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Why is working memory related to fluid intelligence?

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Nearly 1,000 adults performed a battery of cognitive tests and working memory tasks requiring simultaneous storage and processing of information. Because the amount of to-be-remembered information, or set size, varied randomly across trials, the relation between fluid intelligence and working memory could be examined across different levels of complexity and across successive trials in the working memory tasks. Strong influences of fluid intelligence were apparent in the simplest versions and on the initial trials in the working memory tasks, which suggests that the relation between working memory and fluid intelligence is not dependent on the amount of information that must be maintained, or on processes that occur over the course of performing the tasks.

It has recently been proposed that working memory (WM) is closely related to fluid intelligence (Gf) or general intelligence (*g*), and might even be the key to understanding Gf. In part for this reason, tasks assumed to assess WM have been claimed to be "among the most widely used measurement tools in cognitive psychology" (Conway et al., 2005, p. 769). However, a broad variety of tasks has been used to assess WM, and it is not clear that they all reflect the same construct. To illustrate, Schweizer and Moosbrugger (2004) used two tasks requiring mental rearrangement of items in a sequence to assess WM, Oberauer, Süß, Schulze, Wilhelm, and Wittmann (2000) included measures of verbal fluency, random number generation, and task switching as measures of WM, and the WM index in the WAIS–III (Wechsler, 1997) is based on scores in simple forward-and-backward digit span, arithmetic word problems, and letter–number sequencing tasks. Because some of the WM assessments closely resemble tests of reasoning and higher order cognition, it may not be reasonable to claim that the WM construct is theoretically more tractable or less opaque than are intelligence constructs, given the fact that it is operationalized in so many different ways that appear to have little conceptual integration.

The strategy in the present study was to adopt a deliberately narrow conceptualization of WM based on tasks that require simultaneous storage and processing of information, with different trials varying with respect to the amount of processing and the number of to-be-remembered items (i.e., set sizes). Although this approach has the limitation that the tasks may not adequately reflect all aspects of the WM construct, it is less susceptible to the criticism that the observed Gf–WM relation is strong because the WM construct is assessed by the same types of tasks used to assess Gf.

The primary question of interest in the present project is what is responsible for the relation between Gf and WM; that is, what is it about WM tasks that is responsible for the strong relations they have with measures of higher order cognition? We focus on two major possibilities. One is that the critical factor is the amount of information that can be kept simultaneously active. The rationale is the following: As the amount of information that must be processed and remembered increases, there may be more engagement of processes of attention switching, maintenance of information during distraction, resistance to proactive interference, or retrieval from secondary memory. If the Gf–WM relationship is dependent on how much information can be maintained while simultaneously processing other information—as implied by the use of terms such as WM span and WM capacity—the strongest relations to Gf might be expected when the demands on the WM task are the greatest. In other words, Gf–WM relations might be weak with small set sizes, because nearly everyone is capable of handling a small amount of information; but the relations may become stronger at larger set sizes as individual differences in the ability to handle more information increase in importance.

A second possibility is that the critical factor in the Gf–WM relationship is qualitative rather than quantitative. For example, if the relationship depends on the need to coordinate simultaneous processing and storage, or to retrieve information from secondary memory that has been displaced during processing, presence or absence of the critical process may be more important than the number of times the critical processes must be executed. To the extent that Gf–WM relations are determined by whether, not necessarily by how much, relevant processing is required, Gf–WM relations would be expected to remain fairly constant as set sizes increased; in fact, a recent study

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by Unsworth and Engle (2006) found fairly constant correlations between Gf and WM across different set sizes, with an average correlation of .41.

