A latent variable analysis of working memory capacity, short-term memory capacity, processing speed, and general fluid intelligence

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Abstract

Significant relationships exist between general fluid intelligence and each of the following constructs: short-term memory capacity, working memory capacity (WMC), and processing speed. However, the interrelationship among all four constructs has not been investigated. Multiple measures of each of these constructs were obtained from 120 healthy young adults. Structural equation modeling was then performed to determine which construct served as the best predictor of general fluid intelligence. The results suggest that WMC, but not short-term memory capacity or processing speed, is a good predictor of general fluid intelligence in young adults. Possible mechanisms underlying the link between WMC and general fluid intelligence are discussed. © 2002 Elsevier Science Inc. All rights reserved.

Keywords: Working memory; Short-term memory; Intelligence; Individual differences; Factor analysis; Structural equation modeling; Cognitive ability; Controlled attention; Strategy

1. Introduction

A decade has passed since Kyllonen and Christal (1990) inquisitively exclaimed "Reasoning ability is (little more than) working memory capacity?!". Despite an impressive

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series of projects demonstrating correlations between working memory capacity (WMC) and reasoning ability in the range of .80–.88 (Kyllonen & Christal, 1990), the leap to the notion that WMC is the basis of Spearman's *g* (Kyllonen, 1996) has not yet been universally embraced. The most notable challenges have been the claims that processing speed accounts for the relationship between WMC and fluid abilities (Fry & Hale, 1996; Jensen, 1998; Kail & Salthouse, 1994; Salthouse, 1996) and that WMC may not be a unitary resource, but rather, can be divided into separate resource pools for spatial and verbal processing (Shah & Miyake, 1997). In contrast, recent work that has clarified the distinction between WMC and short-term memory capacity (Cowan 1995; Engle, Tuholski, Laughlin, & Conway, 1999) has supported the notion that WMC is strongly linked to fluid abilities (Engle, Tuholski, et al., 1999). With this new information in hand, we explore the four-way relationship between WMC, short-term memory capacity, processing speed, and fluid intelligence.

It is clear from previous research that significant intercorrelations exist between measures of short-term memory capacity, WMC, processing speed, and fluid intelligence. However, investigations of these constructs typically involve only two-way relationships, such as the relationship between processing speed and fluid intelligence (for reviews, see Neisser et al., 1996; Vernon, 1987), or between short-term memory capacity and fluid intelligence (Bachelder & Denny, 1977a, 1977b), while some have examined different three-way relationships (Engle, Tuholski, et al., 1999; Fry & Hale, 1996; Kyllonen & Christal, 1990). In the current project, we explore the complex relationship that exists between these constructs in order to identify the primary contributor to individual differences in fluid intelligence. This is particularly necessary because some theorists posit that processing speed accounts for the relationship between WMC and fluid intelligence (Fry & Hale, 1996; Jensen, 1998; Kail & Salthouse, 1994; Salthouse, 1996), while others posit that WMC is the primary predictor of fluid intelligence (Carpenter, Just, & Shell, 1990; Engle, Tuholski, et al., 1999; Kyllonen, 1996; Kyllonen & Christal, 1990). This approach is also useful in that it has the potential to clarify the subtle distinction between the short-term memory and working memory constructs and to illustrate how these constructs relate to fluid abilities (Engle, Tuholski, et al., 1999).

Before exploring this complex relationship, it is important to clearly define each construct. First, we propose a distinction between working memory and short-term memory (Cowan, 1995; Engle, Tuholski, et al., 1999). We view short-term memory as a simple storage buffer, the capacity of which is determined by practiced skills and strategies, such as rehearsal and chunking. In contrast, working memory is more complex in that it consists of a storage component as well as an attention component. The function of working memory is to maintain memory representations in the face of concurrent processing, distraction, and/or attention shifts (Baddeley & Hitch, 1974; Engle, Tuholski, et al., 1999; Miyake & Shah, 1999). Therefore, the extent to which a task demands WMC is determined by the extent to which it requires the maintenance of activation to memory representations that could otherwise be lost from the focus of attention due to interference or decay. We view this capacity as a general resource, which contributes to cognitive performance in any domain which demands this type of controlled processing (Cowan, 1995; Engle, Tuholski, et al., 1999; Lovett, Reder, & Lebiere, 1999).

Empirical support for this framework comes from a latent variable analysis of the relationship between short-term memory capacity, WMC, and fluid abilities (Engle, Tuholski, et al., 1999). Engle, Tuholski, et al. (1999) administered several memory tasks and two measures of fluid abilities, Raven's Progressive Matrices (RAVENS) and Cattell's Culture Fair Test (CATTELL), to 133 healthy young adults. Some of the memory measures were traditional span tasks, such as a simple word span task, in which words are presented one per second and the participant must recall all the words at the end of a series. Some of the other memory measures were "complex" span tasks, such as the reading span (RSPAN) task (Daneman & Carpenter, 1980), in which participants read a series of sentences and remembered the last word of each sentence for later recall. Complex span tasks are thought to tap not only the storage component but also the processing component of working memory (Daneman & Carpenter, 1980; Daneman & Merikle, 1996; Engle, Tuholski, et al., 1999). Engle et al. argued that individual differences in performance on complex span tasks such as RSPAN, operation span (OSPAN) (Turner & Engle, 1989), and counting span (CSPAN) (Case, Kurland, & Goldberg, 1982) are primarily due to differences in the central executive component of working memory. In contrast, they argue that individual differences in performance on simple span tasks are primarily due to differences in domain-specific abilities such as chunking and rehearsal (in the case of verbal span tasks). They therefore predicted that a latent variable derived from the complex span tasks would be correlated with fluid intelligence (as measured by Raven's and Cattell's tests) but the latent variable derived from the simple span tasks would not be correlated with fluid intelligence. Indeed, the latent variable derived from RSPAN, OSPAN, and CSPAN, which they labeled "working memory," was a significant predictor of fluid intelligence, while the latent variable derived from the simple span tasks did not significantly predict fluid intelligence. Furthermore, when the variance common to the working memory latent variable and the short-term memory latent variable was removed from the working memory–intelligence relationship, the working memory latent variable still served as a significant predictor of fluid intelligence.

