Working-Memory Capacity as a Unitary Attentional Construct

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Acknowledgments

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- Andrew R. A. Conway
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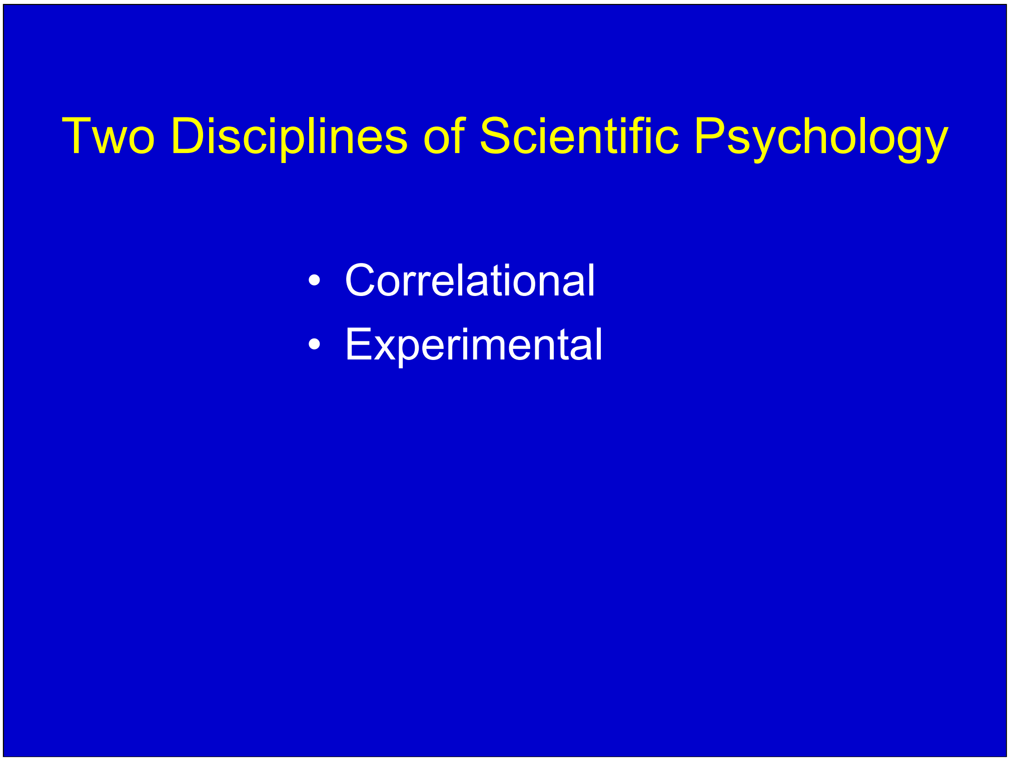
- David Z. Hambrick
- Tabitha W. Payne
- Stephen W. Tuholski
- Oliver Wilhelm

I’d like to begin by acknowledging my collaborators for their involvement in the work I’ll present today.



At a most general level, our approach to the study of executive control attempts to marry what Cronbach called the two disciplines of scientific psychology: the correlational and the experimental.

Two Disciplines of Scientific Psychology

"A united discipline will study both of these, but it will also be concerned with the otherwise neglected interactions between organismic and treatment variables." (Cronbach, 1957, p. 681)

Cronbach argued that Psychology needed to align these disciplines, and in this vein, our aim has been to use both experimental and psychometric approaches as converging means to understand executive control and WM capacity

“Span” Measures of STM and WM Capacity

Word Span (STM)	Reading Span (WM)	Operation Span (WM)
JOB	The tiger leapt to the ridge. **JOB**	Is (3 x 1) – 1 = 3 ? **JOB**
ANT	I’ll never forget my days of combat. **ANT**	Is (10 / 2) + 1 = 6 ? **ANT**
CAKE	Andy was arrested for speeding. **CAKE**	Is (8 / 4) – 1 = 1 ? **CAKE**
JAIL	The mirror cast a strange reflection. **JAIL**	Is (3 x 3) + 1 = 12 ? **JAIL**
SEA	Broccoli is a good source of nutrients. **SEA**	Is (4 x 3) + 2 = 14 ? **SEA**

The point of departure for our work lies in comparing individual differences in simple span tasks of STM to complex span tasks of WM.

“Span” Measures of STM and WM Capacity

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SEA	Broccoli is a good source of nutrients. **SEA**	Is (4 x 3) + 2 = 14 ? **SEA**

Simple STM tasks, such as digit or word span, require subjects to immediately recall a short list of stimuli in correct serial order.