Although the preceding possibilities can be examined with simple bivariate correlations, as in Unsworth and Engle (2006), more informative analyses can also be carried out. For example, several cognitive abilities can be examined simultaneously to determine the unique influences of each. When only a single predictor is examined, as with simple correlations, that variable absorbs all of the variance it shares with other variables that are not included in the analyses, and therefore the results could be misleading with respect to the unique contribution of the variable that is included. To illustrate, assume that perceptual speed ability were related to both Gf and WM. If Gf were the only predictor in the analysis, as in a simple correlation, all of the influences on WM shared between Gf and speed would be attributed to Gf. This problem of omitted predictors can be minimized by using a contextual analysis procedure (Salthouse, 2005; Salthouse, Siedlecki, & Krueger, 2006), in which multiple cognitive abilities are included in the same analysis. That is, when several cognitive abilities are examined simultaneously, the influence of one ability, such as Gf, can be determined after controlling for influences of other abilities, such as perceptual speed, episodic memory, and vocabulary.

The participants in the present project varied widely in age, which is, therefore, also included as a predictor in the analyses. This not only allows influences of age to be controlled when examining relations among the Gf and WM variables, but relations of age on the WM variables can be examined after controlling for influences of cognitive abilities.

A second potentially informative analytical procedure involves examining the Gf relations at each level of complexity in the WM task after adjusting for influences at simpler levels. Figure 1 illustrates an analytical model that can be used to investigate unique relations of Gf at different positions in an ordered sequence (e.g., Salthouse, 1992b, 1996). The boxes in this diagram correspond to variables in a sequence, such as successively larger set sizes, and the arrows represent the relations whose magnitudes are to be estimated. The parameter estimates for any given element in the sequence (e.g., Element 3) could be derived from a multiple regression equation, in which the target variable is predicted from all of the variables to which it is connected by arrows (e.g., Element 1, Element 2, and Gf). However, all of the parameter estimates can be obtained simultaneously with a structural equation model, which also has the advantage of allowing the Gf variable to be represented as a latent construct determined by the variance common to several variables. An important feature of this analytical method is that effects on earlier elements in the sequence are statistically controlled when effects on a later element are examined. This allows the influences of Gf on any element (e.g., Element 2) to be decomposed into effects that are direct (dotted lines) and effects that are indirect (solid lines) and mediated through prior elements (e.g., Element 1).

As with simple correlations, the pattern of unique Gf relations could increase, decrease, or remain stable across successive elements. However, an advantage of sequential analyses is that the effects on a given element represent influences that are statistically independent of influences from prior elements in the sequence. When only simple correlations are examined, as in Unsworth and Engle (2006), it is impossible to distinguish effects carried over from earlier elements in the sequence from effects that are unique to a specific element.

Influences of Gf can also be examined across successive trials in the task to investigate the magnitude of the Gf–WM relationship at different phases in the performance of the WM task. For example, the Gf involvement might be expected to progressively increase across trials if it is needed to prevent the buildup of proactive interference (e.g., Bowles & Salthouse, 2003; Bunting, 2006; Lustig, May, & Hasher, 2001), or to assist in the development of efficient strategies for dealing with two simultaneous activities.

Two studies were conducted with similar samples and identical cognitive and WM tasks, but with the addition of the Reading Span task in Study 2. Both studies involved moderately large sample sizes to provide relatively precise estimates of the magnitude of the relations.

METHOD

Participants

Participants were recruited from newspaper advertisements, flyers, and referrals from other participants. As can be seen in Table 1, about two thirds of them were women, most of whom claimed to be in very good to excellent health; on average, they had completed over 3 years of college.