While the Engle, Tuholski, et al. (1999) study nicely dissociates short-term memory capacity from WMC, it is important to note that no one task is a "pure" measure of either short-term memory capacity or WMC. All span tasks, simple and complex, will tap each capacity to some extent. We argue that the more a task forces the participant to engage in controlled effortful processing rather than automatized skills, the more that task will tap WMC, and the less it will tap short-term memory capacity.

As with short-term and WMC, we assume that there are no tasks that are pure measures of processing speed. But before we discuss tasks, we need to establish what is meant by "processing speed." As mentioned above, some researchers have argued that processing speed accounts for the relationship between WMC and fluid intelligence. According to this argument, processing speed is a general characteristic which determines capacity because processing (encoding, transforming, retrieving) information within working memory takes time. The faster the rate of processing, the greater the amount of information that can be processed in one unit of time. Thus, an individual with above-average WMC may functionally have a greater capacity than others but the causal attribute is a global processing speed (Jensen, 1998; Kail & Salthouse, 1994; Salthouse, 1996).

An obvious key to investigating the relationship among these constructs is choosing tasks that are valid measures. We argue that previous research has been limited by two methodological points: (1) not recognizing the subtle difference between working memory tasks and short-term memory tasks, and (2) not considering the working memory demands of "speed" tasks. To illustrate these points, we will describe tasks used in a recent project by Fry and Hale (1996).

Fry and Hale (1996) examined developmental trends in WMC, processing speed, and fluid intelligence. The reason we cite this particular paper is not because we have strong disagreement with the theoretical claims, but rather because the tasks used nicely illustrate the two points mentioned above.[1] Consider the "working memory" tasks used by Fry and Hale. As noted above, we argue that there is a critical distinction between short-term memory and working memory. According to our framework (see Engle, Kane, & Tuholski, 1999; Engle, Tuholski, et al., 1999), two of the tasks are clearly "simple" span tasks that should tap short-term memory capacity in young adults and two of the tasks are "complex" span tasks that should tap WMC in young adults. For example, one of the simple span tasks was a digit span task, in which participants are presented with a series of digits and then asked to recall the digits in correct serial order. This task is a good measure of verbal short-term memory capacity because performance heavily relies on practiced skills and strategies such as rehearsal and chunking. In contrast, one of the complex span tasks involved naming the color of each digit presented while also remembering each digit for later recall. This extra component "slides" the task down the scale, away from a short-term memory task and towards a working memory task, because the extra component demands the maintenance of information (digits) in the face of concurrent processing (naming colors). Fry and Hale's aggregate measure of the working memory construct was the average of performance on these simple span tasks and the complex span tasks. Therefore, because they are collapsing across short-term memory ability and working memory ability, in our view the predictive validity of each individual construct is indeterminate. To circumvent this problem in the current project, we use a latent variable approach. Measures of WMC include RSPAN, OSPAN, and CSPAN. We also used several versions of a simple word span task to measure short-term memory capacity.

Next, consider the processing speed tasks reported by Fry and Hale (1996). There were four tasks, two of which place minimal demands on working memory and two of which place heavy demands on working memory. The two that place minimal demands on working memory are disjunctive choice reaction time and shape classification. In the former task, two vertical arrows pointing in either the same or different directions are presented and the participant provides a same/different judgment. In the latter task, two geometric forms whose

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[1] It is important to note that the factors that account for developmental differences in fluid intelligence are not necessarily the same factors that account for individual differences in fluid intelligence in young adults. Furthermore, an individual task may be a good measure of working memory capacity in children but not in adults and vice versa. That said, there is still quite a bit of theoretical overlap between the literatures on developmental differences in cognitive ability and individual differences in cognitive ability, therefore we will return to this issue in the Discussion.

shapes are either the same or different are presented and the participant provides a same/different judgment. These tasks place minimal demands on working memory because the information relevant to the judgment is provided on the computer screen. Memory representations do not need to be maintained in the face of concurrent processing. In contrast, the two other processing speed tasks, visual search and abstract matching to sample, place demands on working memory. In the visual search task, the participant had to search for a red square target stimulus in a field of distractors consisting of green squares and red circles. Given that this is a conjunctive search condition, the task requires controlled attention (Treisman & Gelade, 1980) and therefore may place demands on working memory (Tuholski, Baylis, & Engle, 2001). In the abstract matching to sample task, three patterns that could vary along four dimensions (shape, color, number, and orientation) are presented and the participant provides a judgment as to which of two upper patterns best matched the lower pattern. Given that there are three relevant stimuli with four relevant dimensions each, it is likely that some of this information had to be maintained internally while other information was encoded, which would require working memory. As with the memory tasks, Fry and Hale derived an overall speed score by averaging across all four of these tasks. Again, because they aggregated across tasks that in our view tap different abilities, the predictive validity of processing speed is indeterminate.

Therefore, in the current project we chose speed tasks that place minimal demand on memory and attention. The tasks we chose were digit–symbol substitution (DIGSYM), pattern comparison (PAT), letter comparison (LET), and digit copying (Salthouse, 1996).[2] Each of these tasks are described in detail in the Method section, but we mention here that the demand for the maintenance of information in the face of concurrent processing and/or attention shifts is minimal, and therefore the demand on working memory is minimal.[3]

Our interest in the current project is in the degree to which individual differences in short-term memory capacity, WMC, and processing speed predict performance on tests of fluid intelligence. Therefore, we also administered two tests of fluid abilities, RAVENS (Raven, Court, & Raven, 1977) and CATTELL (Cattell, 1963). We chose these tests because they have been shown to load highly on a general factor (i.e., Spearman's g) in psychometric studies of intelligence (Carroll, 1993) and because they are primarily nonverbal. For example, Raven's test and the matrices subtest of CATTELL involve inductive reasoning about spatial features and relations (Carpenter et al., 1990; Carroll, 1993). Thus, discovering a relationship between fluid abilities measured with these tasks and WMC, measured with verbal span tasks, will afford an argument that WMC does indeed reflect a domain-free cognitive ability.

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[2] The materials for the paper-and-pencil tasks as well as the computer program for the digit–symbol task were obtained from Tim Salthouse.

