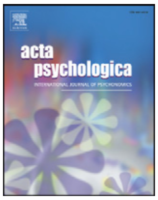
Acta Psychologica 139 (2012) 425–433

Contents lists available at SciVerse ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/ locate/actpsy



The unique contributions of the facilitation of procedural memory and working memory to individual differences in intelligence

C.A. Was [a,*], J. Dunlosky [a], H. Bailey [b], K.A. Rawson [a]

[a] Kent State University, Kent, OH 44242,United States
[b] Washington University, One Bookings Drive, St. Louis, MO 3130, United States

A R T I C L E   I N F O

Article history:
Received 21 July 2011
Received in revised form 21 December 2011
Accepted 31 December 2011
Available online 8 February 2012

PsychINFO classification:
2340

Keywords:
Working memory
Procedural memory
Intelligence
Fluid intelligence
Comprehension
Individual differences

A B S T R A C T

Individual differences in working memory account for a substantial portion of individual differences in complex cognitive processes (e.g., comprehension) and fluid intelligence. However, a large portion of the variance in fluid intelligence and comprehension is unexplained. The current investigation was conducted to evaluate whether individual differences in the facilitation of procedural memory accounts for unique variance in intelligence not accounted for by working memory. To measure variability in the facilitation of procedural memory, we used a task that required participants to first classify exemplars of two categories; facilitation was then operationalized by subsequent improvements in the speed of classifying new exemplars from those categories (i.e., an operation-specific memory procedure). Three measures of each focal construct (facilitation in procedural memory, working memory, comprehension and fluid intelligence) were administered to 256 participants. We used structural equation modeling to examine the relationships among these latent variables. Working memory did account for variance in fluid intelligence and comprehension, but most important, individual differences in facilitation of procedural memory accounted for unique variance in fluid intelligence and comprehension.

1. Introduction

Working memory (WM) has been touted as a major source of individual differences in learning and problem solving since Baddeley and Hitch (1974) proposed the multiple components model of WM. Measures of WM are related to comprehension, reasoning ability, crystallized intelligence (*gC*) and fluid intelligence (*gF*). Nevertheless, as we discuss below, WM is not identical to higher-order cognition, and in particular, *gF*. That is, WM accounts for only a portion of *gF*, with a large portion of variance left unexplained. Accounting for this unexplained variance is the focus of our investigation, so we will briefly discuss previous research on the relations between WM and *gF* that motivate it.

A great deal of the research on intelligence and reasoning ability has focused on the relationship between WM and *gF* (e.g., Kyllonen & Christal, 1990), which continues to demonstrate that these two constructs are highly related. Based on these consistent results, several researchers have argued that WM and *gF* (or perhaps general intelligence) are unitary concepts (for reviews, see Ackerman, Beier, & Boyle, 2005; Kane, Hambrick, & Conway, 2005; Oberauer, Schulze, Wilhelm, & Süß, 2005), but this view is no longer well received. For instance, Heitz et al. (2006) explained that although WM and *gF* are indisputably related ($r = .70$), approximately 50% of the variance between the two constructs is not shared. Ackerman et al. (2005) completed a meta-analysis and found the average correlation (r) between WM and *g* to be .48. Given that the majority of variance between the two constructs is unexplained, the question remains: If WM and *gF* are not unitary concepts, what other cognitive processes contribute to *gF*?

Another potential contributor to variance in gF was described by Was and Woltz (2007), who investigated the relationship between WM, discourse comprehension, and a new task referred to as *the availability of long-term memory* (ALTM) task (see also Woltz & Was, 2006). This task in part measures the facilitation of procedural memory, and in particular the facilitation of the procedures involved in classifying exemplars from a specific category. They proposed that individual differences in this facilitation accounted for unique variance in discourse comprehension. To better understand their rationale, we describe the ALTM task in detail next, and then we more fully explore how the construct that it taps (i.e., facilitation of procedural memory) differs functionally from WM. The procedure for measuring the facilitation of procedural memory (Woltz & Was, 2006, 2007) is illustrated in Fig. 1, which presents an example trial of the original ALTM task (Woltz & Was, 2006). Each trial in the task includes four components. All four trial components were completed before moving on to the next trial.

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[*] Corresponding author at: Kent State University, Educational Foundations and Special Services, 405 White Hall, Kent, OH 44242, United States. Tel.: +1 330 672 2929; fax: +1 330 672 3407.

E-mail addresses: cwas@kent.edu (C.A. Was), jdunlosk@kent.edu (J. Dunlosky), hroth@artsci.wustl.edu (H. Bailey), krawson1@kent.edu (K.A. Rawson).

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doi:10.1016/j.actpsy.2011.12.016