Procedure

The participants came to the laboratory for three separate sessions within a 2-week period. Sixteen cognitive tasks used to assess five reference cognitive abilities were administered during the first session, and a mixture of other tasks, including the WM tasks, ad-

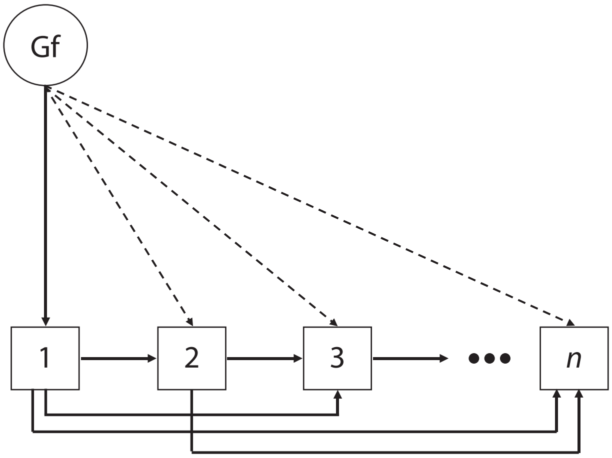

Figure 1. Illustration of a model to investigate the influence of Gf on successive elements in an ordered sequence after taking influences on earlier elements in the sequence into consideration.

Table 1
Descriptive Characteristics of the Participants, Arbitrarily Divided Into Three Groups, With Standard Deviations

	Age Group									
	18–39		40–59		60–98		All		Age *r*	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Study 1										
Number	219	–	278	–	257	–	754	–	–	–
Age	26.6	6.5	50.7	5.6	70.0	6.9	50.2	18.3	–	–
Prop. females	.64	–	.75	–	.62	–	.68	–	−.03	–
Health	1.6	0.9	1.7	1.0	1.8	0.9	1.7	0.9	.11*	–
Years of education	15.1	2.3	15.7	2.4	16.3	2.9	15.7	2.6	.21*	–
Study 2										
Number	73	–	91	–	72	–	236	–	–	–
Age	27.7	5.7	5.6	5.5	71.1	8.2	49.8	18.2	–	–
Prop. females	.60	–	.62	–	.69	–	.64	–	.05	–
Health	2.0	.9	2.2	1.0	2.2	.8	2.1	.9	.08	–
Years of education	14.9	2.9	15.2	2.5	16.5	2.6	15.5	2.7	.23*	–

Note—Health is a self-rating on a scale of 1, for *excellent*, to 5, for *poor*. *$p < .01$.

ministered in the second and third sessions. All of the participants in a given study performed the tasks in the same order.

The reference cognitive tasks have been described in other articles (e.g., Salthouse, 2005; Salthouse, Atkinson, & Berish, 2003). The following tasks were used to assess each ability: Raven's Progressive Matrices, Letter Sets, Shipley Abstraction, Spatial Relations, Paper Folding, and Form Boards for Gf; Logical Memory, Multiple Trial Word Recall, and Paired Associates for episodic memory; Digit Symbol Substitution, Letter Comparison, and Pattern Comparison for perceptual speed; and WAIS Vocabulary, Picture Vocabulary, Synonym Vocabulary, and Antonym Vocabulary for vocabulary. All of the variables had coefficient α estimates of reliability of .70 or greater, and loadings of .60 or higher on the factors corresponding to Gf, episodic memory, perceptual speed, and vocabulary abilities.

The three storage-plus-processing tasks have been described in Conway et al. (2005) and Unsworth, Heitz, Schrock, and Engle (2005), and were obtained from psychology.gatech.edu/renglelab. Each task requires the participant to perform a processing component while simultaneously remembering a series of items. The processing and storage components are initially performed separately, to familiarize the participants with each aspect of the task. The number of to-be-remembered items (i.e., set size) in the combined storage-plus-processing phase varied randomly across trials for different participants such that, on average, there was no correlation between set size and trial number. The primary measure of performance in each WM task was the number of to-be-remembered items recalled in the correct sequence.

In the Operation Span (OSpan) task, the storage component consisted of a sequence of three to seven letters, and the processing component involved verification of arithmetic operations (e.g., $[8/2] + 3 = 6?$). The storage component in the Symmetry Span (SSpan) task consisted of a sequence of two to five positions of dots in a matrix, and the processing component involved judgments about whether patterns of filled cells in an 8×8 grid were symmetrical along the vertical axis. The Reading Span (RSpan) task was nearly identical to the Operation Span task with letters as the to-be-remembered material, except that the processing component consisted of making decisions about whether sentences were meaningful or nonsensical, instead of making decisions about the validity of arithmetic operations.