"Span" Measures of STM and WM Capacity

Word Span *(STM)*	Reading Span *(WM)*	Operation Span *(WM)*
JOB	The tiger leapt to the ridge. **JOB**	Is (3 x 1) – 1 = 3 ? **JOB**
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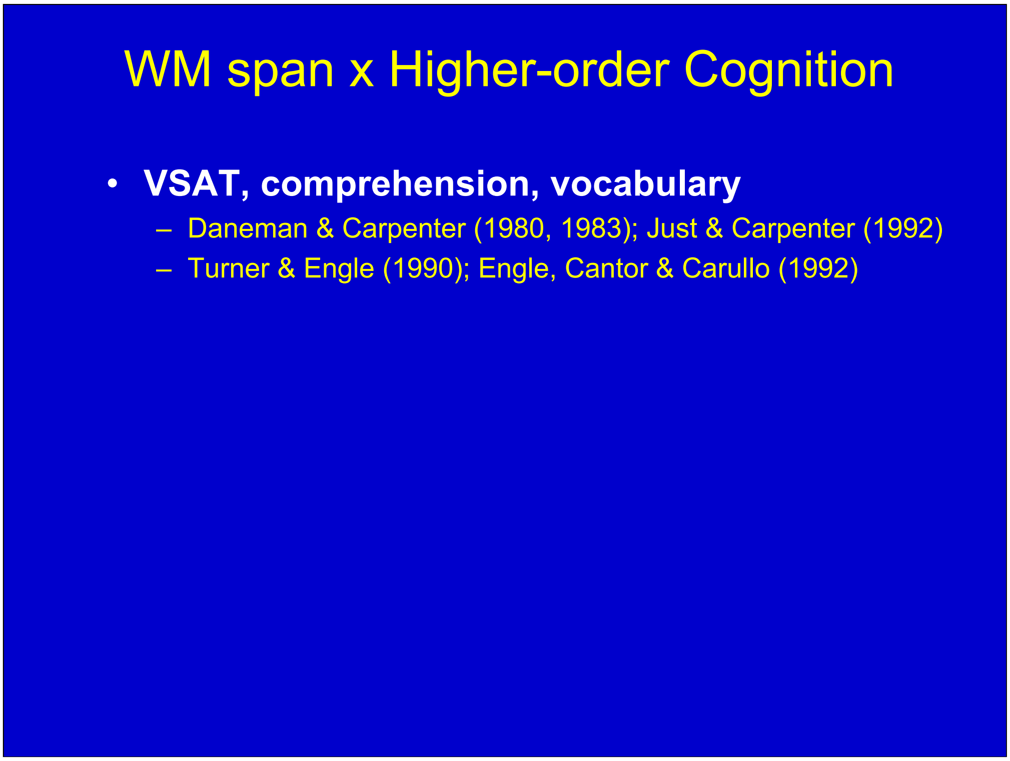
JAIL	The mirror cast a strange reflection. **JAIL**	Is (3 x 3) + 1 = 12 ? **JAIL**
SEA	Broccoli is a good source of nutrients. **SEA**	Is (4 x 3) + 2 = 14 ? **SEA**

Complex WM tasks, such as Reading Span and Operation Span, have the same memory-span requirement, but the memoranda alternate with a secondary task such as judging sentences or verifying equations.



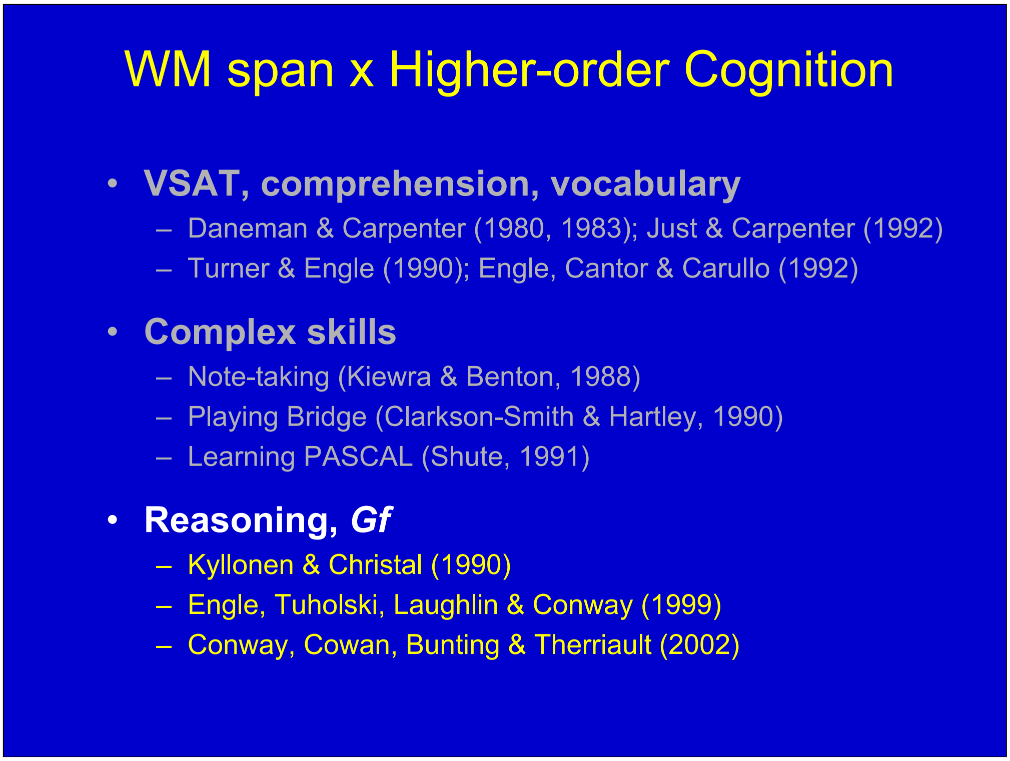
WM span tasks, such as Reading Span and Operation Span, have attracted researchers' interest because, in contrast to STM span, they consistently do a good job of predicting individual differences in a range of complex cognitive abilities, such as:

Language comprehension and verbal ability...