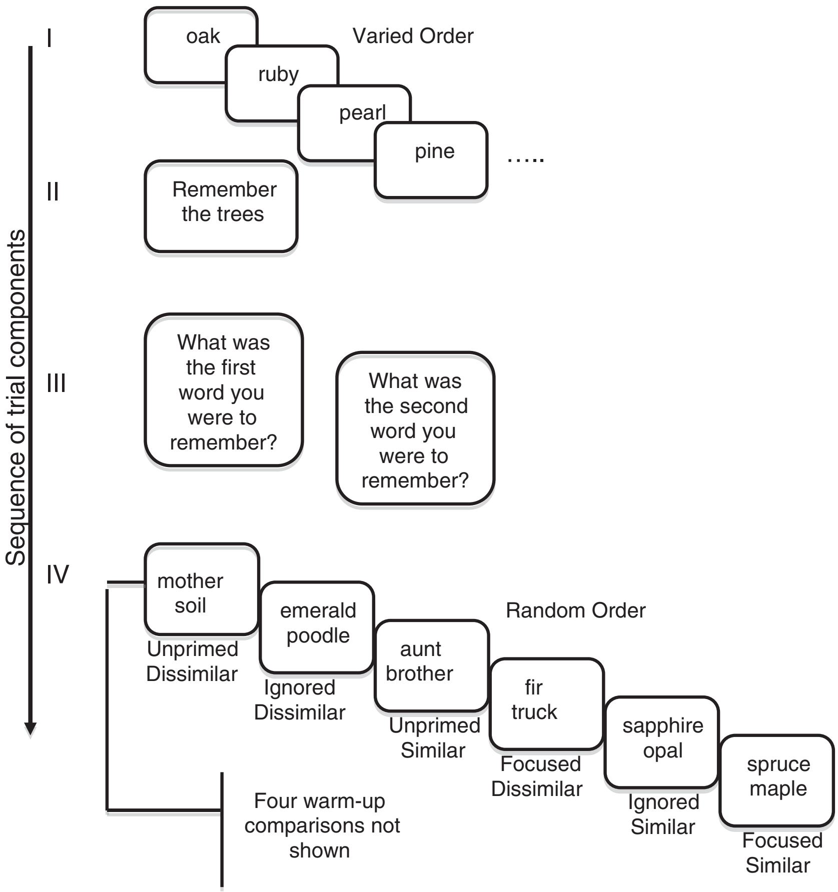

Fig. 1. Example trial from Woltz and Was (2006).

The first component was a memory load of four words (typically 2 syllables each) that were presented one at a time for later recall. The words came from two semantic categories; in Fig. 1, the categories are *trees* and *precious stones*. The second component was a concurrent demand that increased the amount of processing allocated to one of the semantic categories. This focused allocation was accomplished by instructing the participant to identify and remember the words from one of the two presented categories (e.g., *trees*). This *selection instruction* could take one of several forms, such as "remember the trees." This component was designed to engage procedures involved in identifying exemplars from one category, while concurrently requiring participants to maintain the memory load. The third component was recall of the words that participants were instructed to remember (e.g., *oak*, *elm*). The fourth component consisted of a series of *same-different* category verification frames in which two exemplars were presented and the participant determined whether the stimuli were exemplars of the same category (e.g., *oak elm*) or different categories (e.g., *diamond uncle*). Importantly, stimuli presented in the memory load (component 1) were not later presented in the category verification frames; instead, stimuli presented in the verification frames were exemplars from the memory load categories that were not previously presented (e.g., *maple*). Therefore, each new category verification frame contained exemplars from one of three categories: the *focused* category from the memory load (i.e., the category that participants had been instructed to remember — *trees*), the *ignored* category from the memory load (e.g., *precious stones*), and an *unprimed* category that was not presented in the memory load (e.g., *family members*). Increased facilitation of procedural memory was measured by the difference in response speed to previously processed categories as compared to the unprimed category that was not previously processed. Most important, on average, response times for the category verification were faster for focused than unprimed categories, and substantial individual differences arose in the amount of this facilitation. This facilitation is not due to repetition priming, because exemplars in the memory-load component did not appear in the category verification frames.

Originally, Woltz and Was (2006) were attempting to evaluate models of WM that propose cognitive processing requires efficient access to elements in long-term memory elements (e.g., Anderson, Reder, & Lebiere, 1996; Cowan, 1995; Oberauer, 2002) and hence the task was referred to as the availability long-term memory task. For example, Cowan's embedded processes model of WM assumes that WM consists of a hierarchical structure of long-term memory, a subset of activated long-term memory elements, and a subset of activated long-term memory elements currently in the focus of attention. Woltz and Was attempted to demonstrate that simple processing in the focus of attention would lead to temporally limited residual activation of related but unattended memory elements as described by Cowan. However, across multiple experiments, Woltz and Was (2006, 2007; Was, 2010) ruled out several alternative explanations for individual differences on the ALTM task that relate to the construct of activated long-term memory, such as explanations based on spreading activation, episodic priming, and perceptual priming. Put differently, the ALTM (despite its name) does not appear to measure long-term memory retrieval.

Based on this and other evidence, Woltz and Was (2006, 2007; see also Was, 2010) have proposed this enhanced response speed was in part due to the facilitation of a specific memory procedure (called *procedural memory*). Procedural memory here is akin to a condition-action rule or production as conceptualized in ACT-R (Anderson, 1995). Anderson's (1993) model of memory differentiates between the semantic components of declarative memory and procedural memory and describes the spread of activation as short-lived compared to the more persistent memory for cognitive operations. Was (2010) interpreted long-lasting facilitation demonstrated in the ALTM tasks as the "strengthening of an operation-specific but item-general memory operation" (p. 367), or in the present terms, it represented facilitation of procedural memory. Thus, although we retain the name "Activation of Long-Term Memory" (ALTM) for consistency with prior papers, the name does not reflect individual difference in the component process that it taps (i.e., facilitation of procedural memory).

More specifically, the ALTM task measures the facilitation of the use of a production for classifying a given category of items, such as facilitation in a production for classifying given exemplars (maple, fir, elm) as "trees." Note that facilitation of procedural memory refers to strengthening a procedure for classifying items and hence is functionally distinct from WM tasks, which largely tap people's attentional control. It is also distinct from retrieving a specific item from secondary memory — a point we return to in detail in the Discussion section. Most relevant for the present purposes, although the tasks used to measure WMC (e.g., span tasks) and facilitation of procedural memory (i.e., ALTM tasks) do share variance and hence tap some of the same processes (Was & Woltz, 2007), the facilitation of basic procedures used to analyze stimuli (e.g., by classifying) could explain unique variance in *gF*.