[3] This is not to say that these tasks place "zero" demand on memory and attention. Each task requires sustained attention such that a goal be maintained and attained, selective attention such that the participant focus on the task at hand, and memory for goals and stimuli. However, we submit that the demand for controlled attention and working memory in these speed tasks is less than other speed tasks that have been used in previous research, such as those used by Fry and Hale (1996).

Furthermore, such a finding will provide a challenge to theories of working memory that do not assume a general domain-free capacity (cf. Shah & Miyake, 1997).

Therefore, in the current project multiple measures of each of the four constructs, WMC, short-term memory capacity, processing speed, and fluid intelligence were administered to 120 young adults. Latent variables for each construct are derived and the relationship among constructs is explored via structural equation modeling. According to the theoretical distinction between working memory and short-term memory discussed earlier (Cowan, 1995; Engle, Kane, et al., 1999; Engle, Tuholski, et al., 1999), the latent variable derived from the working memory measures should be highly predictive of fluid intelligence while the latent variable derived from the short-term memory measures should not. Also, given that the processing speed tasks used here make minimal demands on working memory, this framework predicts a weak relationship between processing speed and fluid intelligence.

2. Method

2.1. Participants

A total of 120 first-year undergraduates from the University of Illinois at Chicago participated in the project. All were native English speakers, received course credit for their participation, and were treated in accordance with the ethical guidelines of the American Psychological Association and the University of Illinois.

2.2. Materials/tasks

2.2.1. Working memory tasks

2.2.1.1. Reading span.   This task required participants to read sentences aloud while trying to remember unrelated words. Each participant was presented with a series of displays. Each display consisted of a sentence of 12–14 words, followed by an unrelated word in capital letters. The participant was instructed to read the sentence aloud and attempt to remember the capital letter word for later recall. After the participant read the sentence and the word aloud, the experimenter pressed the spacebar, which caused the next sentence/ word pair to be presented. After a number of displays had been presented, a recall cue consisting of three question marks "???" prompted the participant to recall all the words from the series. The number of displays per series varied from two to six. Three series of each length were performed for a total of 15 series and the order of presentation of these series was randomized.

In addition, for half of the series, each participant was tested for comprehension of one to four of the sentences from that series. The test consisted of the experimenter asking the participant a question about one of the sentences. In all, comprehension was tested on 22 of the 60 sentences. Participants who missed more than 10 of the comprehension questions were excluded from the final analyses.

The task was scored by awarding points for series that were recalled perfectly and in correct order. The total number of points awarded was equal to the number of displays in the series. For example, if the participant recalled all three series length 2 and one series length 3, then his or her span score would be 9.

2.2.1.2. Operation span. This task required participants to solve mathematical operations while trying to remember unrelated words. Each participant was presented with a series of displays. Each display consisted of a math problem and a word (e.g., "IS $10/2 + 2 = 7$? DOG"). The participant was instructed to read the math problem aloud, state whether the given answer was correct or incorrect by saying "yes" or "no," and then say the word. The given answer was correct on half the displays. After the participant said the word, the experimenter pressed the spacebar which caused the next operation/word pair to be presented. After a number of displays had been presented, a recall cue consisting of three question marks "???" prompted the participant to recall all the words from the series. The number of displays per series varied from two to six. Three series of each length were performed for a total of 15 series and the order of presentation of these series was randomized.

If the participant incorrectly answered more than eight of the math problems, their data were excluded from the final analyses. The task was scored in the same manner as RSPAN.

2.2.1.3. Counting span. This task required participants to count aloud while trying to remember digits. Each participant was presented with a series of displays, each display consisting of a varying number of targets (dark blue circles) and distractors (dark blue squares and light blue circles). The participant was instructed to count aloud the number of targets and remember the count total for later recall. When the participant finished counting, the experimenter pressed the spacebar which caused the next display to be presented. After a number of displays had been presented, a recall cue consisting of three question marks "???" prompted the participant to recall all the digits (count totals) from the series. The number of displays per series varied from two to eight. Three series of each length were performed for a total of 21 series and the order of presentation of these series was randomized.

If the participant committed a counting error, it was noted by the experimenter and the erroneous total was used to judge memory performance (i.e., if the participant counted four instead of five, then recall would be scored as correct if they remembered four). The task was scored in the same manner as RSPAN and OSPAN.

2.2.2. Short-term memory tasks

Short-term memory capacity was evaluated with four variations of a simple word span task. Two manipulations to the standard span task were introduced and crossed resulting in four different tasks. One manipulation was having participants engage in articulatory suppression versus none during the presentation of stimuli (Baddeley, 1986; Baddeley & Hitch, 1974) and the other manipulation was fixing the pool of seven words from which stimuli were drawn versus an unlimited set (La Pointe & Engle, 1990). With articulatory suppression and an unlimited set of words, we hoped to deny the participant the luxury of relying on domain-specific abilities such as rote rehearsal and chunking thereby requiring the

participant to rely more on controlled attention to perform the task. In each version, the participant was presented with words on a computer screen at a rate of one word per second. In the versions without articulatory suppression, the participant was instructed to read the words aloud as they were presented. In the versions with articulatory suppression, participants were required to repeat "ABC" while the words were presented. After a varying number of words, a recall cue of three question marks "???" was presented, at which time the participant would recall all the words in the series. The number of words per series varied from two to seven and three series of each length were performed for a total of 18 series. The order of series was fixed with series length 2 presented first and series length ascending with series length 7 presented last. All the words were common mono- and disyllabic words.

The four versions are named STM_U, STM_F, STM_{US}, STM_{FS} to designate whether the pool of words was unlimited (U) or fixed (F) and whether articulatory suppression was required (S) or not.

2.2.3. Processing speed tasks

2.2.3.1. Digit–symbol substitution. This was the only computerized speed task (the others were paper-and-pencil tasks). Participants were presented with a set of nine symbols, each symbol corresponding to a number (1–9). Symbol and number pairings were displayed at the top of the computer screen, in two rows of boxes (nine boxes per row). The top row contained the numbers and the bottom row contained the corresponding symbols. On each trial, a number–symbol pairing was displayed in the center of the screen. Participants were instructed to verify, as quickly and accurately as possible, whether the pairing was "valid" according to the digit–symbol pairs at the top of the screen. If the pair was valid, the participant pressed the 'z' key on the keyboard. If it was invalid, they pressed the '?' key (without the shift key). The word 'same' appeared at the bottom left of the screen and the word 'different' appeared at the bottom right of the screen to aid participants in using the correct keys. Response time was measured from display onset until participant response. There were five blocks of trials, and symbol–number pairings remained consistent across each block. The first block was considered practice. The DIGSYM score used in subsequent analyses is the mean response time in Blocks 2–5.