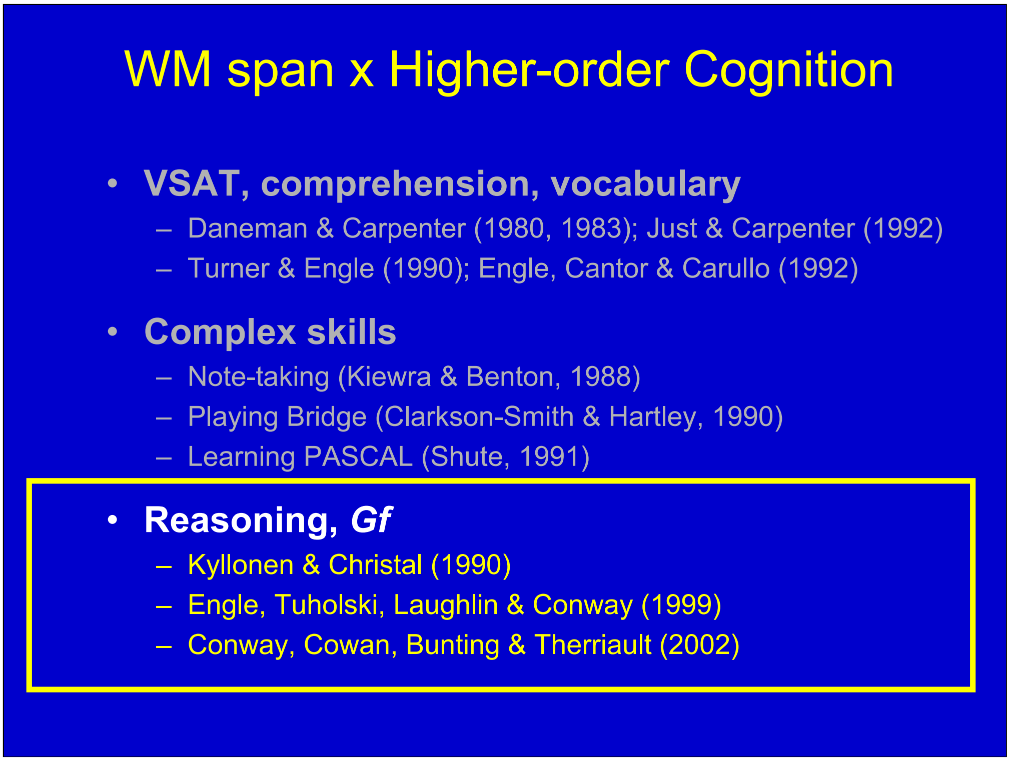
WM span x Higher-order Cognition

- **VSAT, comprehension, vocabulary**
  - Daneman & Carpenter (1980, 1983); Just & Carpenter (1992)
  - Turner & Engle (1990); Engle, Cantor & Carullo (1992)
- **Complex skills**
  - Note-taking (Kiewra & Benton, 1988)
  - Playing Bridge (Clarkson-Smith & Hartley, 1990)
  - Learning PASCAL (Shute, 1991)

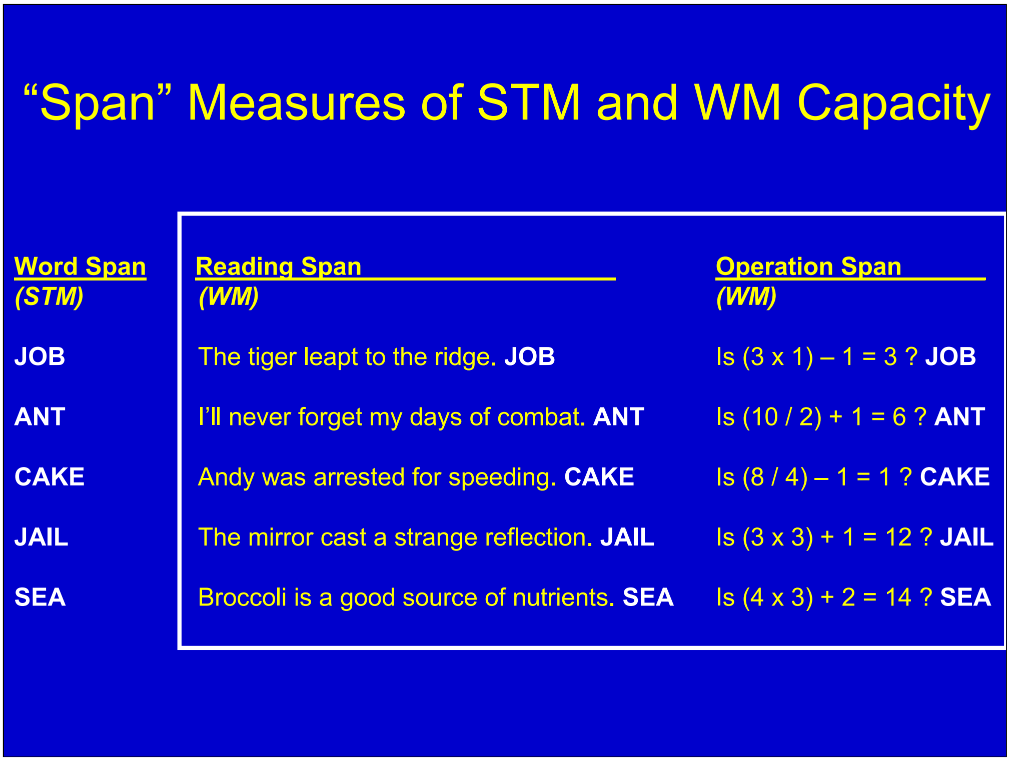
Complex skills such as taking notes in class, playing bridge, and learning computer programming...



And complex reasoning, including on non-verbal tests of general fluid intelligence.



This latter finding is very important, because it indicates the domain-generality of the WM capacity construct. That is, because verbal WM span tasks predict non-verbal, domain-general fluid ability, it suggests that “verbal” WM capacity is not solely a verbal construct.