This possibility finds preliminary support from research reported by Was and Woltz (2007), who conducted two individual differences studies that included measures of the facilitation of procedural memory, WM, and comprehension. Structural equation modeling (SEM) demonstrated significant relationships between these constructs. Most important, performance on the ALTM tasks accounted for unique variance in comprehension that was not accounted for by WM. Although Was and Woltz (2007) did not examine *gF*, this evidence suggests that the facilitation of procedural memory may account for unique variance in *gF*, because *gF* and *gC* are partially related constructs (Bickley, Keith & Wolfe, 1995; Carrol, 1993; Cattell, 1971; Undheim & Gustafsson, 1987). A tenable explanation of the predicted relationship between facilitation of procedural memory and *gF* is that facile use of cognitive procedures for evaluating stimuli is critical for successfully completing tasks that measure *gF* (cf. Cowan, 1999; Ericsson & Kintsch, 1995). Our proposal is that although WM is related to *gF*, facilitation of procedural memory will account for unique variance in *gF* not accounted for by working memory, because the WM tasks tap the ability to maintain goal-relevant information in the face of interfering materials (i.e., attentional control), whereas the ALTM tasks tap one's ability to efficiently use procedures that access goal-relevant information.

To evaluate these possibilities in the present research, individual differences in the constructs of the facilitation of procedural memory, WM, *gF*, and comprehension were measured. The facilitation of procedural memory was measured using ALTM tasks similar to those used in the previous study conducted by Was and Woltz (2007), which included a category exemplars task (described above), a synonyms task, and a category attributes task. Working memory measures included three complex span tasks. Measures of *gF* included the Advanced Ravens progressive matrices and two tasks from the Kit of Reference Tests for Cognitive Factors (Ekstrom, French, Harman, & Dermen, 1976). Comprehension was assessed using the comprehension materials from the Air Force Officer Qualifying Test (AFOQT) used by Kane et al. (2004), the Shipley Vocabulary Test (Zachary, 1986), and ACT scores. With more than 250 participants, we used structural equation modeling to estimate latent factors for each of the above constructs. We then tested models of the interdependent and independent influence of WM and facilitation of procedural memory on *gF* and comprehension.

Besides estimating the relations among facilitation of procedural memory, WM, and *gF*, the current investigation also provides an extension of Was and Woltz (2007), who concluded that facilitation of procedural memory accounted for unique variance in comprehension. In particular, the inclusion of *gF* in the current investigation may attenuate – and potentially eliminate – the relationship between facilitation of procedural memory and comprehension.

2. Method

2.1. Participants

Two hundred sixty-one undergraduates at a large Midwestern state university participated for partial course credit and monetary compensation. Five participants were dropped from the final analysis due to missing data.

2.2. Materials and procedure

2.2.1. Complex span tasks

All three span tasks were versions of those described in Kane et al. (2004): operation span (*OSPAN*), reading span (*RSPAN*), and counting span (*CSPAN*). Performance on all span tasks was computed using partial-credit unit scoring (for details, see Conway et al., 2005).

2.2.2. OSPAN task

We used the OSPAN task variation described in Kane et al. (2004). In this version, participants were presented with mathematical operation-word pairs via computer screen. Participants read each mathematical operation aloud (e.g., "Is $(4\times2)+5=10$?"), reported whether it was correct, and then read a target word aloud (e.g., "phone"). Immediately thereafter, the experimenter pressed a key to present the next operation-word pair on-screen. Following the final pair of the trial, subjects recalled the target words in serial order. The OSPAN task consisted of 15 experimenter-paced trials that ranged from three to seven operation-word pairs. The words and the order of set sizes were initially randomized and that order was used for all subjects.

2.2.3. RSPAN task

We used a modified version of the RSPAN task from Kane et al. (2004). Sentence–word pairs were presented via computer screen. Participants read a sentence aloud (e.g., "Mr. Owens left the lawnmower in the lemon."), indicated whether it made sense, and then read an unrelated word aloud (e.g., "eagle"). After the word was read aloud, the experimenter triggered the computer to display the next sentence-word pair appeared on-screen. After the final pair of each trial, participants wrote the target words in serial order. The RSPAN task consisted of 15 experimenter-paced trials that ranged from three to seven sentence-word pairs presented in random order.

2.2.4. CSPAN task

In the CSPAN, participants were presented with a random array of shapes, each of which contained between 3 and 9 dark blue circles as well as a varying number of light blue circles and dark blue squares. Participants were asked to count the number of dark blue circles, to click on each one using the mouse (a checkmark appeared on the dark blue circle once they clicked on it), and to memorize the total number for a later recall test. After clicking on the last dark blue circle within an array, a new array appeared onscreen. Following the completion of the final array, a recall cue appeared and participants recalled the total number of dark blue circles from each array in that trial in serial order. For instance, if the first array had 4 dark blue circles, the second had 7, and the third had 3, then the participant would type "4, 7, 3". As in the other complex span tasks, the task consisted of 15 trials that ranged from two to six arrays (i.e., 2–6 to-be-remembered numbers) presented in a fixed random order.