RESULTS

The correlation between the number of items recalled in the correct order in the OSpan and SSpan tasks in Study 1 was .52, and the correlations in Study 2 were .61, .71, and .56 between the OSpan and SSpan, OSpan and RSpan, and SSpan and RSpan tasks, respectively. Correlations with the score on the Raven's Progressive Matrices were .49 for OSpan and .60 for SSpan in Study 1, and .52, .57, and .49 for OSpan, SSpan, and RSpan, respectively, in Study 2. Finally, the correlation between the WM latent construct (based on the variance common among the two [Study 1] or three [Study 2] span variables) and the Gf latent construct (based on the variance common among the six Gf variables) was .86, and .78 after partialling the influence of age from all variables in Study 1; and in Study 2, the correlation between the constructs was .74, and .66 after partialling age from all variables. These findings confirm the existence of strong relations between Gf and WM, even for individual WM and Gf variables. Furthermore, the results also indicate that the correlations in these samples are not attributable to the relationship of the variables to age, because the correlations were only

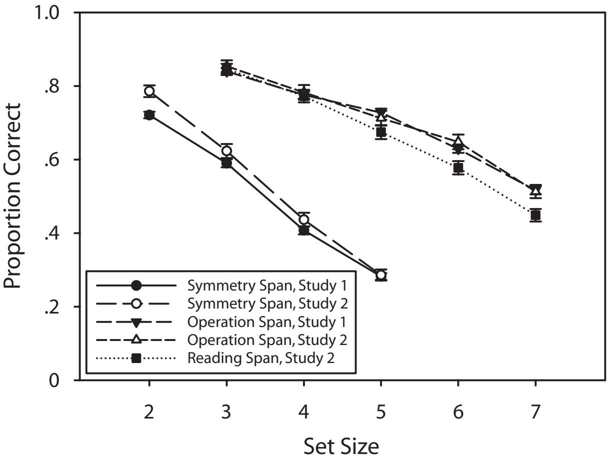

Figure 2. Means (and standard errors) for the proportion of correctly recalled items in the working memory tasks as a function of set size.

Table 2
Contextual Analysis Results for Variables From Different Set Sizes in the Working Memory Tasks

Variable	Total	Unique	Gf	Memory	Speed	Vocabulary	%Var
			Study 1				
Operation Span							
All	−.33*	.03	.40*	.07	.20*	.03	36.3
Set 3	−.29*	.07	.30*	.14	.18*	−.04	25.5
Set 4	−.32*	.00	.35*	.04	.17*	.03	27.7
Set 5	−.32*	−.04	.26*	.06	.22*	.11	30.2
Set 6	−.35*	−.05	.42*	.08	.07	.03	32.7
Set 7	−.33*	−.01	.38*	.10	.10	.01	30.4
Symmetry Span							
All	−.50*	−.10	.71*	−.05	.01	−.13*	51.1
Set 2	−.36*	−.01	.54*	.04	.03	−.05	34.4
Set 3	−.39*	−.06	.54*	−.03	.06	−.05	34.8
Set 4	−.46*	−.09	.58*	.05	−.01	−.13	40.5
Set 5	−.45*	−.12	.66*	−.11	−.04	−.14	36.7
			Study 2				
Operation Span							
All	−.32*	−.01	.57*	.14	−.07	−.06	38.7
Set 3	−.20*	.11	.43*	.13	−.00	−.12	19.6
Set 4	−.22*	.07	.48*	.01	.08	−.00	26.7
Set 5	−.26*	−.06	.40	.17	−.08	.03	27.4
Set 6	−.28*	−.00	.54*	.18	−.14	−.08	32.2
Set 7	−.35*	−.09	.56*	.08	−.09	−.05	34.4
Symmetry Span							
All	−.60*	−.11	.65*	−.04	.14	−.27*	56.5
Set 2	−.38*	.11	.53*	.06	.13	−.35*	29.1
Set 3	−.45*	−.03	.41*	.05	.18	−.23	32.7
Set 4	−.53*	−.16	.65*	−.12	.05	−.19	44.8
Set 5	−.51*	−.18	.55*	−.13	.07	−.19	36.7
Reading Span							
All	−.22*	−.12	.40*	.05	−.03	.21	34.0
Set 3	−.19*	−.01	.23	.16	.04	.06	18.7
Set 4	−.12	.03	.32	−.02	.11	.15	20.0
Set 5	−.15	−.16	.29	.06	−.09	.28	25.8
Set 6	−.20*	−.06	.46*	.05	−.08	.12	28.4
Set 7	−.22*	−.16	.36	.01	−.07	.17	22.8