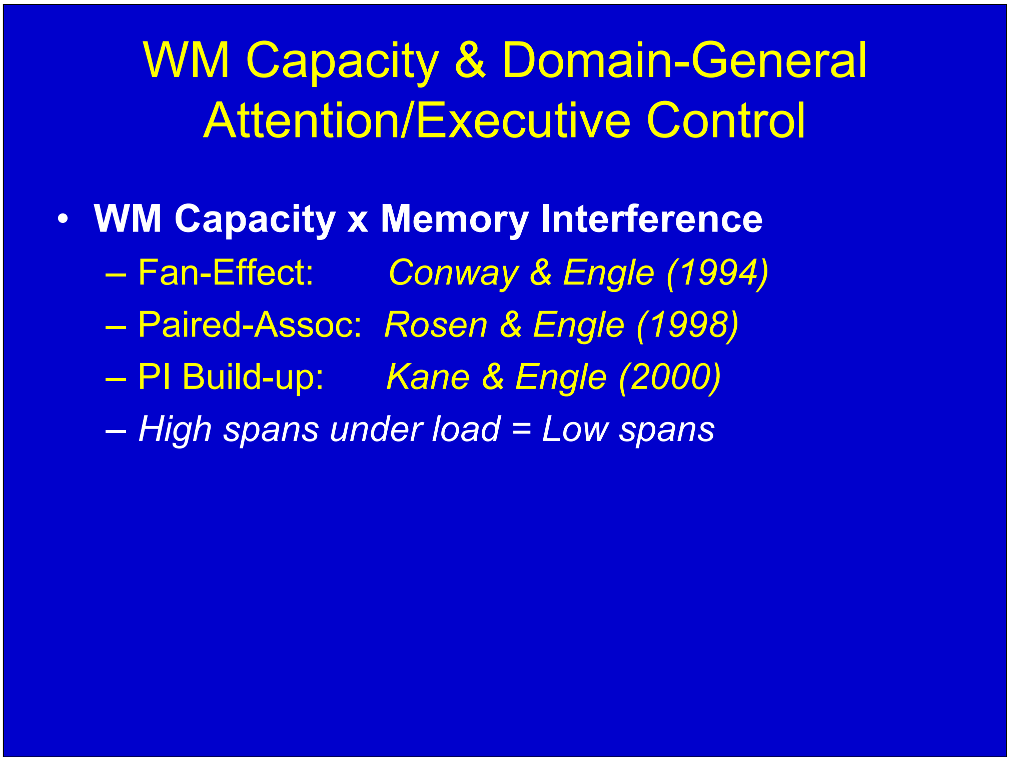
So, WM span tasks are good measures of a domain-general construct that is important to broad aspects of cognitive ability.

Although WM span tasks make similar memory demands to STM tasks, and probably reflect some of the same mechanisms, WM tasks additionally force attention shifts to and from the target items. That is, WM span tasks require maintaining target information in an active, accessible state in the face of interference and distraction. We suggest that these attention demands are critical to WM span’s utility in predicting complex cognition.

WM Capacity & Domain-General Attention/Executive Control

- **WM Capacity x Memory Interference**
  - Fan-Effect: *Conway & Engle (1994)*
  - Paired-Assoc: *Rosen & Engle (1998)*
  - PI Build-up: *Kane & Engle (2000)*

Evidence for our view comes from experimental work demonstrating that low scorers on a verbal WM span task show greater vulnerability to interference than do high scorers.



Moreover, the performance of low-span subjects under interference can be simulated by dividing the attention of high-span subjects, consistent with the idea that attention-control ability separates high from low WM individuals.

WM Capacity & Domain-General Attention/Executive Control

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  - Fan-Effect: *Conway & Engle (1994)*
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  - PI Build-up: *Kane & Engle (2000)*
  - *High spans under load = Low spans*
- **WM Capacity x Low-Level Attention Control**

However, if WM capacity is really an executive-attention construct, then WM differences should extend beyond memory contexts and into “simpler” attention tasks. In fact, they do.

WM Capacity & Domain-General Attention/Executive Control

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  - Fan-Effect: *Conway & Engle (1994)*
  - Paired-Assoc: *Rosen & Engle (1998)*
  - PI Build-up: *Kane & Engle (2000)*
  - *High spans under load = Low spans*

- **WM Capacity x Low-Level Attention Control**
  - Dichotic Listen: *Conway et al. (2001)*

In an extension of the classic "cocktail party" phenomenon, Conway and colleagues found that low spans were 3x more likely than high spans to notice their name spoken in the distractor channel. Low spans were thus less able to block attention to a salient auditory distractor.

WM Capacity & Domain-General Attention/Executive Control

- **WM Capacity x Memory Interference**
  - Fan-Effect: *Conway & Engle (1994)*
  - Paired-Assoc: *Rosen & Engle (1998)*
  - PI Build-up: *Kane & Engle (2000)*
  - *High spans under load = Low spans*

- **WM Capacity x Low-Level Attention Control**
  - Dichotic Listen: *Conway et al. (2001)*
  - Antisaccade: *Kane et al. (2001)*

In an antisaccade task, Kane et al. found that high and low spans performed equally in looking *toward* the appearance of a salient visual stimulus, but low spans were slower and more error prone when required to look *away from* this powerful orienting cue. Again, low spans failed to block a pre-potent, reflexive response in favor of a goal-directed one.

