, composite of simple memory span list-lengths 5–7.

question guiding these analyses was: "What accounts for the shared variance in predicting fluid abilities, retrieval from secondary memory, the capacity of primary memory, or both?" Shown in Table 4 are the zero-order correlations for these variables based on the composites used in the previous regression analyses. The correlations show that the primary memory estimates are highly related to the longest simple span list-lengths, moderately related to all of the complex span list-lengths, and less related to the gF composite. Furthermore, supporting the conclusions from the previous regression analyses, second-order partial correlation analyses suggested that the primary memory estimates do not uniquely relate to gF, but that both all the complex span list-lengths and the longest simple span list-lengths do. That is, the correlation between the primary memory estimates and the fluid abilities composite partialling out all of the complex span list-lengths and the longest simple span list-lengths was near zero, $pr(161) = -.08$, $p > .30$. The correlation between all of the complex span list-lengths and fluid abilities partialling out the primary memory estimates and the longest simple span list-lengths remained significant, $pr(161) = .24$, $p < .01$. Similarly, the correlation between the longest simple span list-lengths and fluid abilities remained significant after paritalling out the primary memory estimates and all of the complex span list-lengths, $pr(161) = .25$, $p < .01$. Both the longest simple span list-lengths and all of the complex span list-lengths account for approximately 6% unique variance out 27% total variance in gF. This suggests that roughly 15% of the variance is shared among the variables (i.e., $27 - 6 - 6 = 15$).

To examine these relations more fully, we partitioned the variance using the same set of regression analyses as used previously (see Table 5). As shown in Fig. 6, the results suggest that 8.2% of the variance is shared by all the complex span list-lengths and the longest simple span list-lengths independently of the primary memory estimates. However, unlike the previous analyses with the shortest simple span list-lengths, a larger portion of the variance is shared by all three predictor variables (8.8%). Finally, the remaining variance is once again uniquely accounted for by all the complex span list-lengths (4.7%) and by the longest simple span list-lengths (4.4%). Thus, it appears that a large portion of the variance in predicting fluid abilities is shared by the complex span tasks, the longest list-lengths from the simple span tasks, and estimates of primary memory. Furthermore, there is substantial shared variance between the longest simple span list-lengths and all the complex span list-lengths in predicting variability in fluid abilities independent of variability in primary memory estimates.

Table 5
R^2 values for regression analyses predicting gF for various predictor variables

Predictor variables	R^2	F
1. ComLLAll, PME, SimLL5-7	.270	19.19
2. ComLLAll, PME	.226	22.93
3. ComLLAll, SimLL5-7	.267	28.42
4. PME, SimLL5-7	.223	22.53
5. ComLLAll	.217	43.82
6. PME	.097	17.06
7. SimLL5-7	.220	44.54

Note. All R^2 values are significant at $p < .01$. PME, primary memory estimates; SimLL5-7, simple memory spans list-lengths 5–7; ComLLAll, all complex memory span list-lengths.

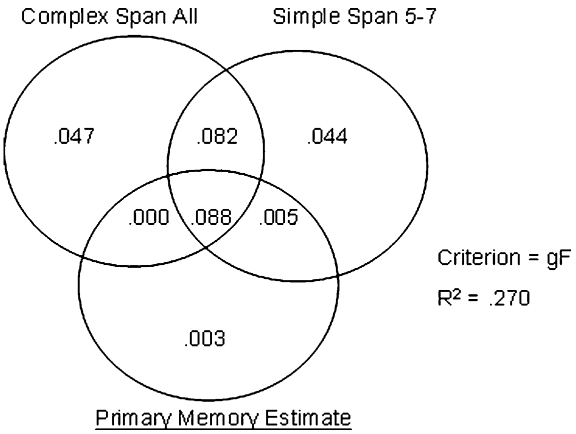

Fig. 6. Venn diagrams indicating the amount of variance accounted for in fluid abilities (gF) by all the complex span list-lengths, simple span list-length 5–7, and estimates of primary memory. Numbers are based on regressions from Table 5.

