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Faster, smarter? Working memory capacity and perceptual speed in relation to fluid intelligence

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Numerous studies have found that working memory capacity and perceptual speed predict variation in fluid intelligence. Within the cognitive ageing literature, perceptual speed accounts for substantial ageing variance in working memory capacity and fluid intelligence. However, within young adults, the interrelationships among these three abilities are less clear. The current work investigated these relationships via confirmatory factor analyses and structural equation modelling using tasks with verbal, spatial, and numerical content. The results indicate that working memory capacity and perceptual speed were not related in a large, cognitively diverse sample of young adults. However, both working memory capacity and perceptual speed accounted for unique variance in fluid intelligence. The results are discussed in relation to previous research with young and older adults.

Keywords: Fluid intelligence; Individual differences; Perceptual speed; Working memory capacity.

> The centrality of the working memory capacity factor leads to the conclusion that working memory capacity may indeed be essentially Spearman's *g*. (Kyllonen, 1996, p. 73)

> Among the most meaningful ways to conceptualize mental capacity is in terms of an individual's processing speed. (Kail & Salthouse, 1994, p. 201)

Recent attempts at discovering the cognitive processes responsible for the manifestation of intelligence have been heavily influenced by information-processing theory. Many researchers have taken what has been termed the "cognitive-correlates" approach to study fluid intelligence (Gf) by examining the relationship between theorised cognitive components and Gf (Sternberg, 1985). The goal of this approach is to provide a more tractable way to learn about Gf by examining ostensibly more specific cognitive processes that are strongly related to Gf. Two examples of cognitive constructs linked to Gf are working memory capacity (WMC) and perceptual speed (PS). Proponents of the WMC view (Engle, Tuholski, Laughlin, & Conway, 1999; Kane, Hambrick, & Conway, 2005) have linked individual differences in WMC to Gf in healthy young adults, whereas PS theorists have relied mostly on evidence obtained from developmental studies of children (Kail & Salthouse, 1994) or older adults (Verhaeghen & Salthouse, 1997). We first review the literature to clarify what is already known about individual differences in WMC, PS, and Gf, before presenting a new study designed to answer how these constructs are interrelated.

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WMC AND PS AS PREDICTORS OF GF

"Complex span" tasks such as Operation Span are variants of memory span measures commonly included in intelligence batteries (e.g., Digit Span). Instead of being given a list of digits to serially recall as in Digit Span, participants completing Operation Span see a series of to-be-remembered letters interleaved with an unrelated arithmetic task. Complex span tasks like Operation Span are also known as storage-plus-processing tests, as they all combine the recall of some items (e.g., letters) while also performing a secondary processing task (e.g., maths operations). Over the past 30 years, research has demonstrated that complex span measures of WMC such as Operation, Reading, and Symmetry Span are consistently highly correlated with Gf measures (Kane et al., 2005). The strong relationship between WMC and Gf has been observed in both young and older adults (Verhaeghen & Salthouse, 1997).

We (Engle et al., 1999; Unsworth & Engle, 2007) have argued that individual differences in WMC represent the ability to maintain and retrieve information and control attention under conditions of high interference. In terms of performance on the complex span tasks themselves, maintenance, retrieval, and attention are important to (1) switch back and forth between the processing and storage aspects of the task; (2) sustain current-list item information with or without the benefit of maintenance rehearsal; (3) search for items that have been displaced from the focus of attention; and (4) counteract proactive interference from earlier trials. Although none of the mechanisms responsible for individual differences in performance on complex span tasks are yet known, performance on these tasks has been observed repeatedly to correlate with a variety of reasoning tasks measuring Gf. Because complex span tasks have been central to this account, these tasks were chosen as measures of WMC for the current research.

Developmental and psychometric research has demonstrated that PS is also related to Gf. Although different kinds of mental speed are discussed in the psychological literature, our focus is on PS. One particular PS measure (Number Comparison; Ekstrom, French, Harman, & Dermen, 1976) and similar variants (Letter and Pattern Comparison) have been used (e.g., Kail & Salthouse, 1994; Verhaeghen & Salthouse, 1997) to demonstrate that PS accounts for developmental differences in higher order cognition, including WMC and Gf. On PS comparison tasks, participants decide whether the content on either side of a blank line is an identical match (FTRMZN___FTRMZN) or a nonmatch (HPCVKM___HDCVKM).