2.2.3.2. Digit and letter copying (DIG). This was a paper-and-pencil task. The participant was presented with a packet including an instruction sheet, a sheet with a series of digits, two sheets with series of letters, and an additional digit sheet. They were instructed to copy as many digits or letters as possible per page within 30 s. The DIG score used in subsequent analyses is the total number of digits and letters copied correctly.

2.2.3.3. Pattern and letter comparison. This was a paper-and-pencil task in which a form contained a series of pairs of items with a horizontal line between the members of a pair. The task for the participants was to write an S (for same) or a D (for different) on the line between the two members of the pair and to complete as many items as possible within 1 min. PAT was made progressively more difficult by increasing the complexity of the patterns. LET was

made progressively more difficult by adding more letters to the string. The PAT and LET scores are the total number of patterns and letters, respectively, compared in 1 min.

2.2.4. Fluid intelligence tests

Two standardized intelligence tests were used: RAVENS and CATTELL. These tests were chosen because they have been shown to be good predictors of fluid intelligence and typically load highly on a general factor in psychometric studies (Carroll, 1993). The tests were presented on paper and in accordance with the standardized rules that accompany the tests.

2.2.4.1. Raven's Standard Progressive Matrices. Participants were presented with 60 patterns/matrices composed of abstract shapes, lines, and nonverbal figures, each of which was missing a piece. For each pattern, 6 choices (pieces) were presented. The participant's task was to choose the piece that fit best in the empty space. Participants had as much time as they needed to complete this task. The total number of correct choices was used as the RAVENS score.

2.2.4.2. Cattell's Culture Fair Test. This test is composed of four separate and timed paper-and-pencil subtests. Participants were allowed 2.5 to 4 min to complete each subtest (exact time varies for each subtest). When time expired for a subtest, participants were instructed to stop working on that subtest and begin the next. At no point were the participants allowed to go back to work on previous subtests.

In the first subtest, *Series*, participants saw 13 incomplete, progressive series of abstract shapes and figures, along with 6 alternatives for each, and selected the alternative which best completed the series. In the second subtest, *Classifications*, participants saw 14 problems comprised of abstract shapes and figures, and selected which two out of the five differed from the other three. Figures and shapes differed in size, orientation, or content. The third subtest was *Matrices*, which is similar to the RAVENS. Participants were presented with 13 incomplete matrices containing four to nine boxes of abstract figures and shapes as well as an empty box and six choices. Participants had to infer the relationships among the items in the matrix and choose an answer which correctly completed each matrix. In the final subtest, *Conditions*, participants were presented with 10 sets of abstract figures consisting of lines and a single dot, along with five alternatives. The participants' task was to assess the relationship among the dot, figures, and lines and choose the alternative in which a dot could be placed according to the same relationship. For example, if the dot had been placed inside a circle, but outside a square, the participant needed to choose the alternative in which a single dot could be placed inside a circle but outside of a square. The CATTELL score was the sum of all correct answers, across all four subtests.

2.3. Procedure

Upon arrival participants were informed that the project would be conducted in three 1-h sessions, one session per week for 3 weeks. Informed consent was gained from the participants before proceeding with task administration.

The tasks were administered in a well-illuminated, 5×5 m room, furnished with a large desk, a computer, and a chair situated in front of the desk. The experimenter sat in a chair adjacent to the computer desk with the mouse and keyboard situated in front of him to facilitate operation of the tasks. The working memory and short-term memory tasks were controlled by MEL (2.0) software.

The experimenter was present for all tasks, and participants completed the tasks individually. The working memory, short-term memory, and processing speed tasks were administered during the first two sessions. The intelligence tests were administered during the third session. In Session 1, the following tests were presented in the order specified: OSPAN, LET, PAT, STM_U, and CSPAN. In Session 2, the order consisted of RSPAN, STM_F, DIG, STM_{US}, DIGSYM, and STM_{FS}. In Session 3, RAVENS was administered first, followed by CATTELL.

Following completion of the third session, participants were debriefed regarding the purpose of the project. Participants who did not complete all sessions or did not meet the criterion for tasks (see description of tasks) were not included in final data analyses.

3. Results

Data from seven participants were omitted from the following analyses. Two were omitted because they committed too many errors in the OSPAN task. The other five were omitted because they did not complete all three sessions.

The results are presented in three sections. First, descriptive statistics and first-order correlations are presented. Second, a series of confirmatory factor analyses are presented to verify the correct measurement model. Third, a series of structural equation models are presented to examine the relationship among the four main constructs. For all significance tests alpha was .05. For all confirmatory factor analyses and structural equation models, we evaluate the fit of each model using several statistics including chi-square, goodness-of-fit

Table 1
Descriptive statistics for all measures

Measure	Mean	S.D.	Skew	Kurtosis
OSPAN	14.9	6.9	0.83	0.75
RSPAN	11.1	7.6	1.21	2.24
CSPAN	25.7	12.8	0.56	−0.53
STM_U	34.1	9.4	0.65	0.75
STM_F	36.7	10.9	0.36	−0.04
STM_{US}	13.8	6.4	1.08	1.75
STM_{FS}	18.1	7.0	0.89	0.34
LETTER	44.4	9.1	0.14	−0.32
PATTERN	63.1	9.6	−0.09	−0.09
DIGIT	220.5	32.6	0.28	0.52
DIGSYM	1125	186	.72	2.13
CATTELL	25.5	4.7	−0.36	−0.31
RAVENS	48.8	5.3	− 0.95	0.64