Discussion

The present investigation examined the predictive utility of verbal simple and complex span tasks in predicting higher-order cognition in terms of list-length effects. In the introduction, we suggested that one main difference between these tasks is the extent to which items are displaced from primary memory and must be retrieved from secondary memory. We argued that the ability to actively retrieve items from secondary memory is one important reason for the predictive power of the complex span tasks with higher-order cognition and one reason why complex spans show larger and more consistent correlations with gF than simple spans. However, the extent to which simple spans rely on retrieval from secondary memory is a function of list-length. If more than approximately four items are presented, then at least some of those items will be displaced from primary memory and retrieval from secondary memory will be required.

By this rationale, complex spans should show steeper list-length effects than simple spans and the simple span-gF correlation should increase as list-length increases. Each of these predictions were supported by the data. Specifically, examining probability correct the complex spans showed much steeper list-length effects than simple spans, but when compared on the number of items recalled from secondary memory this effect was virtually eliminated. Additionally, the complex span-gF correlation did not change as a function of list-length, but the simple span-gF correlations did. Furthermore, the factor analytic, regression, and partial correlation results suggested that the long simple span list-lengths and all of the complex span list-lengths shared a large amount of common variance that was related to fluid abilities. Finally, the longest simple span list-lengths and all of the complex span list-lengths uniquely predicted fluid abilities to about the same extent. In all analyses estimates of primary memory, whether based on performance on the shortest simple span list-lengths, or based on the point at which perfect performance was no longer obtained, did not uniquely predict fluid abilities. However, the variance partitioning methods suggest that there was substantial shared variance between the estimates of primary memory with performance on all the complex span list-lengths and the longest simple span list-lengths. This shared variance likely reflects the capacity or efficiency of using primary memory (or the focus of attention in Cowan's model, 2001) in these span tasks, which is independent of variation in retrieval processes. This evidence augments the strong view presented in the introduction that variation in primary memory does not provide important individual differences. Rather, the substantial variation in the size (or efficiency) of primary memory supports the contention that individual differences in the capacity of primary memory are one important predictor of higher-order cognition independent of other related processes (Cowan et al., in press).

Additionally, we have argued that another important reason for the correlation between complex and simple span tasks and gF is the ability to successfully retrieve items from outside of primary memory. Why might this be the case? We have argued that recall from primary memory is nearly perfect because items are simply unloaded. However, once an item is displaced from primary memory a search of secondary memory is needed to retrieve and recall that item. This is a cue-dependent search process which can be hindered by many variables such as PI. We suggest that as PI builds, some subjects (those with lower span scores) may have trouble delineating the search set to only the current trial and thus must search through a much larger number of items than subjects with higher span scores. This ability to effectively delimit the search set via cues and maintain items of the current set separate from previous items may be an important variable in differentiating subjects on span tests as well as predicting higher-level cognition. That is, what may be needed on measures of higher-order cognition, such as fluid abilities, is a combination of the efficiency of primary memory with retrieval of representations that have been recently displaced from primary memory. Specifically, it is possible that in matrix reasoning tasks such as the Raven, item solutions are held briefly in primary memory but are quickly displaced due to the need to manipulate other aspects of the problem. The ability to quickly and accurately retrieve representations from secondary memory in the presence of PI, would thus determine performance. Furthermore, this ability may require the use of attentional control for accurate performance on measures of fluid abilities (Unsworth & Engle, 2005a).

At the very least, the results suggest that complex and simple span tasks should not be dichotomized to simply reflect working memory and short-term memory, but rather all immediate memory tasks require a number of processes which may be important for higher-order cognition. That is, in the past, these tasks have been considered to tap two distinct constructs. In reality, however, these tasks most likely reflect a number of processes, some of which overlap and some of which are unique. The results from the present study suggest that this is the case. Simple and complex spans share substantial variance that is important for predicting higher-order cognition as well as some unique variance that is important for predicting performance on higher-order cognitive tasks.