2.2.5. ALTM tasks

To assess facilitation of procedural memory, we modified the task used by Woltz and Was (2006) that was illustrated in Fig. 1. The purpose of the modifications was to enhance the sensitivity of the task to capture individual differences in the facilitation of procedural memory. Three measures of facilitation were used: *Category Task*, *Synonym task*, and *Attribute Task*, with each task having the same structure (see Fig. 2). In each of the three tasks, each of nine trials began with a memory load of five words presented visually at a rate of 2.25 s per word. The five words always represented two semantically related groups. In the Category Task, the words were category exemplars (e.g., *robin oak hawk sparrow pine*). In the Synonym Task, the words were synonyms (e.g., *moist smart damp brilliant soggy*). In the Attribute Task, the words were category attributes (e.g., *chalkboard diagnosis desks surgery prescription*). In lieu of the focus instruction and recall described previously, a question appeared onscreen that asked which concept in the memory load had the most instances (e.g., *More examples of birds or trees?*; *More words meaning wet or intelligent?*; *More attributes of classroom or health care?*). This task demand presumably drew attention to both semantic concepts in each list during maintenance of the memory load. Next, participants responded to a set of visually presented semantic verification items. In the Category Task, the verifications were comparisons of whether two exemplars came from the same category (e.g., *eagle elm*). In the Synonym Task, they were comparisons of whether two words had similar or different meanings (e.g., *clever bright*). In the Attribute Task, they were sentence verifications (e.g., *Nurses are in hospitals*). In each case, an equal number of positive and negative match verifications were used. In all ALTM tasks, half of the items (*facilitated* items) had content related to the two semantic concepts in the previous memory load. In the other half (*non-facilitated* items), the verifications were related to two concepts not in the memory load. Nine facilitated and nine non-facilitated items were presented intermixed in a randomized order in each trial. Feedback was presented after each trial regarding recall accuracy and verification latency and accuracy. The content of the facilitated and non-facilitated items was fixed for all participants rather than counterbalanced. E-prime programs that run versions of each of these ALTM tasks (and conduct the analysis of the corresponding data) are available from the first author.

2.2.6. Fluid intelligence tasks

Two tasks from the Kit of Reference Tests for Cognitive Factors (Ekstrom et al., 1976) were used to assess *gF*: the letter sets task and the locations test. The third measure of *gF* was the RAVENS task (Raven, Raven, & Court, 1998).

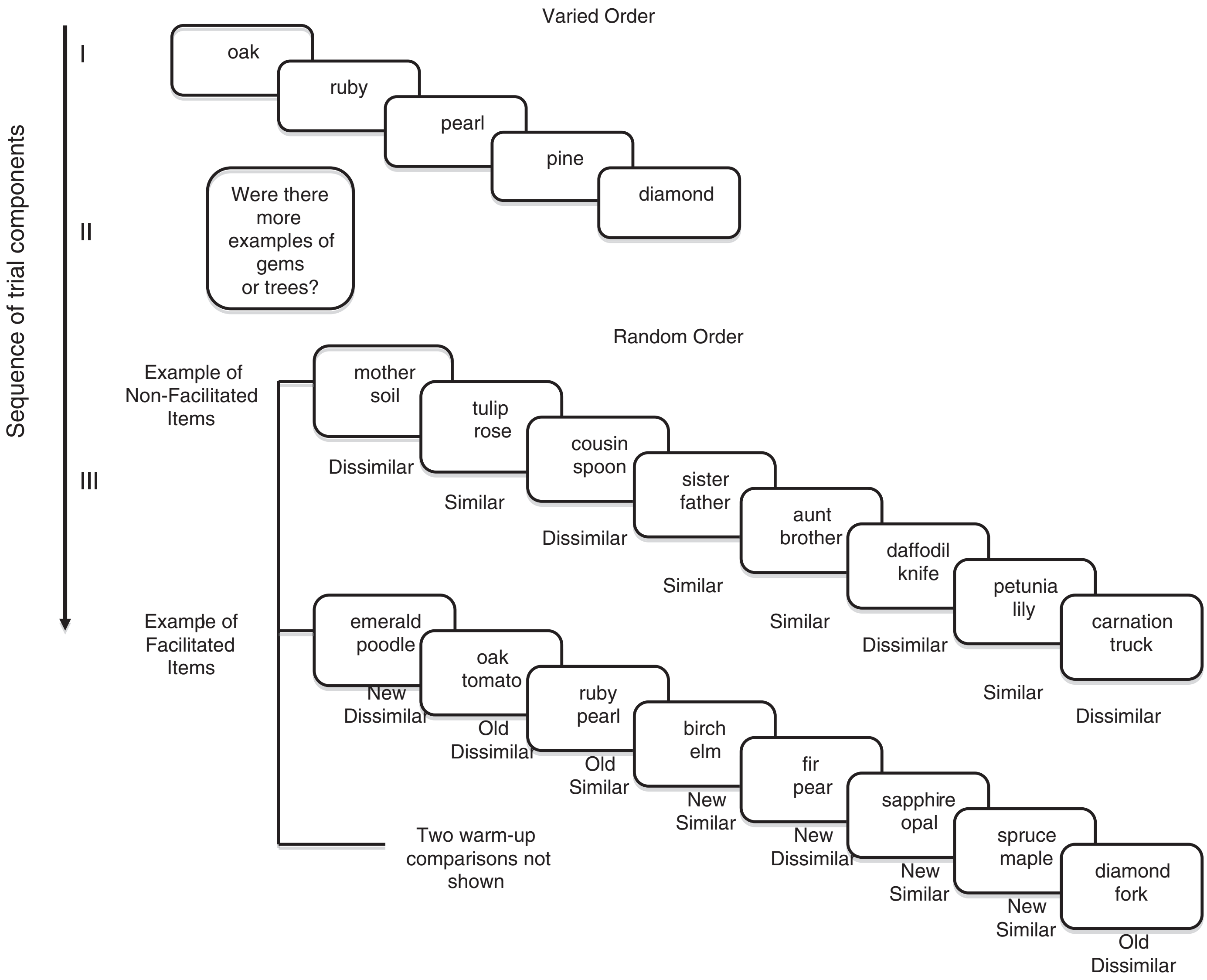

Fig. 2. Example of ALTM task trial.