Table 2
Correlation matrix and reliability estimates

	1	2	3	4	5	6	7	8	9	10	11	12
1. OSPAN	–											
2. RSPAN	**.49**	–										
3. CSPAN	**.50**	**.53**	–									
4. STM$_U$	**.52**	**.50**	**.28**	–								
5. STM$_F$	**.36**	**.46**	**.39**	**.62**	–							
6. STM$_{US}$	**.54**	**.37**	**.39**	**.48**	**.40**	–						
7. STM$_{FS}$	**.39**	**.35**	**.42**	**.45**	**.35**	**.52**	–					
8. LETTER	.15	.15	.13	.13	.03	**.30**	**.24**	–				
9. PATTERN	.18	**.19**	.16	.12	.03	**.32**	**.28**	**.67**	–			
10. DIGIT	.16	**.19**	.05	.18	.08	**.20**	.08	**.54**	**.52**	–		
11. DIGSYM	− .02	.05	− .06	.04	− .04	− .01	− .08	− .05	.01	.04	–	
12. CATTELL	**.28**	**.29**	**.37**	.15	.07	.10	**.21**	.07	**.21**	.09	.06	–
13. RAVENS	**.20**	.15	**.38**	.06	.07	.05	.10	− .09	.03	− .01	− .08	**.57**
Cronbach's alpha	.64	.70	.75	.62	.71	.63	.59	.80	.77	.93		.60

Significant correlations ($P < .05$) are in bold.

index (GFI), adjusted goodness-of-fit index (AGFI), the Tucker and Lewis index (TLI), the comparative fit index (CFI), and the root-mean-square error of approximation (RMSEA). We also rely on chi-square difference tests to compare the fit of different models. All analyses were conducted using AMOS software.

Descriptive statistics are presented in Table 1. Note that all measures meet standard criteria for univariate normality (Kline, 1998) with skew for all measures less than 3 and kurtosis for all measures less than 4. Also, the data were screened for both univariate and multivariate outliers. Univariate outliers were defined as cases more than 3.5 standard deviations from the mean. Multivariate outliers were examined by calculating Mahanalobis' d^2. None of the cases in the data were deemed outliers. Therefore, all instances of all 120 cases are included in the following analyses. The data were also checked for multicollinearity. None of the first-order correlations were above .80 and the highest squared multiple correlation was .73, indicating that multicollinearity is not a problem with these data at the measurement level (Kline, 1998).

First-order correlations are presented in Table 2. A few aspects of the matrix are worth mentioning here. First, the three working memory span tasks have consistent yet moderate correlations in the range of .49–.52. This is consistent with a previous project conducted with undergraduates from the University of South Carolina (Engle, Tuholski, et al., 1999). Second, the speed measures are all highly correlated with the exception of DIGSYM. Because DIGSYM did not correlate with the other speed measures, it was not included in subsequent latent variable analyses.[4] Third, RAVENS and CATTELL are correlated at .57. Fourth, the

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[4] It is unclear why we did not find significant correlations between the digit–symbol task and the other speed measures. In studies with older adults, Salthouse (1996) has found correlations among these measures. Perhaps our young participants developed strategies for performing the digit–symbol task, which would place the locus of individual differences in the realm of domain-specific skills rather than processing speed. Also, the digit–symbol task was the only computerized speed task used in this project.

Table 3
Fit statistics for confirmatory factor analysis and structural equation models

Model	df	χ^2	P	GFI	AGFI	TLI	CFI	RMSEA
CFA1	51	106.33	.00	.92	.81	.82	.89	.14
CFA2	**47**	**67.26**	**.03**	**.92**	**.86**	**.94**	**.96**	**.06**
CFA3	48	80.82	.00	.90	.84	.91	.94	.08
CFA4	48	97.93	.00	.89	.82	.86	.90	.09
SEM1	47	67.26	.03	.92	.86	.94	.96	.06
SEM2	**45**	**61.40**	**.05**	**.94**	**.88**	**.93**	**.96**	**.07**

short-term memory measures are highly correlated with each other and with the working memory measures. In order to make sense of these relationships, we conducted confirmatory factor analyses and then structural equation modeling.

Our intent was to capture four latent variables with the measurement model: WMC, short-term memory capacity, processing speed, and fluid intelligence. The first question we addressed was whether WMC and short-term memory capacity would emerge as separate factors or if all the memory measures would load on one factor. In order to answer this question, we first ran a confirmatory factor analysis with all the memory measures loading on one factor (the speed tasks were specified to load on a factor we called "speed" and the fluid abilities measures were specified to load on factor we called "gF" for general fluid intelligence). We then ran a second model with the three working memory tasks (RSPAN, OSPAN, and CSPAN) loading on one factor and the four short-term memory tasks loading on a separate factor. The fit statistics for these two models are presented in Table 3. All fit indices indicate that the second model (CFA2) was a better fit than the first (CFA1) and a chi-square difference test indicated that the second model did indeed fit the data significantly better than the first ($\Delta\chi^2 = 39.07$, $df = 4$).

We then tested two alternative measurement models. First, we wanted to see if the covariation among memory measures was captured better by deriving a latent variable composed of the main working memory measures and the two short-term memory tasks with articulatory suppression. Second, we wanted to see if the covariation among memory measures was captured better by deriving a latent variable composed of the main working memory measures and the two short-term memory tasks with a fixed pool of words. The fit indices for these two models (CFA3 and CFA4, respectively) are reported in Table 3. Neither of these models fit the data as well as CFA2. Indeed, chi-square difference tests indicated that CFA2 fit the data better than both CFA3 ($\Delta\chi^2 = 13.56$, $df = 1$) and CFA4 ($\Delta\chi^2 = 30.67$, $df = 1$). Based on these analyses, we used the CFA2 measurement model as a basis of subsequent structural equation models.[5]