Further research with young adult participants shows that PS comparison tasks are valid and representative measures of PS ability. Ackerman and Cianciolo (2000) conducted a factor analysis on 21 PS tests and found evidence for three related but separable factors. The PS-Pattern Recognition factor was "dominated by tests that involved the recognition of simple patterns" (p. 273), such as Finding As. The PS-Memory factor was characterised by tasks such as the Digit-Symbol Substitution Test that were "best identified as making substantial demands on working memory" (p. 273). Tests that loaded highly on the PS-Scanning factor, including Number Comparison, "involved scanning, comparison, and lookup processes" (p. 273). In Study 3, Ackerman and Cianciolo showed that the PS-Scanning factor was specifically related to PS abilities; the PS-Pattern Recognition factor had a modest cross-loading with psychomotor speed tests, whereas PS-Memory had a sizeable cross-loading with intelligence tests. Thus, the comparison tasks represent PS separately from the influences of psychomotor ability and Gf. Given these results, and their prominence in the developmental research, comparison tasks are the focus of the current PS research.[1]

HOW ARE WMC, PS, AND GF RELATED?

Studies with children (Kail & Salthouse, 1994) and older adults (Verhaeghen & Salthouse, 1997) have demonstrated strong relationships and overlapping variance among WMC, PS, and Gf, to the point that WMC and/or PS fully accounts for the age-related variance in Gf. This is often evident in cross-sectional data such as in Figure 1A, where WMC, PS, and Gf exhibit a nearly identical trajectory across the adult age range. Based on developmental research, one might expect that WMC, PS, and Gf are all moderately-to-strongly related with each other.

[1] Unless stated otherwise, for the rest of the paper, we will use PS to refer to the PS-Scanning factor in the taxonomy of PS abilities identified by Ackerman and Cianciolo (2000).