2.2.7. Measures of comprehension

The three standard tests of comprehension were as follows: (a) the reading comprehension task from the Air Force Officer Qualifying Test (AFOQT; see Kane et al., 2004), (b) the Shipley Vocabulary Test (Zachary, 1986), and (c) *ACT scores* (participants granted consent for their ACT scores to be accessed from the registrar).

2.3. Procedure

Data collection for this experiment took place as a part of a larger study consisting of 8 one-hour sessions with one to two week delays between each session. The order in which tasks were completed was the same across participants: demographics questionnaire (session 1), locations test (session 1), OSPAN (session 1), RSPAN (session 2), ALTM attributes (session 2), AFOQT (session 3), letter sets test (session 5), ALTM categories (session 6), ALTM synonyms (session 7), RAPM (session 7), Shipley vocabulary (session 7) and CSPAN (session 8).

3. Results

Due mostly to scheduling issues, some participants had missing data. However, none of the retained participants ($N=256$) had missing data for more than one observed variable from a single latent factor. For example, no retained participants failed to complete the OSPAN task and either the RSPAN or CSPAN task. The proportion of missing data for each of the latent factors was as follows: WM = 0.08, FPM = 0.12, *gF* = 0.10, and comprehension = 0.14. The total proportion of missing data was 0.11. Missing values were estimated using maximum likelihood estimated means and intercepts in AMOS 5.0 (Arbuckle, 2003).

Prior research with the ALTM tasks indicates that individual differences in these tasks are contained in both response time and accuracy (e.g., Was, 2010; Was & Woltz, 2007; Woltz & Was, 2007). Woltz and Was (2007; Was & Woltz, 2007) found no speed–accuracy trade-off for these tasks. The Pearson coefficient between accuracy and latency was $r=-.33$, indicating that participants that responded quickly had a tendency to respond accurately. Facilitation effects were present in both latency and accuracy. Thus, in the current study, we combined latency and accuracy of responses in the verification trials to create an adjusted response speed composite, which was calculated as the proportion of correct answers divided by the average response speed for all responses (cf. Was, 2010; Woltz & Was, 2006). The time scale of minutes was used; therefore, the resulting speed scores are interpreted as the number of correct responses per minute.[1] It was necessary to evaluate whether the transformation led to an unexpected increase in variance and hence overestimated the magnitude of individual differences in task performance (which may inflate the correlations with the other measures). We calculated the standard deviations of residual scores for accuracy, latency, and speed (see Table A1, Appendix) and completed a series of *t*-test comparing residuals of accuracy and latency to speed residuals (see Table A2, Appendix). No differences arose between standard deviations among the different measures, indicating there was no inflation of variance when accuracy and latency were transformed into the speed metric.

Facilitation of procedural memory in the ALTM tasks was operationalized as an increase in response speed for verification trials related to content in the memory load (see component 3, Fig. 2, labeled “Facilitated Items”) versus verification trials related to categories *not* in the memory load (component 3, Fig. 2, labeled “Non-Facilitated Items”). This difference was calculated by regressing the facilitated verification response speed of a trial onto non-facilitated verification response speed of an adjacent trial.[2] As explained in the Introduction, only verifications involving stimuli that were not presented in the memory load (component 1, Fig. 2) were included, so facilitation cannot be attributed to repetition priming and instead is closely linked to speed ups in the use of procedure memory to classify stimuli.

Table 1 displays the means, standard deviations, skewness and kurtosis for the outcome measures of each of the 12 observed variables. Although skewness and kurtosis may be a concern for the raw ALTM scores, remember that the measure of facilitation is the residual created by regressing facilitated verification response speed onto non-facilitated verification response speed. Skewness and kurtosis of each of these residual scores are within acceptable limits (see Table 1).

In Table 1, outcomes of the complex span, *gF* and comprehension tasks are reported as the proportion of correct responses, with the exception of ACT Reading. The ACT Reading score is based on a national percentile rank. The mean score of our study ($M=22.55$) indicated that the average percentile rank of participants in our study is 60. Although the mean value for the advanced Ravens task ($M=.34$) is relatively low, its substantial reliability and variance are similar to the values for the other *gF* tasks and hence is suitable for inclusion in the models.

The three ATLM task outcomes are reported as the number of correct responses per minute. For all three ALTM tasks, participants were faster and more accurate on facilitated than on non-facilitated trials, Category ALTM, $t(216)=9.07$, $p<.001$; Synonym ALTM, $t(216)=40.22$, $p<.001$; Attribute ALTM, $t(239)=29.39$, $p<.001$. Table 2 presents the internal consistency estimates and the correlations among the 12 observed variables.

3.1. Structural equation modeling

Facilitation of procedural memory (as measured by the three ALTM tasks) and WM was expected to correlate with each other and with comprehension (Was & Woltz, 2007), and WM was expected to account for individual differences in *gF* and comprehension. These paths were included in our model (Fig. 3), along with expectations based on the prediction that facilitation of procedural memory would account for unique variance in *gF*. This hypothesized model provided a good fit to the empirical data as supported by goodness-of-fit indexes. The chi square statistic was not significant, X^2 (48, $N=256$) = 53.35, $p=.276$, indicating the data do not differ from the hypothesized model. Other fit indexes also indicated the model was appropriate to describe the data ($CFI=.992$ and $RMSEA=.021$). As shown in Fig. 3, all variables loaded significantly on their construct of interest and the latent variables were moderately correlated to one another.