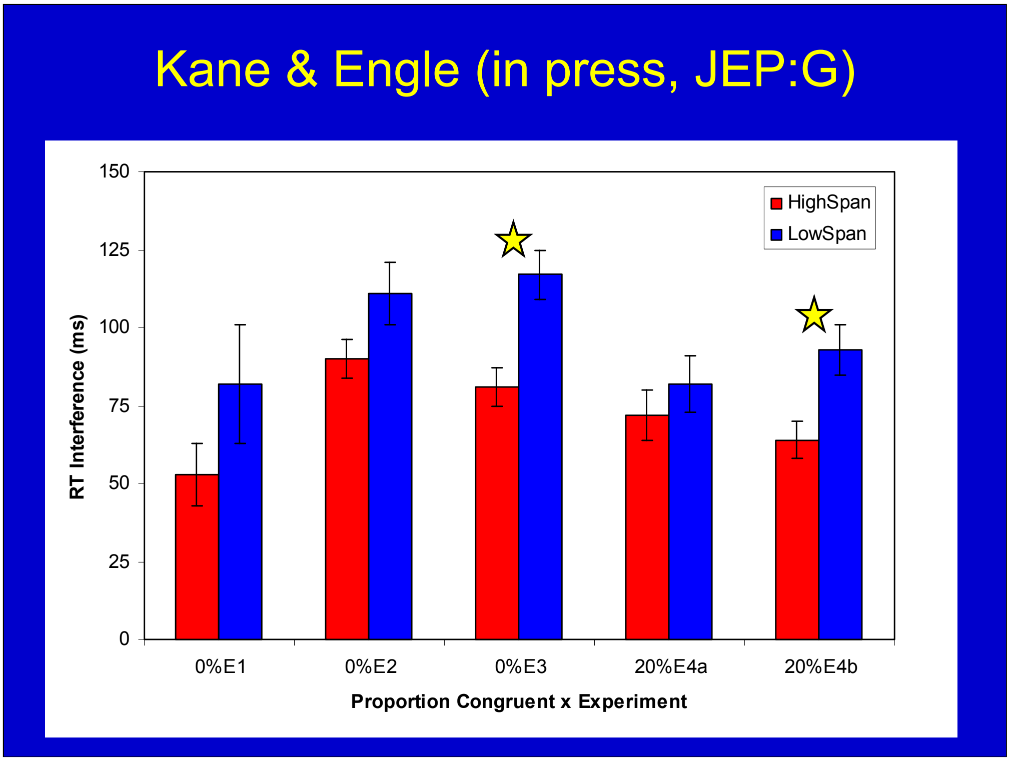
WM Capacity & Domain-General Attention/Executive Control

- **WM Capacity x Memory Interference**
  - Fan-Effect: *Conway & Engle (1994)*
  - Paired-Assoc: *Rosen & Engle (1998)*
  - PI Build-up: *Kane & Engle (2000)*
  - *High spans under load = Low spans*

- **WM Capacity x Low-Level Attention Control**
  - Dichotic Listen: *Conway et al. (2001)*
  - Antisaccade: *Kane et al. (2001)*
  - Stroop: *Kane & Engle (in press)*

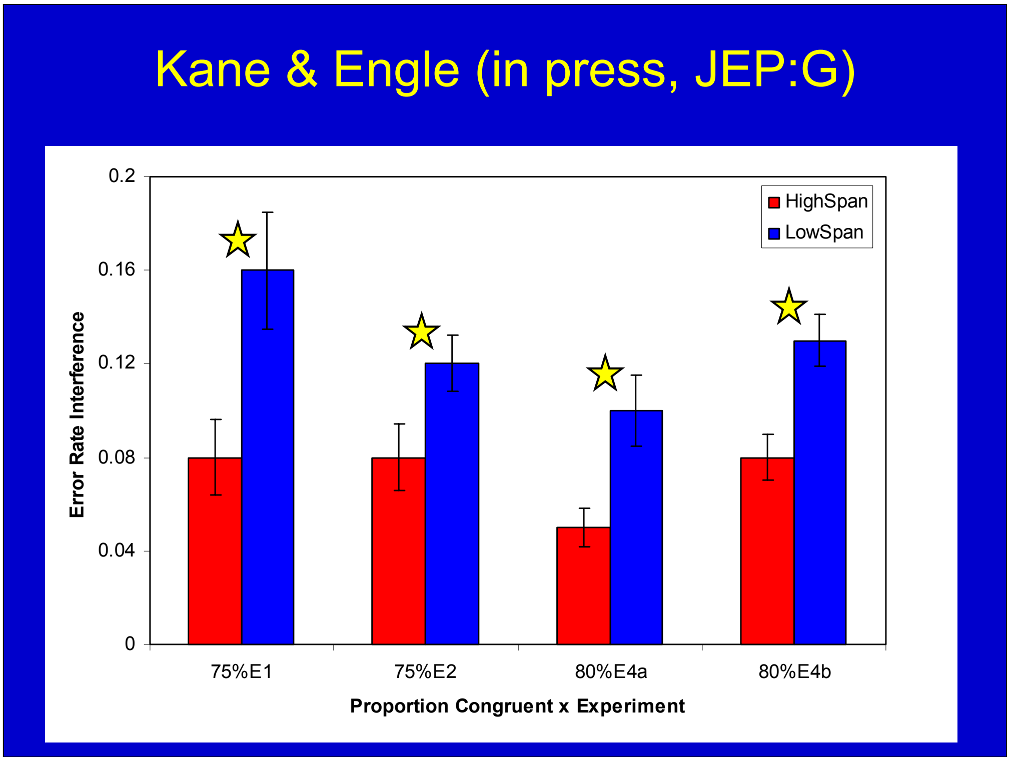
Finally, we have also used the Stroop task to assess the role of active goal maintenance in linking WM capacity to attention control.

In standard conditions, high and low spans saw mostly incongruent Stroop trials, amidst some neutral trials and either a few or no congruent trials, where the color and word matched. Thus, the context reinforced the task goal by presenting lots of conflicting trials. We thought that goal maintenance would be rather unimportant here because the task environment consistently cued the goal of ignoring the word information.



What we found in these conditions was a very modest span difference in RT interference that was only significant in two experiments and required large samples to be detected at all. Thus, when goal maintenance was less critical, span differences were small or absent.

In contrast, when we tested subjects in a version of the Stroop task that put a premium on effective goal maintenance, span differences were robust.