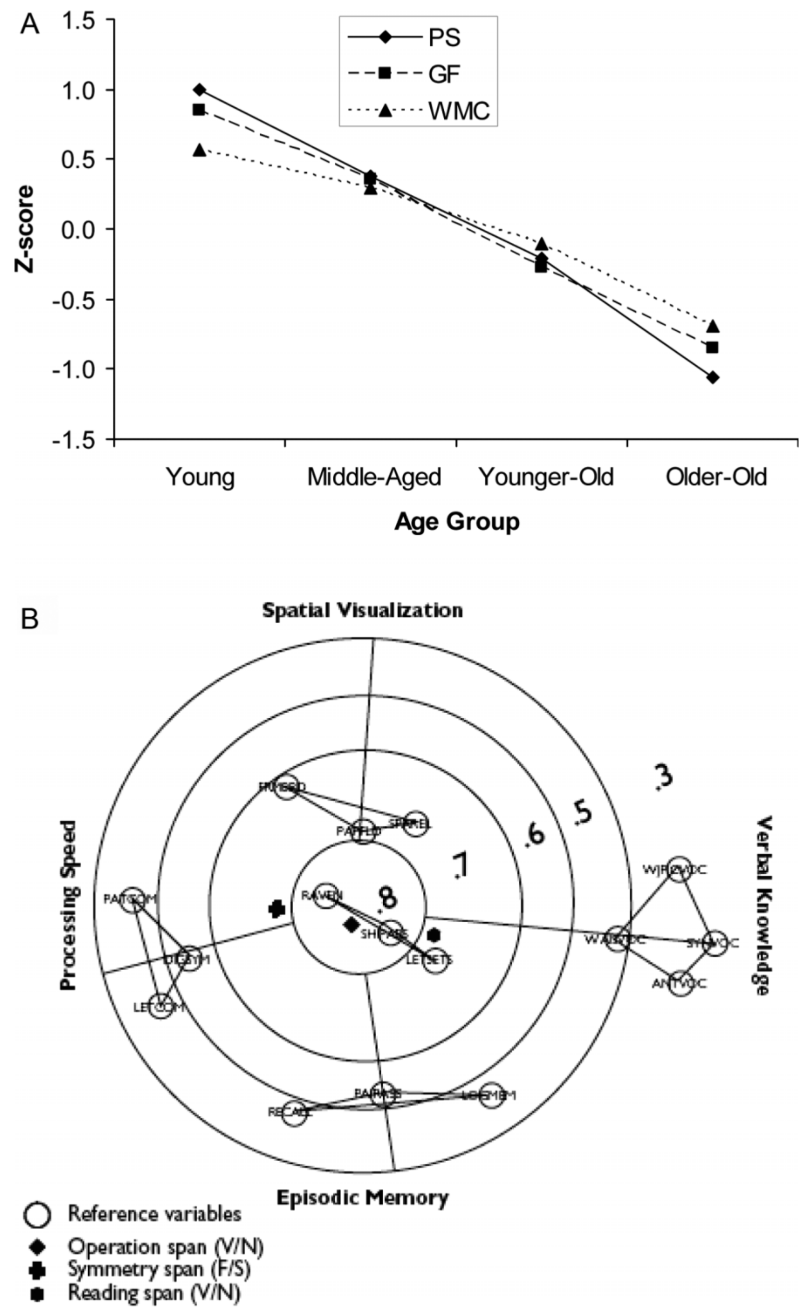

Figure 1. (A) Cross-sectional data showing typical aging effects on WMC, PS, and GF. Figure based on data from McCabe, Roediger, McDaniel, Balota, and Hambrick (2010). (B) Radex model data with WMC tasks included. Other relevant tasks include Pattern Comparison (PATCOM), Letter Comparison (LETCOM), RAVEN (Raven Advanced Progressive Matrices), LETSETS (Letter Sets), and PAPFLD (Paper Folding). Modified figure reprinted with permission from Tucker-Drob & Salthouse (2009).

However, accounting for the age-related variance in cognition is different from accounting for individual differences within an age group (Hofer & Sliwinski, 2001), because the ageing variance is confounded with individual-differences variance. In fact, nondevelopmental research clearly indicates that WMC, PS, and Gf are separable constructs. The radex model (Marshalek, Lohman, & Snow, 1983) categorises the domain-specificity and *g* strength of a particular cognitive ability test. For example, the Raven Advanced Progressive Matrices (Raven; Raven, Raven, & Court, 1998) is a matrix reasoning test commonly used to measure Gf. Raven is centrally located in the radex model, as the test demonstrated the highest *g* loading of all of the cognitive ability tests administered by

Marshalek et al. (1983). In addition, its central location indicates that although the test items are visuospatial, the test itself is largely domain-general. Germane to the current work, the radex approach unquestionably indicates that PS tests (including Number Comparison) have low *g* loadings compared to tests such as Raven, Letter Sets, Paper Folding, and Number Series (Snow, Kyllonen, & Marshalek, 1984; Tucker-Drob & Salthouse, 2009). In addition, as seen in Figure 1B, Tucker-Drob and Salthouse (2009) demonstrated that Operation, Symmetry, and Reading Span were found to have high *g* loadings and be located much closer in the ability space to the Gf tests than the PS tasks.

Two studies (Ackerman, Beier, & Boyle, 2002; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002) explicitly examined individual differences among WMC, PS, and Gf within young adults. Although other studies have administered tests reflecting these constructs, these two studies focused on how these constructs interrelate, and are discussed in detail later. Ackerman et al. (2002) examined the pattern of relationships among the different PS subtypes with composites representing working memory and *g* in 135 young adults. Most relevant for the current paper are the PS-Scanning results, which included Number and Name Comparison. The PS-Scanning composite was significantly correlated with both the working memory composite and the *g* composite ($r = .39$ and .37, respectively). The correlation between working memory and *g* was greater ($r = .56$). Focusing on the PS-Scanning variable, the summary of the Ackerman et al. results is: (1) WMC and PS were significantly correlated; (2) PS and Gf were significantly correlated; and (3) WMC and Gf were correlated slightly higher than PS and Gf.

Interestingly, Ackerman et al. (2002) noted a different pattern emerged when Raven was used as the criterion variable instead of *g*. Specifically, PS-Scanning had a nonsignificant correlation with Raven ($r = .12$), although the working memory–Raven correlation remained significant ($r = .48$). These results show that the use of either a *g* composite of reasoning tests made up of verbal, spatial, and numerical content, or using only a spatial reasoning test leads to different conclusions about the relative importance of WMC and PS in predicting intelligence.

Conway et al. (2002) administered WMC (Operation, Reading, and Counting Span), PS (four tasks, including Letter and Pattern Comparison), Gf (Cattell's and Raven), and short-term memory tests to 113 young adults. To facilitate comparison with Ackerman et al. (2002), we reanalysed the data in Conway et al. by conducting a confirmatory factor analysis (CFA) of the WMC, PS, and Gf tasks only.[2] The results indicated that: (1) the WMC and PS factors were modestly but significantly correlated, $r = .27$, $p < .05$; (2) PS was not correlated with Gf ($r = .13$); and (3) WMC and Gf were significantly correlated, $r = .53$, $p < .05$.