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[5] As stated above, the purpose for including articulatory suppression and fixing the pool of words in the short-term memory tasks was to see whether we could make it impossible for participants to engage in domain-specific strategies such as rehearsal and chunking, which might have forced them to rely upon controlled attention to carry out the tasks. However, the above analyses suggest that our manipulations did not overcome the distinction between the working memory measures and short-term memory measures (see Discussion for further details).
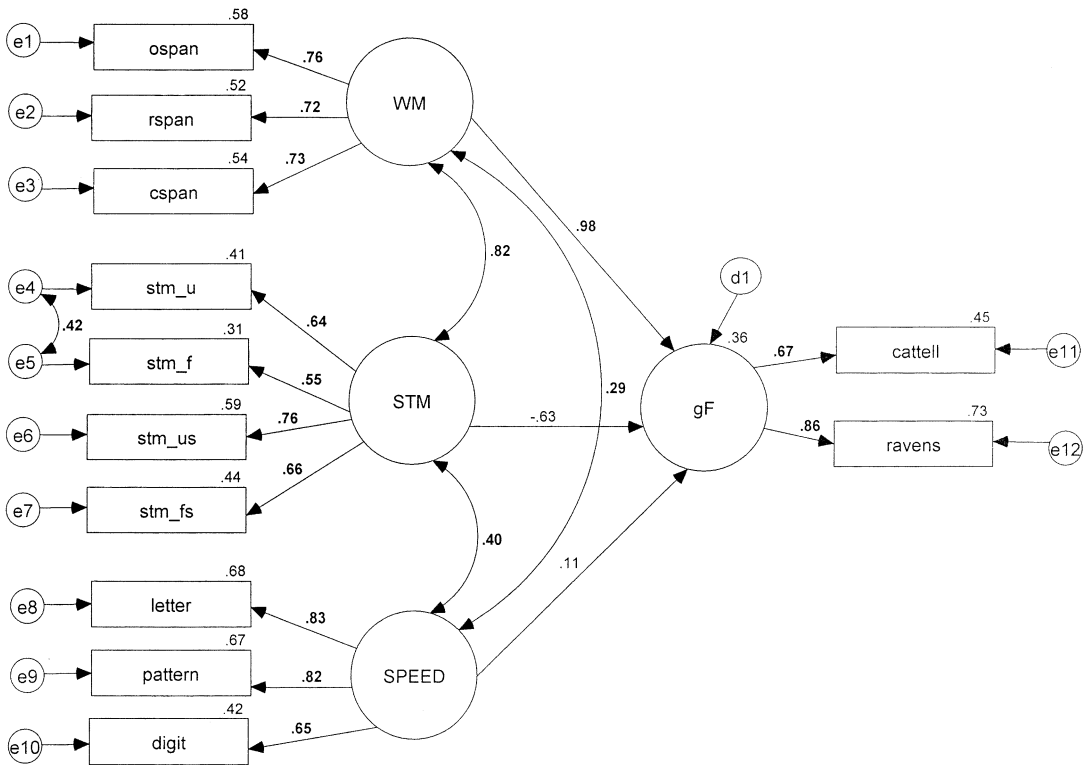
Fig. 1. SEM1. WM: working memory; STM: short-term memory; SPEED: processing speed; gF: general fluid intelligence. Significant path coefficients are in bold.

In the first structural equation model (SEM1), WMC, short-term memory capacity, and processing speed were all correlated exogenous latent variables. Furthermore, each was specified as a predictor of fluid intelligence, which was a latent endogenous variable. The fit indices for this model are presented in Table 3. The model itself is illustrated in Fig. 1.[6] The first thing to note is the strong relationship (path coefficient of .98) between working memory and fluid intelligence. Also surprising is the large negative path coefficient (− .63) between short-term memory and fluid intelligence. However, this negative path is not significant (due to an unusually large standard error) and therefore appears to be an unfortunate consequence of the high correlation between working memory and short-term memory (.82). Given this multicollinearity problem, the path coefficient between working memory and fluid intelligence may be inflated.[7]

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[6] Note that the error terms for STM_U and STM_F are correlated. This modification was added because it substantially improved the fit of the model. Given that STM_U and STM_F consist of the same procedure, with different stimuli, it is not surprising that their residuals are correlated.

[7] We would like to thank Chris Hertzog for alerting us to this problem.

In order to avoid this multicollinearity problem, yet still compare the relative contribution of short-term memory capacity, WMC, and processing speed to fluid intelligence, we took the following approach. As discussed in the introduction, we assume that no task is a pure measure of either WMC or short-term memory capacity. In particular, the tasks used here to measure WMC place great demands on short-term storage ability. Each OSPAN, RSPAN, and CSPAN requires the maintenance of verbal material, therefore tapping short-term memory capacity to some extent. At the same time, however, these tasks require the simultaneous processing and storage of information that is the signature of working memory (Baddeley & Hitch, 1974; Daneman & Carpenter, 1980). Therefore, in our next analysis, we specified all the memory tasks as indicators of short-term memory capacity but only OSPAN, RSPAN, and CSPAN as indicators of WMC.

This model (SEM2) is illustrated in Fig. 2 and the fit statistics are reported in Table 3. Again, the relationship between WMC and general fluid intelligence is strong and significant (path coefficient = .60) while neither short-term memory capacity nor processing speed significantly predicts gF. Also note that the chi-square for this model is non-significant ($P = .052$). This analysis suggests that complex span tasks such as OSPAN,
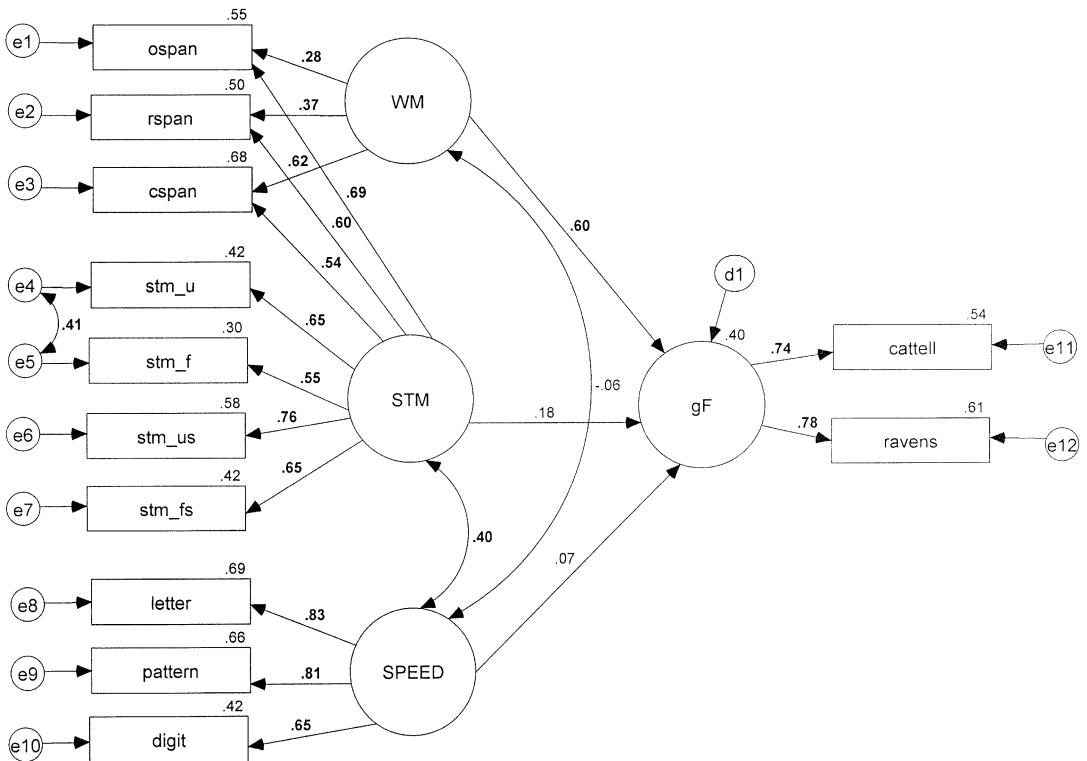