Here we presented subjects with 75 or 80% *congruent* trials, and only a small proportion of incongruent trials. Here, with most words matching their colors, the context no longer reinforced the goal of ignoring the word; successful responding could often be based on word reading, rather than color naming. Thus, accurate responding on the rare incongruent trials, where word and color were in conflict, depended on actively maintaining access to the task goal.

Indeed, low spans showed larger error interference effects here than did high spans, indicating that low spans more often neglected the goal, drifted into word reading, and therefore committed many more errors on incongruent trials.

Domain-General WM Capacity

- **Verbal WM span x Verbal ability**
- **Verbal WM span x Complex skills**
- **Verbal WM span x *Gf***
- **Verbal WM span x Executive/Attention control**

So we now see substantial evidence that WM capacity largely reflects a domain-general construct. Not only do verbal WM span tasks predict verbal ability and complex verbal skills, but they also predict non-verbal general fluid intelligence and low-level attention control and goal neglect.

Domain-General WM Capacity

- **Verbal WM span x Verbal ability**
- **Verbal WM span x Complex skills**
- **Verbal WM span x *Gf***
- **Verbal WM span x Executive/Attention control**

- **Verbal WM span x *Visuo-spatial* WM span?**
- **Verbal WM span x *Visuo-spatial* ability?**
- ***Visuo-spatial* WM span x Verbal ability?**

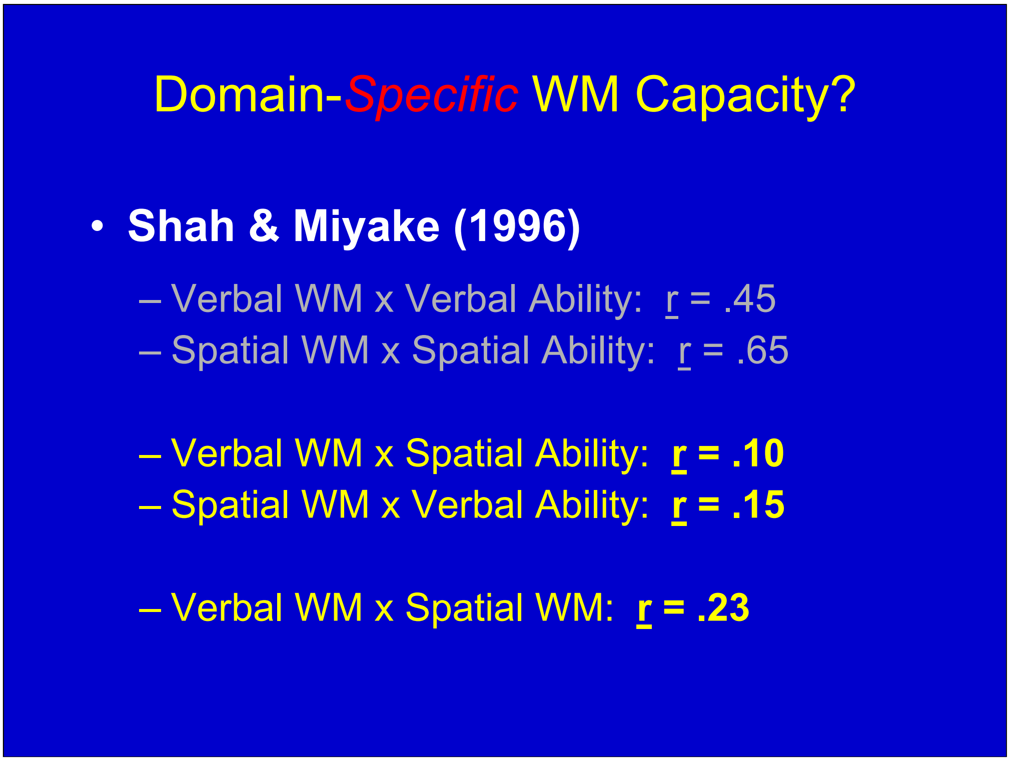
However, we have yet to demonstrate WM capacity's generality across verbal and visuo-spatial domains. At the level of STM (or the slave systems of Baddeley's model), there is lots of evidence for distinct verbal and visuo-spatial rehearsal and storage capacities.

Domain-*Specific* WM Capacity?

- **Shah & Miyake (1996)**
  - Verbal WM x Verbal Ability: **r = .45**
  - Spatial WM x Spatial Ability: **r = .65**