There are discrepancies (the PS-Gf relationship) and similarities (the WMC-PS and WMC-Gf relationships) between the Ackerman et al. (2002) and Conway et al. (2002) conclusions about WMC, PS, and Gf. This is partially due to differences in the selection of tasks to represent the three constructs. For example, Conway et al. used only matrix reasoning tests (Raven and Cattell's) to measure Gf. This might have caused the lack of relationship between PS and Gf, similar to Ackerman et al.'s results when using only Raven to represent Gf. In addition, Ackerman et al. used tasks to represent working memory that might have been considered as short-term memory measures by Conway et al., based on previous research (e.g., Backward Digit Span and ABCD Order did not load on the same factor as Operation Span and Reading Span in Engle et al., 1999).

CURRENT STUDY

Our goal was to clarify the relationship of individual differences in WMC, PS, and Gf. We administered multiple indicators of WMC, PS, and Gf to a large sample of young adults, to avoid the influence of age-related variance. In addition, the tasks chosen to represent each construct reflected verbal, spatial, and numerical content, in contrast to both Ackerman et al. (2002)—no spatial PS tasks) and Conway et al. (2002—no spatial WMC or PS tasks, no verbal or numerical Gf tasks). We also selected Gf tests that load highest on the *g* factor in the radex model. However, we did not use Raven as a Gf measure because Ackerman et al. criticised the overuse of Raven as the "univocal operationalization of intelligence" (p. 586).

[2] The complete results of this reanalysis can be obtained by contacting the first author. The fit was excellent: $\chi^2(24) = 24.03, p = .46$; $\chi^2/df = 1.00$; NNFI = 1.00; CFI = 1.00; 1.00; RMSEA < .01; SRMR = .05.

METHOD

Participants

The sample consisted of 150 young adults between the ages of 18 and 30 ($M = 22.2$, $SD = 3.1$). Ninety-two participants were female. Participants were students at various Atlanta area colleges or nonstudents recruited via advertisements. Participants were compensated with class credit or US$20 per session.

Materials

All of the WMC measures completed in the first session followed a similar administration—the exact content of the processing and storage tasks varied across each. The participant completed a processing task, which was immediately followed by a to-be-remembered item. After a series of processing problems and to-be-remembered items, the participant was prompted to recall the items in serial order. The dependent variable was the total number of items recalled in the correct serial order across trials.

Operation span (Redick et al., 2012). Participants were presented with simple math operations composed of three single digits and two separate operations [$(2 \times 2) + 5 \ = ?$]. Participants were presented with a number and instructed to click either TRUE or FALSE if the number presented on the screen matched the number from the mental calculation. After all of the items for the current trial had been presented, the participant was shown a fixed grid of letters from which all to-be-remembered items were randomly drawn (F, H, J, K, L, N, P, Q, R, S, T, and Y). Three sets of each list length (3–7) were presented randomly, for a maximum possible score of 75.

Symmetry span (Redick et al., 2012). Participants were presented with figures that were either vertically symmetrical or asymmetrical. Participants were asked if the matrix was symmetrical and instructed to click either TRUE or FALSE. Immediately after responding, a single box in a 4×4 grid was highlighted in red. After all of the items for the current trial had been presented, participants were shown a blank 4×4 grid matching that shown when the to-be-remembered items were presented. They then clicked in serial order the boxes that were highlighted in the previous set. Three sets of each list length (2–5) were presented randomly, for a maximum possible score of 42.

Reading span (Redick et al., 2012). The storage aspect of the Reading Span was identical to Operation Span. For the processing task, the participant was shown a grammatically correct sentence that was either sensible or nonsensical. Participants were asked if the sentence made sense and instructed to click either TRUE or FALSE. Immediately after responding, the to-be-remembered letter was shown. Three sets of each list length (3–7) were presented randomly, for a maximum possible score of 75.

The PS and Gf tasks were completed during the second session. Participants were instructed to complete as many items as accurately as possible within the amount of time provided. In the PS tasks, participants wrote *S* or *D* if the items were the same or different, respectively. There were two pages for each task, and the items on each page were equally divided into match and non-match items. Participants had 30 s to complete each page, with the total correct across the two pages used as the dependent variable.

Letter comparison (Salthouse & Babcock, 1991). Consonants grouped into three, six, or nine were randomly distributed throughout each page of the task.

Pattern comparison (Salthouse & Babcock, 1991). Shapes consisting of line drawings were randomly distributed throughout each page of the task.

Number comparison (Salthouse & Babcock, 1991; see also Ekstrom et al., 1976). Numbers grouped into three, six, or nine were randomly distributed throughout each page of the task.

Each Gf test was time-limited, and the total number correct was used as the dependent variable.

Letter sets (Ekstrom et al., 1976). On each problem, five sets of letters containing four letters each were presented. Participants were instructed to find the rule that applied to four of the five letter sets, and then indicate the letter set that violated the rule. Participants had 5 minutes to complete 20 items.