Note—The values in the Total column are simple correlation coefficients, and those in the other columns are standardized regression coefficients. %Var, percentage of variance in the target variable accounted for by all of the predictor variables. *$p < .01$.

slightly smaller after partialling the effects associated with age from each variable.

Set Size Effects

Proportion correct recall in each span task is plotted by set size in Figure 2. Decision accuracy and time for the processing components in the WM tasks were also examined as a function of set size, but none of the relations were significant, and thus these measures of performance were not considered further.

Simple (zero-order) correlations were computed between the latent Gf construct and the number of items correctly recalled at each set size. The correlations ranged from .47 to .53 for Study 1 OSpan, .57 to .61 for Study 1 SSpan, .43 to .57 for Study 2 OSpan, .46 to .59 for Study 2 SSpan, and .41 to .52 for Study 2 RSpan.

The contextual analysis procedure was next applied in separate analyses for the recall variables at every set size, with each variable treated as though it were independent of all other variables. Reference cognitive abilities were represented as latent constructs in a structural equation model with the four abilities and age all related to the target variable, and age also related to each reference ability (see Salthouse, 2005; Salthouse et al., 2006). The results of these analyses, with the coefficients in standardized units, are presented in Table 2. It can be seen that speed ability was related to some of the OSpan variables, but this was true only in Study 1, not in Study 2. There were also negative relations between vocabulary and some of the SSpan variables, indicating that people with greater word knowledge recalled fewer dot positions. However, the dominant pattern for most variables was a substantial influence of Gf, and very little influence of the other cognitive abilities.

The magnitude of the Gf relations was slightly greater at higher set sizes, and this pattern was also apparent in the simple correlations (not reported). Although the total effects of Gf were greater at larger set sizes, the increases were generally small relative to the effects apparent on the smallest set sizes. To illustrate, the total standardized effects of Gf from the smallest set size to the set size with the largest effect were .57 and .61 for SSpan in Study 1,

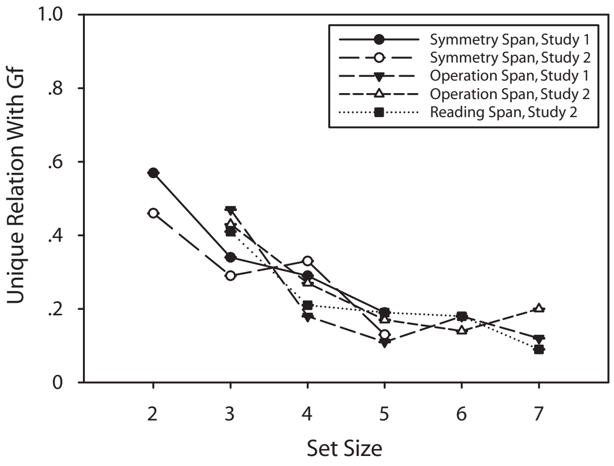

Figure 3. Standardized regression coefficients derived from the model in Figure 1, with the elements in the sequence corresponding to increases in set size.