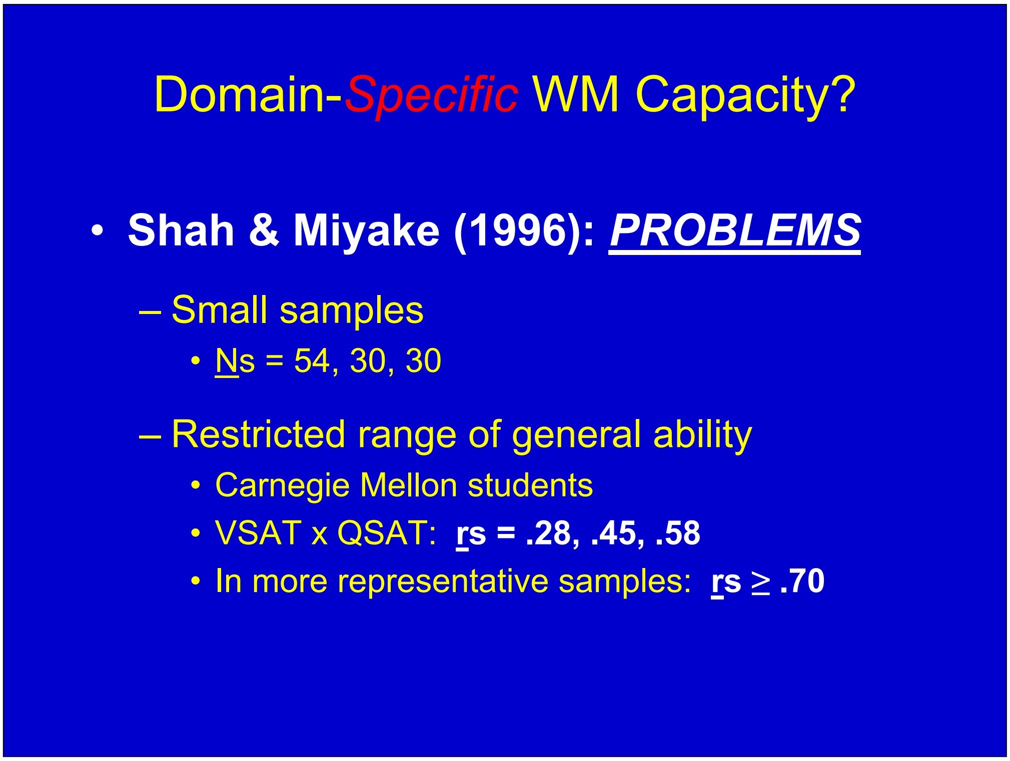
Moreover, a *widely* cited study provides evidence for the domain-specificity of WM capacity.

Shah & Miyake tested subjects in a Reading Span task of verbal WM, and a Rotation Span task of spatial WM. They also tested subjects' broad verbal and spatial abilities. When the stimulus domain matched between memory and ability tests, the correlations between them were strong.



But, when the domains were crossed, the correlations between span and ability were very low, as was the correlation between the two span tasks.

Shah and Miyake interpreted these findings to indicate separable, domain-specific resources for verbal and spatial WM.



However, there are problems with Shah & Miyake's study.

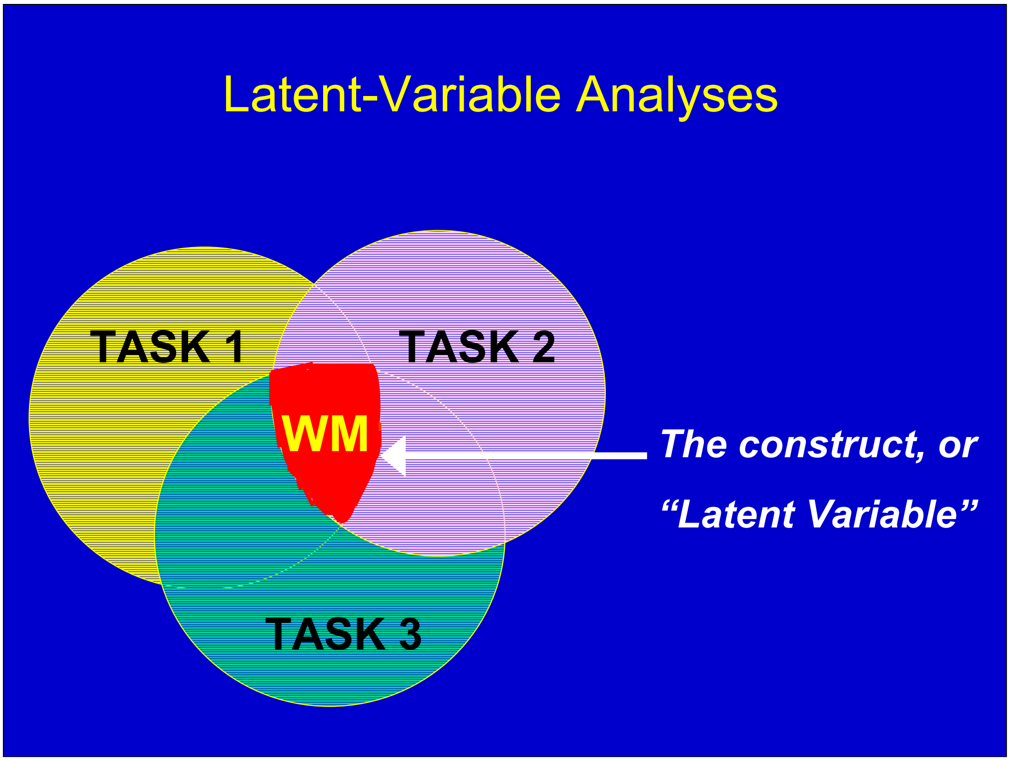
First, they used very small samples for individual-differences work. More importantly, though, they tested a very restricted range of ability in their subjects. Most were Carnegie Mellon students, and so most had high *general* cognitive ability. When samples are drawn from such a narrow ability range, any observed variation must result from *domain-specific* skills, knowledge or strategy.

We therefore suggest that Shah & Miyake underestimated the domain generality of these measures and constructs, and if they had tested a broader slice of humanity, the generality would be clearer.

Domain-*Specific* WM Capacity?