Paper folding (Ekstrom et al., 1976). On each problem, a figure representing a square piece of

TABLE 1
Correlation matrix for all measures ($N = 150$)

Variable	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
WMC									
1. Operation Span	—								
2. Symmetry Span	.65	—							
3. Reading Span	.81	.64	—						
PS									
4. Letter Comparison	.01	.04	.02	—					
5. Pattern Comparison	.03	.05	.00	.59	—				
6. Number Comparison	.03	.02	.01	.72	.54	—			
Gf									
7. Letter Sets	.39	.45	.38	.33	.36	.35	—		
8. Paper Folding	.26	.46	.34	.18	.26	.14	.56	—	
9. Number Series	.31	.44	.29	.19	.14	.27	.59	.50	—
Mean	55.31	26.76	53.10	24.56	39.69	31.04	9.54	9.93	8.10
SD	14.98	9.10	15.72	5.23	6.78	5.23	3.50	4.06	2.72
Reliability	.88[a]	.83[a]	.88[a]	.61[b]	.73[b]	.68[b]	.78[c]	.84[c]	.73[c]
Skewness	−1.01	−0.55	−0.98	0.27	−0.09	−0.11	0.15	0.33	−0.18
Kurtosis	0.68	−0.50	0.86	0.18	−0.27	−0.11	−0.21	−0.56	−0.27

Correlations >.16 are significant at $p < .05$. [a]Reliability calculated by combining the first presentation of each list length into a single score, the second presentation into a single score, and the third presentation into a single score, and computing Cronbach's alpha across the three scores. [b]Reliability calculated by correlating scores on the first page with the second page of the test. [c]Reliability calculated by computing Cronbach's alpha.

paper is presented on the left. The markings indicate that the paper has been folded a certain number of times, and then a hole was punched through the paper. The participant was instructed to identify the response option that best represented what that piece of paper would look like if it was completely unfolded. There were two, 10-item parts of the test, and participants had 5 minutes to complete each section.

Number series (Thurstone, 1938). On each problem, a series of numbers was presented, and the participants were instructed to identify the response option that was the next logical number in the sequence. Participants had 4.5 minutes to complete 15 items.

Results

Descriptive statistics for all measures are provided in Table 1. Correlations (Table 1) demonstrate convergent and discriminant validity, with higher intercorrelations among the three tasks theorised to measure each construct than with the tasks measuring other constructs. In addition, there is little evidence from the pattern of correlations in Table 1 that the test content (verbal, spatial, numerical) determined the correlation magnitudes.

Confirmatory factor analyses. The first CFA examined a model in which the three complex span tasks load on a WMC factor, the three comparison tasks load on a PS factor, and the three reasoning tasks load on a Gf factor (Figure 2A).[3] As can be seen in Table 2, the fit for this model (CFA A) was good, despite the significant χ^2-test. The loadings for each of the tasks onto its theorised construct are very high. Although the correlation between the WMC and PS factors was not significant ($t = 0.31$), each construct was significantly correlated with Gf (both *t*s > 5.28). We also tried an alternative

[3]Before providing the results of the confirmatory factor analyses (CFAs) and structural equation models (SEMs), we note the criteria used to assess model fit provided by LISREL. A nonsignificant ($p > .05$) χ^2-value is desirable, although with sufficiently large sample sizes, a significant χ^2-value will be obtained and not necessarily be indicative of poor model fit. We also report a ratio of the χ^2-value and the degrees of freedom in the model, with a ratio value of two or less indicating acceptable fit. Values of the nonnormed fit index and the comparative fit index greater than .90 indicate acceptable model fit (Kline, 1998). Root mean square error of approximation values and standardised root mean square residual values less than .08 indicate acceptable model fit (Kline, 1998). In order to statistically compare models, χ^2-tests of the difference ($\Delta\chi^2$) between the two models were used, with $p < .05$ indicating better statistical fit. In addition, the Akaike information criterion was used to compare models, with the model associated with the smallest value representing the best statistical fit.