.46 and .59 for SSpan in Study 2, .47 and .55 for OSpan in Study 1, .43 and .57 for OSpan in Study 2, and .41 and .52 for RSpan in Study 2.

The simple correlations between age and the variables were significant at every set size, with somewhat larger correlations at higher set sizes. However, none of the unique age-related influences on any of the WM variables was significantly different from zero after considering influences from the cognitive abilities.

Gf was the only variable with consistent unique relations in the contextual analyses, and thus it was the only predictor included in the sequential analyses based on the model in Figure 1. The standardized regression coefficients from Gf to the variables at each set size obtained from these analyses are displayed in Figure 3. Inspection of the figure reveals that the strongest Gf influences were on the initial element in the sequence. The unique effects of Gf were successively smaller across positions in the ordered sequence, but with the exceptions of the final positions in the Study 2 SSpan and RSpan tasks, they were each significantly greater than zero. These results indicate that even though the total Gf influence (corresponding to the simple correlation) was slightly greater at larger set sizes, most of the effects were carried over from the smaller set sizes because the unique influences decreased with increasing set size.

Trial Effects

Because a very small amount of data was available from each participant on each trial, the analyses of the trial data are only reported for the data from Study 1, in which the sample size was relatively large. The patterns in Study 2 were generally similar, but more variable. Figure 4 indicates that there were slight increases in the number of items recalled across successive trials. Results of the contextual analyses on the trial data are reported in Table 3, where it can be seen that when the trials were considered independently, there were nearly constant relations of the cognitive abilities on successive trials.

Sequential analyses on the trial data only included the three immediately prior trials to avoid excessively complex and potentially nonidentifiable models. Figure 5 portrays standardized coefficients from the sequential analyses on the trial data. It can be seen that the results are similar to those with the set size analyses portrayed in Figure 3, since the largest effects were on the first trial, with unique influences of Gf diminishing across successive trials. Note that, consistent with the greater Gf influ-

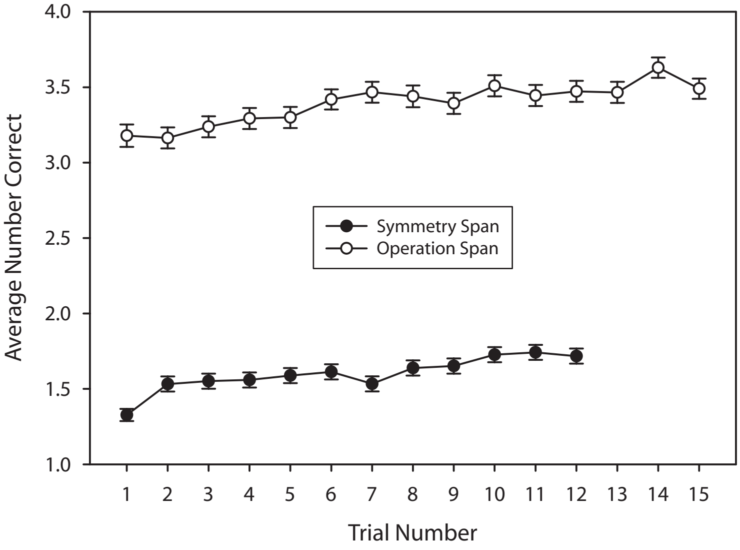

Figure 4. Means (and standard errors) for the number of items correctly recalled as a function of trial number in the Symmetry Span and Operation Span tasks.