The estimated path coefficients in the hypothesized structural equation model are displayed in Fig. 3. The standardized path coefficients are shown in bold face and estimated factor correlations are in parentheses (error variances are not included). All parameters in the model met the criteria for significance at an alpha of .05, including

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[1] Although confounded by the fixed stimuli order, it was important to test for significant priming effects in the ALTM tasks as measured by accuracy and latency as separate measures for all three tasks. The rationale behind these tests is to ensure that the speed measure was not due to a speed–accuracy trade-off. If one measure or the other was non-significant it might indicate a bias based on one measure of priming. Accuracy for facilitated trials was significantly greater than for non-facilitated trials in all 3 measures, Attribute ALTM, $t(241)=13.09$, $p<.001$, $Md=.03$, CI [.02; .04]; Category ALTM, $t(216)=5.80$, $p<.001$, $Md=.24$, CI [.16; .32]; Synonym ALTM, $t(216)=16.13$, $p<.001$, $Md=.05$, CI [04; .06]. Response time (in milliseconds) for facilitated trials was significantly less than response time for non-facilitated trials, Attribute ALTM, $t(241)=15.56$, $p<.001$, $Md=147$, CI [129; .166]; Category ALTM, $t(216)=5.04$, $p<.001$, $Md=57$, CI [34; .79]; Synonym ALTM, $t(216)=13.67$, $p<.001$, $Md=166$, CI [143; 190].

[2] Although difference scores are a common index of change, residual scores have been used by many researchers due to particular advantages (Donaldson, 1983; Kyllonen, Tirre, & Christal, 1991; Was & Woltz, 2007; Woltz, 1990). Reliability for residuals is greater under many circumstances (Linn & Slinde, 1977) and difference scores are problematic when attempting to capture individual differences in measures with varying baselines. For example, those who respond quickly and accurately on unprimed trials have little room for improved performance as compared to those who are initially more inaccurate and slow to respond.

Table 1
Descriptive statistics for twelve observed variables.

Variable	M	SD	Skewness	Kurtosis
Category ALTM[a]-facilitated	50.39	16.14	2.96	26.44
Category ALTM-non-facilitated	47.19	13.71	1.56	12.05
Category ALTM-residual	.00	.43	.94	4.59
Attribute ALTM-facilitated	47.33	12.14	−.13	−.36
Attribute ALTM-non-facilitated	41.18	11.15	−.08	−.25
Attribute ALTM-residual	.00	.48	−.08	−.09
Synonym ALTM-facilitated	44.79	15.32	1.40	4.33
Synonym ALTM-non-facilitated	38.47	13.33	3.07	19.70
Synonym ALTM-residual	.00	.46	−.17	4.99
C-span	.88	.13	−1.95	4.95
R-span	.63	.13	−.31	1.10
O-span	.65	.12	−.18	.36
Ravens	.34	.20	.54	−.41
Letters	.80	.22	−1.33	.98
Locations	.63	.22	−.23	−.79
ACT-READ	22.55	5.35	.21	−.42
AFOQT	.49	.24	.18	−.87
Vocabulary	.69	.11	.34	.50

[a] ALTM tasks are presented in the metric of number of correct responses per minute, Span, *gF*, and comprehension tasks are presented as proportion of correct responses, with the exception of ACT-READ which is based on a scale of 1–36.

the direct effects of the latent factors facilitation of procedural memory and WM on *gF* and comprehension. The estimated standardized total effects of facilitation of procedural memory on *gF* were $\beta = .23$ and of facilitation of procedural memory on comprehension were $\beta = .21$, whereas the estimated standardized total effects of WM on *gF* were $\beta = .53$ and of WM on comprehension were $\beta = .45$. WM and facilitation of procedural memory together accounted for 43.2% of the variance in *gF* and 32.2% of the variance in comprehension.

Of particular interest is the reduction in magnitude of the relationships between the two exogenous factors (WM and the facilitation of procedural memory) and the two endogenous variables (*gF* and comprehension). The correlations between all latent factors are presented in parentheses in Fig. 3 and displayed in Table 3. In Fig. 3, the zero-order correlations between all latent factors are attenuated when all factors are included in the model. The decrease in the magnitude of these relationships indicates that a portion of the variance in *gF* and comprehension is shared between WM and the facilitation of procedural memory.

Most important, although a large portion of the individual differences in *gF* are accounted for by variance shared between the facilitation of procedural memory and WM, both factors also account for unique variance in *gF* (as well as comprehension). That is, facilitation of procedural memory accounts for variance in *gF* that is not accounted for by WM.

Three alternative models were also estimated. To verify that facilitation of procedural memory accounted for unique variance in *gF* and comprehension, we tested one alternative model in which the paths to *gF* and comprehension from the facilitation of procedural memory were constrained to be zero. If such a constrained model provided a better fit to the data than the hypothesized model the assumption that facilitation of procedural memory contributes to *gF* and comprehension would not be tenable. To verify that WM accounted for unique variance in *gF* and comprehension, we tested a second alternative model in which the paths to *gF* and comprehension from WM were constrained to be zero. This model assumes that WM does not make a significant contribution to *gF* and comprehension. Finally, the third alternative was tested to ensure that WM and facilitation of procedural memory did not constitute a single latent variable. The model consisted of a single latent variable constructed of the observed WM tasks and ALTM tasks. This variable acted as an exogenous variable with predictive paths to both *gF* and *comprehension*. Table 4 displays the fit indices for the hypothesized and alternative models, which confirms that the hypothesized model provides the best fit to the data.

4. Discussion

In the current data, a strong correlation exists between *gF* and comprehension, and not surprisingly, WM was correlated with both *gF* and comprehension and accounted for a significant amount of variance in both constructs. Nevertheless, WM did not account for all of the variance in *gF* and comprehension. Because some variance was left unexplained, we considered the role of facilitation of procedural memory in the model.