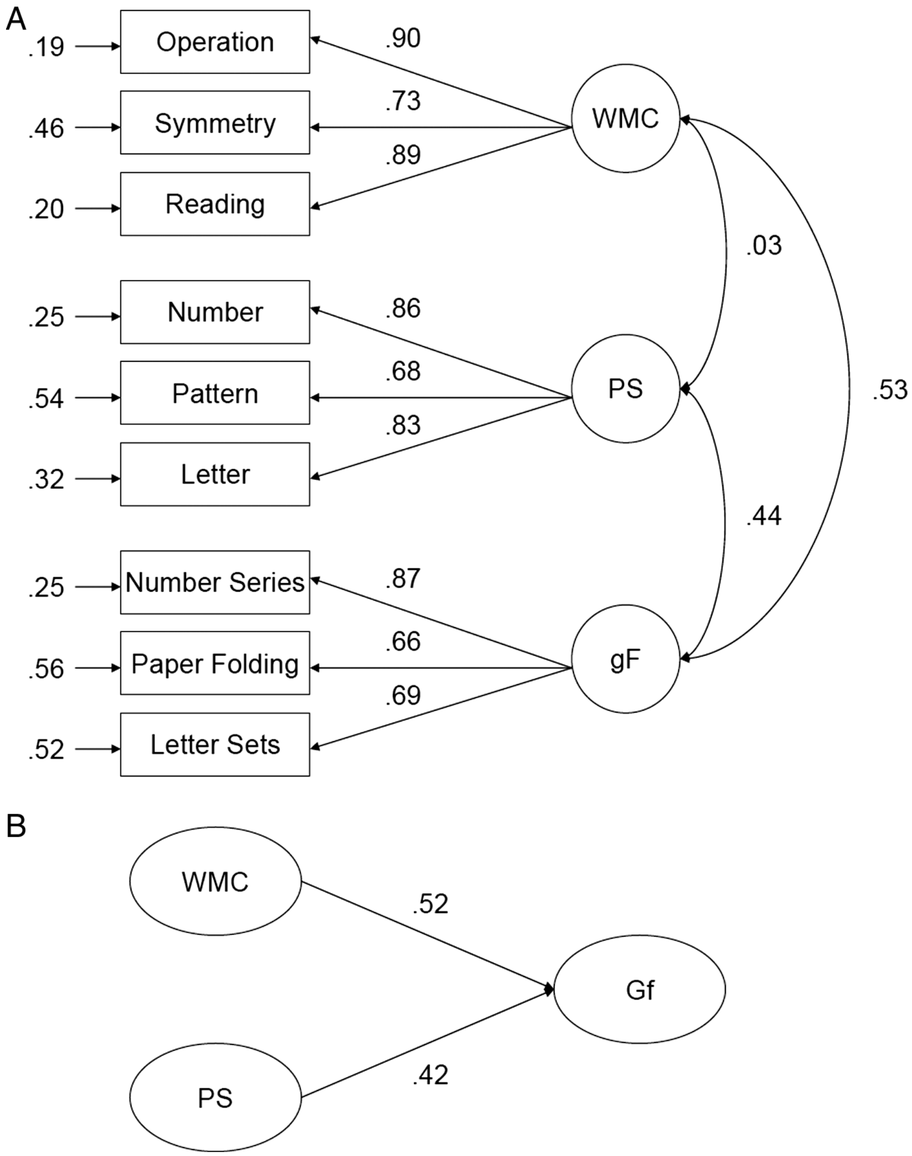

Figure 2. (A) Confirmatory factor analysis of WMC, PS, and Gf (CFA A). (B) Structural equation model with WMC and PS as predictors of Gf (SEM D).

measurement model based on the content (verbal, spatial, numerical) of the tasks (CFA B), but the fit was poor (Table 2). Overall, the CFA results indicate that the representative measures load on the theorised constructs independent of content, and that WMC and PS are independently related to Gf in the current sample of young adults.

Structural equation models. After establishing that CFA A was the endorsed model, we tested a series of SEMs where Gf was the criterion and WMC and PS were the predictors. In SEM A, the correlation between WMC and PS, the path from WMC to Gf, and the path from PS to Gf were freed. The fit of SEM A was identical to CFA A (Table 2), as the same paths and loadings were estimated in both models. Using SEM A as a baseline model, we compared the relative fits of SEM B (the path from WMC to Gf was fixed to 0), SEM C (the path from PS to Gf was fixed to 0), and SEM D (the correlation between WMC and PS was fixed to 0) to SEM A. As can be seen, SEM A had superior fit statistics, a smaller Akaike value, and provided a significantly better fit to the data than SEM B or SEM C: SEM B, $\Delta\chi^2(1) = 29.83$, $p < .01$; SEM C, $\Delta\chi^2(1) = 19.96$, $p < .01$. However, the fit of SEM D was not

TABLE 2
Fit statistics for confirmatory factor analysis and structural equation models