Table 3
Contextual Analysis Results From Study 1 for Variables From Successive Trials in the Working Memory Tasks, With Each Trial Considered Independently

Variable	Total	Unique	Gf	Memory	Speed	Vocabulary	%Var
			Operation Span				
Trial 1	−.27*	.06	.33*	.03	.22*	−.01	24.1
Trial 2	−.23*	.07	.32*	.02	.17*	−.07	16.6
Trial 3	−.20*	.04	.20	.06	.17	.02	13.9
Trial 4	−.20*	.02	.13	.07	.22*	.05	14.0
Trial 5	−.28*	−.05	.30*	.00	.12	.01	18.1
Trial 6	−.23*	.08	.34*	.08	.16	−.02	22.1
Trial 7	−.21*	−.02	.19	−.02	.22*	.11	16.7
Trial 8	−.22*	−.05	.10	.05	.23*	.14	17.7
Trial 9	−.22*	.00	.21	.17	.07	.01	16.7
Trial 10	−.20*	.07	.32*	.13	.05	−.05	16.7
Trial 11	−.22*	.02	.28*	.07	.08	−.04	13.8
Trial 12	−.17*	.00	.19	.05	.12	.07	12.4
Trial 13	−.23*	−.02	.30*	.04	.08	.01	16.1
Trial 14	−.20*	−.01	.25*	.11	.04	.04	15.5
Trial 15	−.16*	.13	.26*	.06	.19*	−.05	13.4
			Symmetry Span				
Trial 1	−.34*	−.08	.56*	−.05	−.04	−.04	27.4
Trial 2	−.34*	−.06	.43*	−.07	.09	−.10	21.9
Trial 3	−.30*	−.05	.41*	−.11	.09	−.09	17.3
Trial 4	−.32*	−.04	.36*	.05	.07	−.09	20.4
Trial 5	−.32*	−.12	.38*	−.04	.03	.00	20.1
Trial 6	−.27*	−.05	.34*	.06	−.03	−.08	14.8
Trial 7	−.35*	−.11	.37*	.13	−.08	−.12	21.0
Trial 8	−.28*	.00	.49*	−.06	.02	−.11	18.9
Trial 9	−.28*	.04	.62*	−.13	−.01	−.19*	21.4
Trial 10	−.33*	−.17*	.39*	−.08	.00	.03	20.8
Trial 11	−.32*	−.03	.59*	−.07	−.06	−.15*	23.5
Trial 12	−.30*	−.01	.35*	.07	.09	−.05	21.5

Note—The values in the Total column are simple correlation coefficients, and those in the other columns are standardized regression coefficients. %Var, percentage of variance in the target variable accounted for by all of the predictor variables. *$p < .01$.

ence on the symmetry span variables in Tables 2 and 3, the unique influences of Gf were stronger on the symmetry span variable than on the operation span variable for all trials except Trial 6.

GENERAL DISCUSSION

Inspection of Tables 2 and 3 reveals that nearly every variable had a significant negative correlation with age but only one variable had a unique age relation that was statistically independent of influences mediated through the reference cognitive abilities. These results imply that there may not be anything special about WM variables with respect to their relations with age, because there is nearly complete overlap of the age-related influences on these variables and on established cognitive abilities. The mechanisms responsible for these shared influences are not yet obvious, but the present results suggest that the same mechanisms are likely operating with both types of variables.

The major findings of the project are the relatively small increases in the relations of Gf on WM with increases in the amount of to-be-remembered information (set size), and across successive trials. The nearly constant simple correlations across different set sizes replicates a recent finding by Unsworth and Engle (2006), but the discovery that the simple relations were also fairly constant across successive trials is new. Furthermore, by analyzing the variables in an ordered sequence, as in Figure 1, the simple correlations can be decomposed into effects carried over from earlier elements in the sequence and effects specific to a particular element. This type of decomposition can be very informative because simple correlations could remain constant across elements in a sequence if increases (or decreases) in effects propagated from previous elements were offset by decreases (or increases) in direct effects. In fact, as illustrated in Figures 3 and 5, the sequential analyses revealed that the direct (unique) influences of Gf diminished across successive set sizes and across successive trials.