Regarding our primary goal, the current results indicated that performance on the ALTM tasks accounts for a unique proportion of variance in *gF*. Fluid intelligence is defined as the cognitive ability to solve problems, reason, and manipulate symbols independent of acquired declarative knowledge. It is reasonable to assume that *gF* is reliant upon specific cognitive procedures that allow for efficient use of long-term memory elements to support higher-order cognitive processes. We contend that the ALTM tasks used in the current study measure the strengthening of memory for previously performed cognitive operations. Put differently, individual differences in facilitation of item-general but operation-specific processes are apparently a tenable explanation for a portion of the individual differences in *gF* as defined above.

Nevertheless, despite the unique contribution of both WM and facilitation of procedural memory to *gF*, variance in *gF* was still unexplained. Another candidate that may also contribute that has recently received attention is secondary memory. In particular, Unsworth and Engle (2007) proposed a model of memory that consists of a limited capacity component that actively maintains a small number of memory elements for a short duration and a component described as a more durable store that maintains memory elements for long durations. They refer to these components as primary memory and

Table 2
Correlations among twelve observed variables.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
1. Category ALTM	(.96)*											
2. Attribute ALTM	.53	(.86)**										
3. Synonym ALTM	.39	.38	(.73)									
4. C-span	.18	.28	.12	(.82)								
5. R-span	.19	.24	.19	.38	(.93)							
6. O-span	.10	.11	.18	.34	.39	(.89)						
7. Ravens	.16	.19	.06	.17	.29	.26	(.77)					
8. Letters	.21	.26	.15	.29	.39	.24	.46	(.85)				
9. Locations	.23	.34	.14	.20	.31	.19	.50	.50	(.76)			
10. ACT-READ	.25	.32	.20	.14	.36	.24	.30	.37	.39	(n/a)		
11. AFOQT	.19	.29	.23	.15	.38	.20	.44	.48	.47	.66	(.75)	
12. Vocabulary	.18	.17	.11	.22	.16	.16	.23	.27	.29	.50	.58	(.72)

Diagonal values are Cronbach's Alpha reliability estimates.

* $p < .05$ for values above .14.

** $p < .01$ for values above .18.

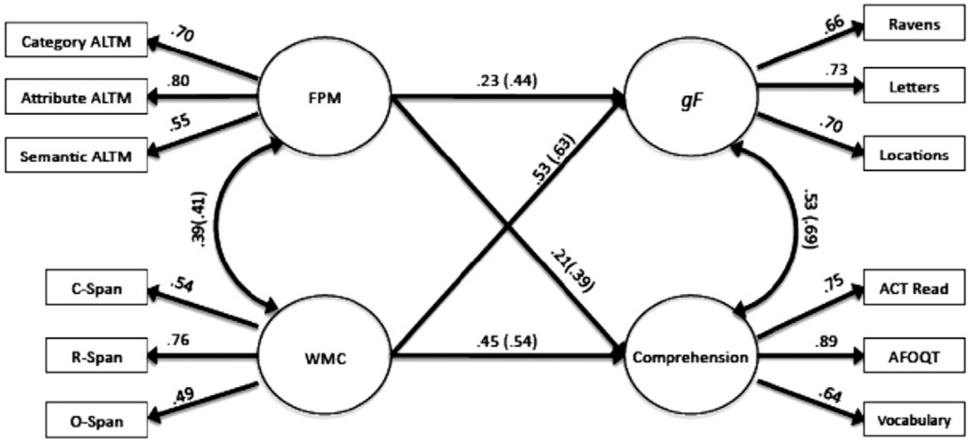

Fig. 3. Hypothesized model displaying standardized parameter estimates. Note: Standardized path coefficients are shown in normal type and estimated factor correlations are in parentheses (error variances are not included).

secondary memory, respectively. The capacity of working memory, according to Unsworth and Engle (2007), relies on the attention processes necessary to maintain elements in the primary memory store and cue-dependent search processes used to retrieve information from secondary memory. Thus, individual differences in WM (as measured by the complex span tasks; cf. Conway et al., 2005) originate in differences in both the ability to maintain information in primary memory, and differences in retrieval of information from secondary memory.

Mogle, Lovett, Stawski, and Sliwinski (2008) investigated the relationships between primary memory, secondary memory, and WM. Secondary memory was the most influential predictor of *gF* and not only accounted for unique variance in *gF*, but also accounted for all variance in *gF* associated with WM. Mogle et al. proposed that the secondary memory processes of search and retrieval, not the primary memory processes involved in active maintenance of memory elements in the face of distraction, accounted for the empirical relationships between working memory capacity and fluid intelligence. Similarly, Unsworth, Brewer, and Spillers (2009) demonstrated that retrieval from secondary memory and working memory capacity both explained unique variance in general intellectual ability. Unsworth and Engle (2007) proposed that the mechanisms involved in the retrieval of information from both episodic and semantic memory account for a great deal of the covariation between WMC and complex cognitive tasks. In particular, Unsworth and Engle referred to a study by Cantor and Engle (1993) that demonstrated that the ability to fluently retrieve information distinguished high WM span participants from low WM span participants. Furthermore, retrieval accounted for the relationship between WMC and comprehension.