Model	χ^2	*df*	χ^2/df	*NNFI*	*CFI*	*RMSEA*	*SRMR*	*AIC*
CFA A	48.50	24	2.02	.95	.97	.08	.06	90.50
CFA B	356.67	24	14.86	.45	.63	.31	.20	398.67
SEM A	48.50	24	2.02	.95	.97	.08	.06	90.50
SEM B	78.33	25	3.13	.88	.92	.12	.16	118.33
SEM C	68.46	25	2.74	.91	.94	.11	.12	108.46
SEM D	48.56	25	1.94	.95	.97	.08	.06	88.56

All chi-square tests significant ($p < .01$). NNFI: nonnormed fit index; CFI: comparative fit index; RMSEA: root mean square error of approximation; SRMR: standardised root mean square residual values; AIC: Akaike information criterion.

statistically different from SEM A, $\Delta\chi^2(1) = 0.06$, $p = .81$, the Akaike value for SEM D was slightly lower than SEM A, and the loadings and paths in the model were identical to SEM A. In the interest of parsimony, and consistent with the nonsignificant WMC-PS correlation obtained in the CFA measurement model and in SEM A, SEM D was retained as the best-fitting model, and is displayed in Figure 2B. WMC and PS together accounted for 45% of the variance in Gf, but WMC uniquely accounted for 27% of the Gf variance and PS uniquely accounted for 18% of the Gf variance. The SEM results indicate that both WMC and PS independently predict Gf.

DISCUSSION

The zero-order correlations, CFAs, and SEMs converge on the conclusion that WMC and PS are not related to each other, but each independently accounts for significant variance in Gf. In addition, the results indicate that relationships among the tasks administered here were not due to the content of the tests, but instead the underlying constructs that the tasks measured. In relation to previous research with young adults (Ackerman et al., 2002; Conway et al., 2002), the results are partially consistent with both studies, as discussed later.

WMC and Gf

The most consistent finding in Ackerman et al. (2002), Conway et al. (2002), and the current study is that WMC is strongly related to Gf, no matter which particular tasks are used to measure each construct. In the current data, the WMC-Gf relationship is completely independent of PS. This fits nicely with recent work showing that processing time on the complex span tasks themselves also does not mediate the WMC-Gf relationship (Unsworth, Redick, Heitz, Broadway, & Engle, 2009). Thus, we are left with the impression that cognitive processing speed is not an important determinant of the overlapping variance between WMC and Gf.

Of course, this begs the question—what does account for the relationship between WMC and Gf? Previously, we have focused on the role that attention plays on tests of WMC and Gf (Engle et al., 1999). In recent years, it has become clear that retrieval, maintenance, and attention abilities are all important components of individual differences in WMC and Gf (Unsworth & Engle, 2007). Although there may end up being more processes involved, a combination of correlational and experimental approaches that focuses on both measures of WMC and Gf will add to the progress made thus far.

PS and Gf

In the current study, PS did reliably account for variance in Gf, which is in contrast with Conway et al. (2002), who obtained a nonsignificant PS-Gf relationship. One explanation for this discrepancy is that Conway et al. used only matrix reasoning tests to define the Gf construct. In Conway et al., Letter and Pattern Comparison were not correlated with Raven ($r = -.09$ and .03, respectively). As discussed previously, Ackerman et al. (2002) obtained different PS-Gf relationships depending on whether Gf was defined broadly (as in the current study) or via only Raven, a matrix reasoning test (as in Conway et al.). In Ackerman et al., Number and Name Comparison were not correlated with Raven ($r = .09$ and $-.01$, respectively). In contrast, Number and Name Comparison were correlated with Number Series

($r = .16$ and .20, respectively), similar to the magnitude of the PS-Number Series relationships observed in the current study (Table 1). The results are consistent with the notion that when Gf is measured with a broad set of reasoning tasks, PS and Gf share significant variance.

An advantage of the PS tasks is that they are quick and easy to administer, in contrast to some WMC and Gf tests. However, it's not clear what cognitive processes account for the shared variance between PS and Gf. Research has shown that administering reasoning tests under speeded versus unspeeded conditions increases their relationship with mental speed tasks (Wilhelm & Schulze, 2002). Wilhelm and Schulze (2002) did not use the PS or Gf tasks that we used, but administering time-restricted reasoning tasks could partially account for the PS-Gf relationship observed.