These results can be considered robust because they are based on powerful analyses with two large and independent samples, and unique influences were identified by considering several cognitive abilities simultaneously. The small variation in the Gf–WM relations across set sizes suggest that the amount of required simultaneous storage and processing is not critical to the existence, or even much of the magnitude, of the relations between these tasks and other cognitive abilities. The finding that the initial trial in the WM tasks is nearly as informative as later trials with respect to individual differences in Gf also suggests that the relationship of WM variables with

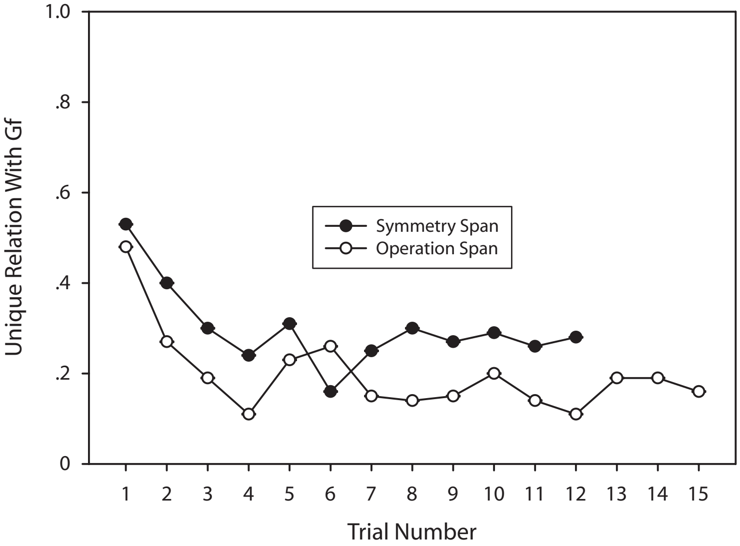

Figure 5. Standardized regression coefficients derived from the model in Figure 1, with the elements in the sequence corresponding to successive trials.

Gf apparently does not depend on processes that extend over successive trials, such as within-task learning or the accumulation of proactive interference.

WM influences have also been examined at different levels of complexity in a variety of Gf tasks, with the results often revealing nearly constant influences of WM at all levels of task complexity. WM in these studies was assessed with the computation-span and reading-span tasks, in which the participant was required to remember some information, either the last digit in an arithmetic problem or the last word in a sentence, while also carrying out designated processing, either performing simple arithmetic or answering questions about sentences. There was an inconsistent pattern of WM–Gf correlations across increases in complexity of three Gf tasks in two studies reported by Salthouse (1992b), but there was no systematic increase in the WM–Gf correlation with more paper folding operations or more integrative reasoning premises in Salthouse, Mitchell, Skovronek, and Babcock (1989), with more keeping-track operations in Salthouse (1992a), or with more relations among elements in Raven's Matrix Reasoning problems in Salthouse (1993). Much like the finding in the present project that substantial Gf relations are evident in the simplest versions of the WM tasks, these earlier results indicate that substantial WM relations are evident in the simplest versions of Gf tasks. Taken together, the two sets of results imply that Gf–WM relations are somewhat independent of the complexity, or amount of required processing, in both WM and Gf tasks. In other words, people seem to be rank-ordered in nearly the same way even with very simple versions of Gf and WM tasks.

Finally, what do these results indicate is responsible for the Gf–WM relationship? Because strong relations are evident in the simplest versions of the tasks, and on the earliest trials in the task, the critical factor does not seem to be related to how much storage and processing is required, or to processes associated with successive trials in WM tasks. At least with these particular methods of assessing WM, the relationship does not appear to be attributable to individuals who perform better in Gf tasks being capable of preserving more temporary information during processing than individuals with lower Gf performance. Instead, the relationship may reflect an ability of people with high levels of Gf to adapt quickly to a new task and perform effectively, even in situations that have minimal demands for simultaneous storage and processing.

AUTHOR NOTE

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