Limitations, alternative explanations, and future directions

There are two main limitations of the framework we propose. First, the view that retrieval from both primary memory and secondary memory contribute to recall in complex and simple span tasks is overly simplistic. The framework does not explain several well known phenomena that affect immediate serial recall such as word frequency, word length, rehearsal, and phonological similarity to name a few. Furthermore, the model is a descriptive model of the underlying processes and thus lacks the rigor of more quantitative models of immediate memory phenomena (e.g., Brown, Preece, & Hulme, 2000; Raaijmakers & Shiffrin, 1981). Despite these limitations, however, we feel that the outlined framework can be beneficial in interpreting performance on span tasks and the individual differences therein. That is, despite the simplistic nature of the view outlined here, it does provide some insights into performance on span tasks, where individual differences will and will not occur, and their relation to higher-order cognition.

Another major limitation is that what the data actually show is that span-length recall does not predict higher-order cognition very well, but that supra-span recall in the simple spans and recall in all of the complex span list-lengths do predict higher-order cognition well and are highly related to one another. Thus, the data do not actually demonstrate that what is important for the relation with higher-order cognition is the ability to effectively retrieve from secondary memory, but rather suggest that what is important is the ability to recall items from supra-span list-lengths in the simple span tasks and all the list-lengths in the complex span tasks. Clearly, more work is needed to demonstrate that individual differences in a cue-dependent search process are important for recall in these tasks and for the relation with fluid abilities.

In terms of possible alternative explanations to our data, there are probably several, but here we will focus on one advocating a unitary memory model. This view (see Crowder, 1982; Nairne, 2002) suggests that all memory phenomena are due to the same underlying system and thus there is no reason to distinguish between primary and secondary memory. In this view, retrieval from memory relies on the effective use of memory cues to access items. Items are remembered or forgotten via the use of a constellation of cues. If the cues uniquely specify an item, then it is correctly recalled, however, if the several items are subsumed under the same retrieval cue (e.g., Watkins & Watkins, 1975), then retrieval of a given item will be difficult. Thus, this view argues that memory over both the short- and long-term is determined by retrieval rules and reliance on retrieval cues. Some items (recency items) have a higher probability of recall not because they sit in special short-term store, or have a higher activation level, but because these items are more distinct either because of temporal distinctiveness (e.g., Glenberg & Swanson, 1986) or because of the added benefit of short-lasting phonological cues (e.g., Tehan & Humphreys, 1995) or other modality dependent cues as in Nairne's (1990) feature model. This is widely held account of how long-term memory works and is gaining acceptance within the study of short-term memory.

We agree with Nairne (2002) that what is important for retrieval from secondary memory is the use of cues that effectively specify the desired items. We suggest, as do many search models, that what is important is that the cues effectively delimit the search set. If one is trying to access only the current items from a trial then the search set needs to be delimited to only include those items and not items from previous trials. Thus, the use of temporal (contextual) cues to delimit the search set allows for accurate recall in these span tasks. If the search set is not effectively delimited, then it will be difficult to select items from secondary memory. Support for this view comes from a recent study we conducted examining the different types and patterns of errors that participants make in verbal WM span tasks (Unsworth & Engle, 2005b). We found that the last item presented is recalled almost always by all participants, but that the longer ago an item was presented, the lower the probability of recall. We argued that the last item presented was recalled from primary memory (see previous section), whereas all of the other items were recalled from secondary memory via a cue-dependent search process. Consistent with temporal distinctiveness (e.g., Glenberg & Swanson, 1986) views, we argued that the lower probability of recall associated with middle list items was due to the fact that temporal cues did not effectively delimit the search set and participants had a difficulty accessing the correct items. Thus, the view espoused here, is actually very compatible with a cue-dependent view, differing only in the notion that some items can be unloaded from primary memory.