WMC and PS

At first, the lack of a WMC-PS relationship was somewhat surprising. A common finding in the cognitive ability literature, known as positive manifold, is that reliable tests produce positive correlations with each other, regardless of the exact underlying construct the measure is designed to assess. Obviously, this is not a power issue, given the size of the current sample and that all nine of the correlations ranged between .00 and .05. In addition, the sample we used was quite diverse relative to other young-adult studies, because our sample consisted of students from a comprehensive public university (Georgia State), a relatively selective public university (Georgia Tech), other metro Atlanta area colleges (Clark Atlanta, Morehouse, Spelman, Agnes Scott), and a number of nonstudent young adults. Therefore, we did not have as much reason to worry about restriction-of-range problems that might also cause a lack of a relationship.

Although our reanalysis of Conway et al. (2002) showed a significant WMC-PS relationship at the latent level, the correlations among the three complex span measures and the two comparison tasks were small ($r = .13 - .19$), so our WMC-PS results are not strikingly different. Recently, Unsworth, Spillers, and Brewer (2011) obtained nonsignificant results using the identical verbal and numerical WMC and PS tasks used in the current study. The four correlations in that study of 156 college students ranged from .04 to .10, and the latent correlation between WMC and PS in their CFA was not significant. Previous large-sample studies of young adults have also obtained similar nonsignificant WMC-PS correlations using complex span and comparison tasks (Babcock & Laguna, 1996; Rogers, Fisk, & Hertzog, 1994, reported in Rogers, 1991; Rogers, Hertzog, & Fisk, 2000), so perhaps the lack of a WMC-PS relationship should not be surprising.

Previously, WMC has been labelled as a ''promiscuous variable'' (Ackerman et al., 2002, p. 581). The current results indicate that WMC's relationship with PS, as defined by comparison tasks, is either nonsignificant or weak in young adults. The utility of WMC for understanding individual differences in higher order cognition is lost if the construct shows no discriminant validity. It is important to demonstrate that WMC is more strongly related to certain constructs to which it is theoretically predicted than other constructs that are less theoretically consistent.

Developmental versus individual differences

In the cognitive ageing literature, WMC and PS have substantial overlapping variance (e.g., Verhaeghen & Salthouse, 1997). However, previous research indicates that studies including older adults are more likely to observe a robust relationship between PS and other cognitive variables such as WMC and Gf. In their meta-analysis, Verhaeghen and Salthouse (1997) separated their samples into young and older adults, based on the age range of 50 years and under classified as young adults, and over 50 years as older adults. The only cognitive relationship that changed as a function of age was the Speed–Reasoning correlation, which was higher in the older adults. Hedden, Lautenschlager, and Park (2005) split their latent-variable sample into young (≤ 54 years old) and older adults (≥ 55 years old). The only factor correlation that was higher for the older adults than the young adults was the WMC-PS correlation. In addition, in the meta-analysis conducted by Ackerman, Beier, and Boyle (2005), they compared the relationships among eight cognitive abilities as a function of samples composed entirely of ages 18 to 30 and samples with a wider adult age range. They observed that the WMC-PS correlation was weaker in the 18–30 sample than in a wider adult age range. Thus, research suggests that relationships among WMC, PS, and Gf is stronger in samples including older adults, when ageing and individual differences variance are not separable (Hofer & Sliwinski, 2001).

Limitations and future directions

One potential criticism of the current work is that our choice of WMC and PS tasks led to narrow definition of the constructs. However, relative to previous research, an advantage of the current research is that we used verbal, spatial, and numerical tasks for all three constructs. The choice to use complex span and comparison tasks was driven both by previous research and a desire to provide a clear picture about the relationship among these constructs. As mentioned earlier, Ackerman et al. (2002) observed different relationships among WMC, PS, and Gf depending on the way that the PS and Gf constructs were defined. We note that Ackerman et al. (2005) used much broader operational definitions of WMC, PS, and Gf in their meta-analysis than was used in the current study. Importantly, their meta-analytic results were largely consistent with our findings—WMC and PS had a lower correlation with each other than WMC had with *g* or other reasoning factors. Therefore, although one could argue that the results here are applicable only to certain measures of WMC, PS, and Gf, we are confident that the results are more informative than if we had included many different kinds of WMC and PS tasks. Future work addressing the issues of how the WMC and PS constructs are defined, and how this affects the prediction of Gf, is important for a more complete understanding of these abilities. Such research would provide a complementary aspect to Ackerman et al. (2002) and their examination of how defining PS and Gf affected relationships with WMC.

CONCLUSION

In the cognitive and developmental literatures, intelligence research has focused on both WMC and PS as candidate abilities to account for variation in Gf. The current research indicates that the WMC and PS both account for significant but independent Gf variance. In addition, WMC and PS are not significantly related in the current sample of young adults. Finally, the relationships among these constructs are independent of the content of the representative tests.

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