Fig. 2. SEM2. WM: working memory; STM: short-term memory; SPEED: processing speed; gF: general fluid intelligence. Significant path coefficients are in bold.

RSPAN, and CSPAN share common variance with measures of fluid intelligence such as RAVENS and CATELL while the short-term memory and speed measures do not. Finally, the factor loading for CSPAN (.62) is higher than for OSPAN (.28) or RSPAN (.37). This is most likely due to the fact that OSPAN and RSPAN, as well as all four short-term memory measures, involved remembering words while CSPAN required the maintenance of digits. Therefore, OSPAN and RSPAN have more in common with this sample of short-term memory measures than does CSPAN. This does not mean that OSPAN and RSPAN are not good measures of WMC. The factor loadings, although lower than expected, are significant. Furthermore, RSPAN and OSPAN are common measures of WMC (Daneman & Merikle, 1996; Engle, Tuholski, et al., 1999).

For comparison, we examined a model similar to SEM2, in which all memory measures loaded on the working memory factor while only the four short-term memory measures loaded on the short-term memory factor. Still, the path between working memory and gF was significant but the path between short-term memory and gF was not, suggesting again that the working memory measures are better predictors of gF than the short-term memory measures.

The other thing to note about these models is that processing speed was not a significant predictor of general fluid intelligence. Indeed, the path between processing speed and gF was not significant in either of the SEM models. Furthermore, it is not the case that the speed measures were unreliable or lacked variability. The reliabilities (Cronbach's alpha) for LET, PAT, and DIG were .80, .77, and .93, respectively, and in both SEM1 and SEM2 the latent variable "speed" correlated significantly with the latent variable short-term memory (.40). Thus, the speed measures were reliable and contributing covariation, but they were not covarying with RAVENS or CATTELL. Finally, restriction of range in gF does not seem to be a problem either because the distribution of RAVENS scores in this sample ($M = 48.8$, S.D. $= 5.3$) is consistent with the US norms for the 18–22 year age range ($M = 50$, S.D. $= 6$) (Raven, Raven, & Court, 1998). Also, although the mean RAVENS score is high (48.8 out of a possible 60), there were no perfect scores and only 5% of the subjects scored greater than 55. Finally, it should be noted that a sample size of 120 is smaller than ideal given the complex models tested here. However, the similarity between the findings reported here and by Engle, Tuholski, et al. (1999) suggests reliable, rather than spurious, effects.

4. Discussion

The results suggest a very strong link between WMC and general fluid intelligence. As such, these data provide support for previous claims that WMC is an essential aspect of fluid abilities (Carpenter et al., 1990; Engle, Tuholski, et al., 1999; Kyllonen, 1996; Kyllonen & Christal, 1990). Also important is that short-term memory capacity is not a significant predictor of fluid intelligence, at least when short-term memory capacity is clearly distinguished from WMC. This finding has implications for classic cognitive ability studies linking short-term memory capacity to general fluid intelligence (Bachelder and Denny, 1977a, 1997b; for reviews see Carroll, 1993; Jensen, 1998). The current results suggest that the tasks

used to measure short-term memory capacity in those classic studies may have tapped into WMC to some extent.[8] Finally, this study suggests that measures of processing speed that place minimal demands on memory and attention do not significantly predict gF. Again, this result stands in contrast to an abundant literature linking processing speed to gF (for reviews, see Jensen, 1998; Neisser et al., 1996; Vernon, 1987). As with the earlier work on short-term memory, it may be that those prior studies did not consider the working memory demands of the speed tasks employed.

The results reported here, as well as prior empirical reports by Kyllonen (1996), Kyllonen and Christal (1990), and Engle, Tuholski, et al. (1999) lead to the speculation that WMC may be the basis of Spearman's g. While this may sound like a bold statement, at least two leading researchers on the topic of information processing approaches to intelligence have made similar claims. For example, in a discussion of factor-analytic studies, Kyllonen stated "... the centrality of the working memory capacity factor leads to the conclusion that working memory capacity may indeed be essentially Spearman's g" (p. 73). Similarly, according to Jensen (1998), "So central is the role of WM capacity in individual differences in information processing that some cognitive theorists equate WM capacity with g itself" (p. 221).

While it is premature to provide an absolute judgment on this claim, we feel that the data merit the speculation. Therefore, in this discussion, we will address the following question: what do measures of WMC, such as RSPAN, OSPAN, and CSPAN, have in common with measures of fluid abilities such as RAVENS and CATTELL?

Before entering into such a discussion, it is imperative to note that Spearman's g may not be determined by one process, capacity, or ability but rather by a combination of factors. The intent of this discussion (and ultimately this project) is not to suggest that WMC is Spearman's g but rather to suggest that WMC might be a "primary determinant" of Spearman's g.

4.1. Working memory and g: the common link

Engle, Tuholski, et al. (1999) suggest that the link between measures of WMC and measures of fluid abilities is the demand for controlled attention. That is, the demand for the active maintenance of information in the face of concurrent processing and/or attention shifts. The demand for controlled attention is thought to be satisfied by the central executive, which they argue to be equivalent to what Norman and Shallice (1986) refer to as the supervisory attentional system and related to what Posner and Peterson (1990) refer to as the anterior attentional system. According to Engle, Tuholski, et al., the central executive component of working memory maintains activation to goal-relevant information and blocks activation to, or inhibits, goal-irrelevant information.