Furthermore, there is evidence suggesting that a distinction between primary and secondary memory is warranted (see Davelaar et al., 2005, for a review). For instance, in the current study we showed that performance on the short-term memory span tasks could be broken down into two components; one representing performance on the shortest list-lengths and one representing performance on the longest list-lengths. We showed that these two components were differentially related to both working memory spans and to fluid abilities. Other studies that have examined this issue via factor analytic techniques have come to a similar conclusion. For instance, Geiselman, Woodward, and Beatty (1982) used classic indicators of primary and secondary memory such as the first few items recalled in immediate free recall and delayed free recall and found that a two factor model fit the data significantly better than a one factor model. Herrmann et al. (2001) also found evidence for a distinction between primary and secondary memory using confirmatory factor analysis. Additionally, Bemelmans, Wolters, Zwinderman, ten Berge, and Goekoop (2002) found evidence that primacy and recency components in immediate free recall loaded on separate factors. As reported by Carroll (1993) other studies have also found that indices of primary and secondary memory loaded on separate and virtually uncorrelated factors. These studies support a distinction between primary and secondary memory both within and across tasks. In all cases, a two factor memory model fit the data better than a unitary memory model.

Together, these studies suggest that items are retrieved via qualitatively different mechanisms which we have labeled primary and secondary memory.

We suggest that a combination of Cowan's view and the reliance of the unitary memory model view on cue-dependent search best accounts for the individual differences in simple and complex span tasks and their ability to successfully predict performance on higher-order cognition. Specifically, we suggest that both views are needed to account for the observed data. Cowan's view highlights the importance of a capacity limited attention component that is needed in a wide variety of tasks. This component can zoom out to handle roughly four separate pieces of information or it can zoom in to focus on only one piece of information (e.g., Cowan, 2004; Usher & Cohen, 1999). In immediate memory tasks, such a component is useful in order to obtain maximal recall performance by protecting some subset of items from proactive interference (e.g., Cowan, Johnson, & Saults, 2005; Craik & Birtwistle, 1971; Davelaar et al., 2005; Halford et al., 1988). Once items have been displaced from this component, a cue-dependent search of secondary memory is undertaken to retrieve displaced items. This search process is aided by the use of cues (temporal, contextual, semantic, etc.) which delimit the search set to the desired set of items (Shiffrin, 1970). Thus, in immediate memory tasks it useful to use both mechanism for accurate recall performance (Raaijmakers & Shiffrin, 1981). In addition, individual differences are likely to occur in both components and be related to higher-order cognitive functioning, perhaps through the use of attentional control requirements in both (i.e., Engle & Kane, 2004). In line with previous researchers (Cohen, 1994; Cronbach, 1957; Melton, 1967; Underwood, 1975), we suggest that research into each of these areas coupled with individuals differences, could provide a better understanding of the processes that are involved in immediate memory tasks such as verbal complex and simple memory spans.

Appendix A

Means, standard deviations, and correlations for all composites

Variable	Mean	Standard deviation	1	2	3	4	5	6	7	8	9	10	11
1. Com2	.93	.11	—										
2. Com3	.74	.18	.477	—									
3. Com4	.56	.23	.491	.657	—								
4. Com5	.27	.14	.383	.616	.773	—							
5. Sim2	.99	.02	.094	.041	.104	.061	—						
6. Sim3	.98	.05	.216	.243	.284	.162	.227	—					
7. Sim4	.92	.10	.328	.380	.412	.290	.152	.257	—				
8. Sim5	.82	.15	.296	.419	.467	.365	.026	.218	.513	—			
9. Sim6	.67	.19	.337	.484	.550	.435	.159	.148	.451	.674	—		
10. Sim7	.49	.20	.399	.593	.577	.498	.024	.197	.503	.667	.741	—	
11. gF	.00	.92	.442	.387	.435	.357	.118	.205	.324	.360	.446	.445	—

Note. $N = 235$. All correlations >.15 are significant at the .05 level. Com, complex span tasks; Sim, simple span tasks.

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