Although retrieval from secondary memory contributes to individual differences in *gF*, it is functionally distinct from facilitation of procedural memory, which concerns how facile an individual is at applying a procedure (in the present case, classification procedures) to items that are in the stimulus environment and hence available in primary memory. Measures of secondary memory, such as immediate free recall (Unsworth, Spillers, & Brewer, 2010), word recognition, word–number paired associates, story recognition (Mogle et al., 2008), and delayed free recall of semantically related and semantically unrelated words (Unsworth & Spillers, 2010), require the retrieval or recognition of recently processed information from secondary memory. In contrast, successful completion of The ALTM tasks requires one to perform a prior memory procedure (e.g., item classification) on memory elements in the focus of attention, which are related to (but not identical to) recently processed items currently in secondary memory. Again, the facilitation of a procedure to analyze domain specific (yet item general) stimuli appears to explain unique variance in *gF*, not explained by the retrieval of recently processed items. Certainly, an important goal of future research will be to directly test the relationship between the measures of the facilitation of procedural memory and measures of secondary memory. A subsequent goal of future research will be to investigate the combined contribution (and their interaction) of these key constructs to fluid and crystallized intelligence.

Regarding our secondary goal of replicating Was and Woltz (2007), the current results support their conclusions including the moderate correlation between the facilitation of procedural memory and comprehension. Was and Woltz concluded that the support that background knowledge provides for comprehension is reliant upon efficient memory retrieval of relevant information. Importantly, the efficiency of retrieval relies upon the facilitation of procedural memory. The current investigation extends the previous findings with the inclusion of *gF* as an endogenous variable in the model. Had the inclusion of *gF* attenuated the relationship between the facilitation of procedural memory and comprehension, a reasonable conclusion would be that the majority of variance in comprehension accounted by facilitation of procedural memory is variance shared with *gF*. To the contrary, the current model provides evidence that

Table 3
Latent factor intercorrelations.

Latent factor	1.	2.	3.	4.
ALTM	–			
WM	.41	–		
Gf	.44	.53	–	
Gc	.39	.54	.69	–

Table 4
Fit indices for all models.

Model	X^2	*df*	X^2/df	ΔX^2	RMSEA	CFI	AIC
Hypothesized	53.35	48	1.11	–	.021	.992	137.36
Model 1	59.79	50	1.20	6.64*	.027	.986	139.79
Model 2	86.98	50	2.10	35.63**	.053	.946	166.98
Model 3	120.91	51	2.37	67.55**	.073	.899	198.91

Note-ΔX^2 , X^2 difference between hypothesized model and alternative model; RMSEA, root mean square of approximation; CFI, comparative fit index; AIC, Akaike information criterion. X^2 indicates whether a significant difference exists between the observed and reproduced covariance matrices. Non-significant values indicate that the data do not differ from the estimated model. X^2 to degree of freedom ratios are also provided. Ratios of less than two indicate an adequate fit. RMSEA values less than .08 and CFI values greater than .90 indicate acceptable fit. Significant ΔX^2 values indicate the hypothesized model is a better fit. AIC values provide a means of comparing nested and non-nested models. Lower AIC values represent a better fit.

* $p<.05$.

** $p<.001$.

facilitation of procedural memory accounts for unique variance in comprehension above and beyond that accounted for by *gF*.

The substantial overlap between WM and facilitation of procedural memory in the current investigation warrants attention. As previously described, Unsworth and Engle (2007) proposed that individual differences in working memory capacity reflect either efficiency of primary memory or the efficiency of search of memory elements in secondary memory. One interpretation of the variance shared between WM and the facilitation of procedural memory in the current investigation is performance on ALTM tasks partly taps facilitation of memory retrieval. Thus, the variance shared between the two latent constructs may in part be due to related retrieval mechanisms. Although possible, tasks used to measure secondary memory typically involve the retrieval of elements in secondary memory that were recently processed in primary memory but displaced by new items or processing. The ALTM tasks do not require the retrieval of specific stimuli from secondary memory that were recently processed. Rather, the ALTM task reflects facilitation of a specific memory procedure that is item-general but category-specific, with facilitation for classifying any item within the particular category (e.g., [X] is a tree). Furthermore, recent research has shown facilitation of procedural memory after a one-day delay (Was, 2010), presumably exceeding the timeframe for maintenance of recently processed information in secondary memory.

An alternative explanation of the shared variance between the two latent constructs is that they reflect individual differences in the ability to actively maintain a memory load. Recall that both the complex span tasks and the ALTM tasks require the active maintenance of a memory load. In the ALTM task, this memory load occurs in the first component of a trial (the category exemplar list) and in the complex span task the memory load is the active maintenance of the to-be-remembered stimuli. Furthermore, the tasks forming both constructs require the maintenance of this memory load while processing other information. Although shared variance between the two latent constructs is explainable, the data indicate that facilitation of procedural memory and working memory capacity is not unitary constructs. More important, the facilitation of procedural memory does account for a small, but significant, amount of unique variance in *gF* and comprehension.

Appendix A

Table A1
Standard deviations of residual scores for accuracy, latency, and speed for ALTM tasks.

Variable	Accuracy	Latency	Speed
Category ALTM	0.50	0.46	0.43
Attribute ALTM	0.45	0.46	0.47
Synonym ALTM	0.57	0.54	0.46

Note: means not displayed (means of residuals are equal to zero).

Table A2
Paired sample *t*-test comparing speed measure of ALTM tasks to accuracy and latency.

Comparison Variables	Mean Difference	95% CI				
		Lower	Upper	*t*	*df*	*p*
Category ALTM Accuracy–speed	0.000	−0.077	0.077	0.00	216	1.00
Attribute ALTM Accuracy–speed	0.013	0.057	0.084	0.38	239	0.70
Synonym ALTM Accuracy–speed	0.008	−0.104	0.089	0.15	216	0.88
Category ALTM Latency–speed	0.000	−0.107	0.107	0.00	216	1.00
Attribute ALTM Latency–speed	0.015	−0.108	0.137	0.24	239	0.81
Synonym ALTM Latency–speed	0.014	−0.136	0.138	0.22	216	0.83

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