According to this perspective (also see Engle, Kane, et al., 1999), activation is supplied to goal-relevant information through the work of the central executive and through

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[8] It is also possible that statistical power was insufficient to detect a significant relationship between short-term memory and fluid intelligence. We thank Chris Hertzog for this suggestion.

automatized routines and strategies. If a task can be performed on the basis of auto-matized routines, such as rehearsal and chunking, then the central executive component of working memory will not be taxed, in which case individual differences in performance of that task will not be related to individual differences in fluid intelligence, but will re-flect domain-specific abilities. Thus, the reason complex span tasks such as RSPAN, OSPAN, and CSPAN are related to measures of fluid intelligence is that they do not al-low the participant to rely on automatized routines to perform the task. In contrast, short-term memory tasks can be performed using well-learned strategies such as rehearsal and chunking. As such, performance on those tasks will not be predictive of performance on measures of fluid intelligence.

Measures of fluid intelligence, such as RAVENS and CATTELL also rely on the ability to maintain activation to goal-relevant information in the face of concurrent processing and/or distraction. In a detailed task analysis of RAVENS, Carpenter et al. (1990) concluded that an important aspect of the task was the discovery and maintenance of rules that govern the variation among entries in a problem. More difficult matrix problems (as evidenced by more errors) typically involve more rules. Thus, in order to solve difficult matrix problems, one must discover a rule and then maintain that rule while searching to discover a second rule and so on. Therefore, the ability to maintain goal-relevant information (i.e., rules) in the face of concurrent processing (i.e., searching for new rules) and distraction (i.e., filtering of irrelevant features) is essential for successful performance on RAVENS.

Thus, one answer to the question of what working memory tasks and tests of fluid abilities have in common is the demand for controlled attention. Of course, more intensive task analyses are necessary to determine exactly what task features lead to the need for controlled attention. Such analyses will also lead to a better understanding of the central executive component of working memory.

Another possible explanation for the strong link between measures of WMC and measures of general fluid intelligence is that all the tasks may be tremendously influenced by strategy deployment. According to this perspective, individual differences in strategy-use contribute to outcome variance in measures of WMC as well as tests of general fluid intelligence (Rogers, Hertzog, & Fisk, 2000; Schunn & Reder, 1998; also see MacLeod, Hunt, & Mathews, 1978; Mathews, Hunt, & MacLeod, 1980). For example, strategies more sophisticated than simple maintenance rehearsal may be particularly important for complex span tasks where rehearsal is prevented. If so, more sophisticated strategy deployment may be the essence of above-average performance (but see Engle, Cantor, & Carullo, 1992). Similarly, successful performance of tasks designed to test fluid abilities, such as RAVENS, may involve the recognition and successful execution of particular strategies. This theoretical approach is consistent with the notion of long-term working memory (Ericsson & Kintsch, 1995). According to this framework, greater WMC is simply the result of greater domain-specific experience. Greater experience in a domain would be associated with a more sophisticated repertoire of strategies, resulting in more efficient knowledge represen-tations, which results in greater capacity and flexibility (Ericsson & Delaney, 1999). Again, more intensive task analyses are necessary to test this hypothesis, as well as the controlled attention hypothesis.

Another aspect of the current results worthy of discussion is the lack of the relationship between processing speed and fluid intelligence. This result stands in stark contrast to a large literature on the relationship between speed and *g* (for reviews, see Jensen, 1998; Neisser et al., 1996; Vernon, 1987). However, one finding that clearly emerges from that literature is that the more "complex" the speed task, the stronger the relationship between speed and intelligence (Jensen, 1998). We interpret this finding to mean that the more the speed task places demands on memory and attention, the stronger the correlation between speed and *g*. Thus, it is not speed per se that predicts fluid abilities, it is the attention component of the speed tasks that predicts fluid abilities (cf. Conway, Kane, & Engle, 1999; Cowan, 1998). Again, more systematic research is needed to test this hypothesis. Furthermore, although speed does not appear to predict fluid abilities, it does appear to predict the remaining, specific STM abilities, as evidenced by the significant correlation between the speed and STM latent variables (also see Baddeley, 1986; Cowan et al., 1998, Experiment 2).

Yet another aspect of the data that is somewhat surprising is the effect of articulatory suppression on performance of the STM tasks. Specifically, subjects scored lower on the STM span tasks when required to engage in articulatory suppression, suggesting that suppression did make the task more difficult, but the STM tasks with suppression were not more predictive of fluid intelligence than the standard STM task. According to the controlled attention view of WMC, engaging in articulatory suppression should have made the STM task more difficult *and* should have made the measure more predictive of fluid intelligence because more controlled attention would be recruited to perform the task. However, this was not the case. For some reason, the dual-task nature of the working memory tasks serves to predict fluid intelligence better than a secondary load manipulation such as articulatory suppression.

Finally, we would like to address the distinction between individual differences in cognitive ability and developmental differences in cognitive ability. There is evidence to suggest that processing speed may be an important factor underlying developmental differences in cognitive ability in childhood (Fry & Hale, 1996) and in aging (Salthouse, 1996). We offer two possible explanations of these findings. First, it is possible that the factors that account for developmental differences in cognitive ability do not match the factors that account for individual differences in cognitive ability in young adults. If so, perhaps processing speed is important for developmental differences in childhood and/or aging but not for individual differences in young adults. Second, it is possible that the speed tasks used in developmental studies tax the working memory system (cf. Fry & Hale, 1996), and therefore, WMC is the underlying factor rather than speed. This second possibility is less likely to be true for developmental differences associated with aging given that Salthouse (1996) has been careful to use relatively "simple" speed tasks such as the ones used in this study.

In conclusion, the current project clearly suggests a strong link between measures of WMC and measures of fluid abilities. The fact that the tasks used to measure WMC were primarily verbal and the tests used to measure fluid intelligence were nonverbal suggests that WMC is domain-free. Furthermore, "simple" speed tasks such as PAT, LET, and digit copying, which place minimal demands on working memory, do not predict fluid

intelligence in young adults. More research is needed to address the notion that controlled attention and/or strategic processes underlie performance on working memory span tasks as well as tests of fluid intelligence.

Acknowledgments

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