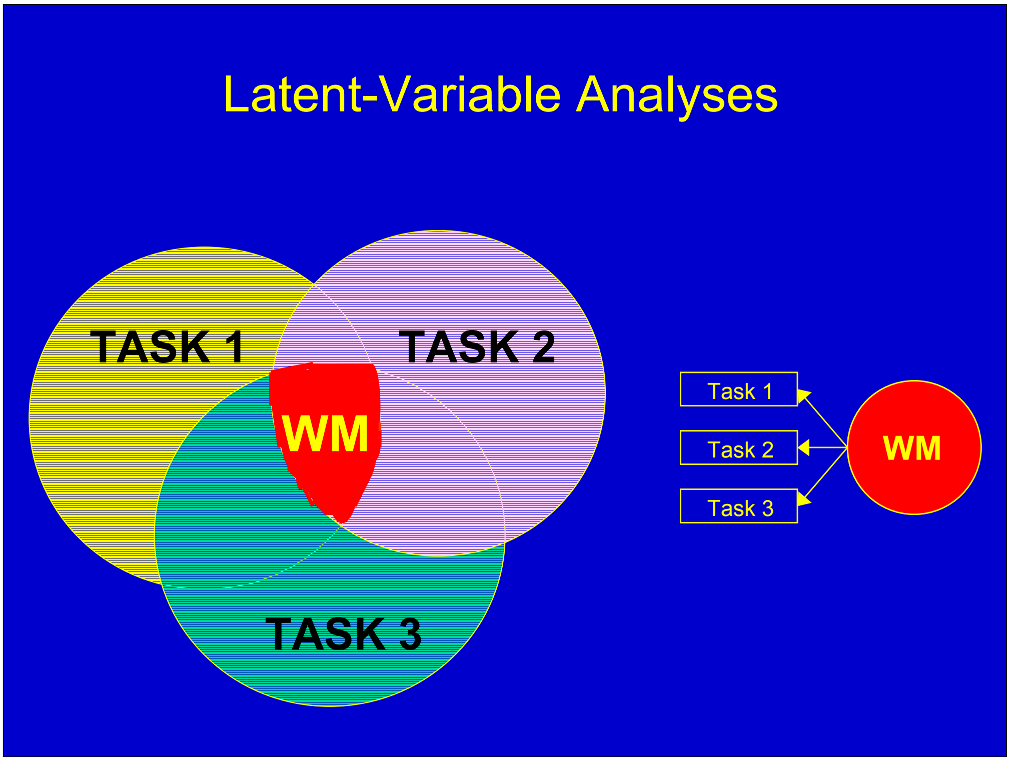
- **Shah & Miyake (1996): *PROBLEMS***
  - Small samples
    - Ns = 54, 30, 30
  - Restricted range of general ability
    - Carnegie Mellon students
    - VSAT x QSAT: rs = .28, .45, .58
    - In more representative samples: rs $\geq$ .70
  - 1 indicator per construct

Finally, Shah & Miyake used only one measure for each memory construct, and so contributions of measurement error to their low correlations cannot be determined.

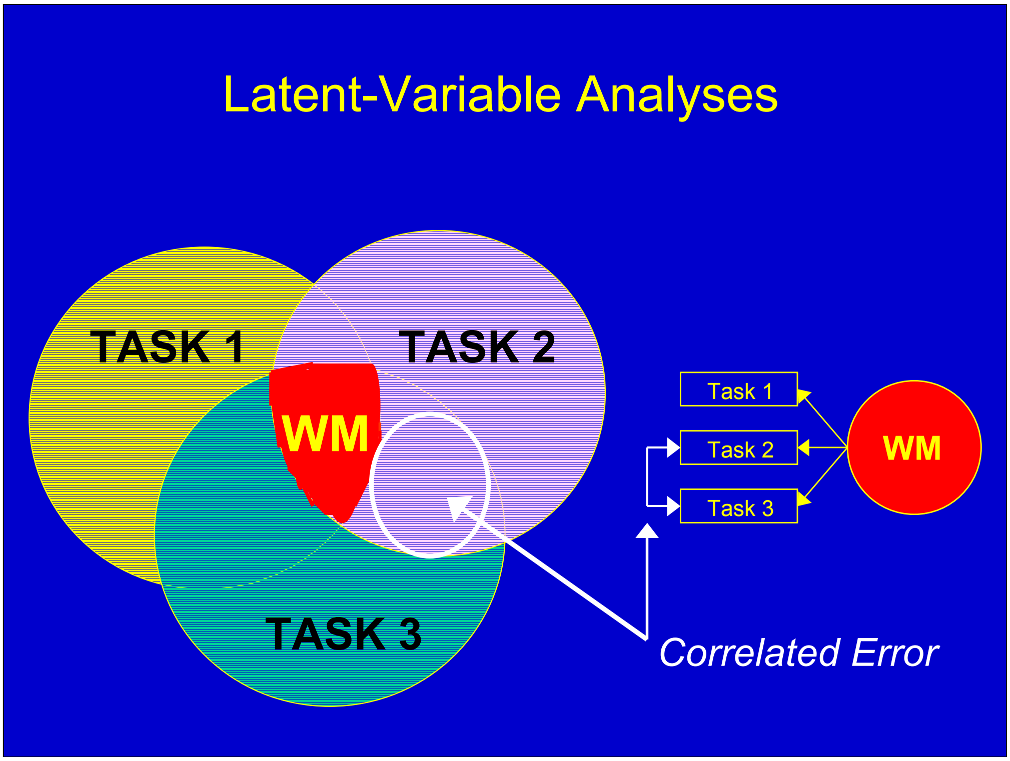


Because all cognitive tasks are imperfect measures of their underlying constructs, a better strategy is to use multiple measures of each construct. With these multiple measures in hand, one can then use latent-variable methods to extract the variance that's shared among these tasks, yielding a purer measure of the construct of interest, free of the measurement error and task-specific variance associated with any one of the tasks.

This is the strategy we used in the present investigation of verbal versus spatial WM.



As is conventional, our data figures will represent latent variables, or the core constructs, with circles, and the individual tasks from which the latents are derived with boxes.



Correlated error, representing the variance shared among a only subset of the measures for a construct, will be represented by arrows connecting the boxes for the correlated tasks. For example, one would expect correlated error among two WM tasks using word stimuli when the third task used numerical stimuli. Word-related processing won't be represented in the variance common to all three tasks, and so it will be reflected as correlated error.

Present Study

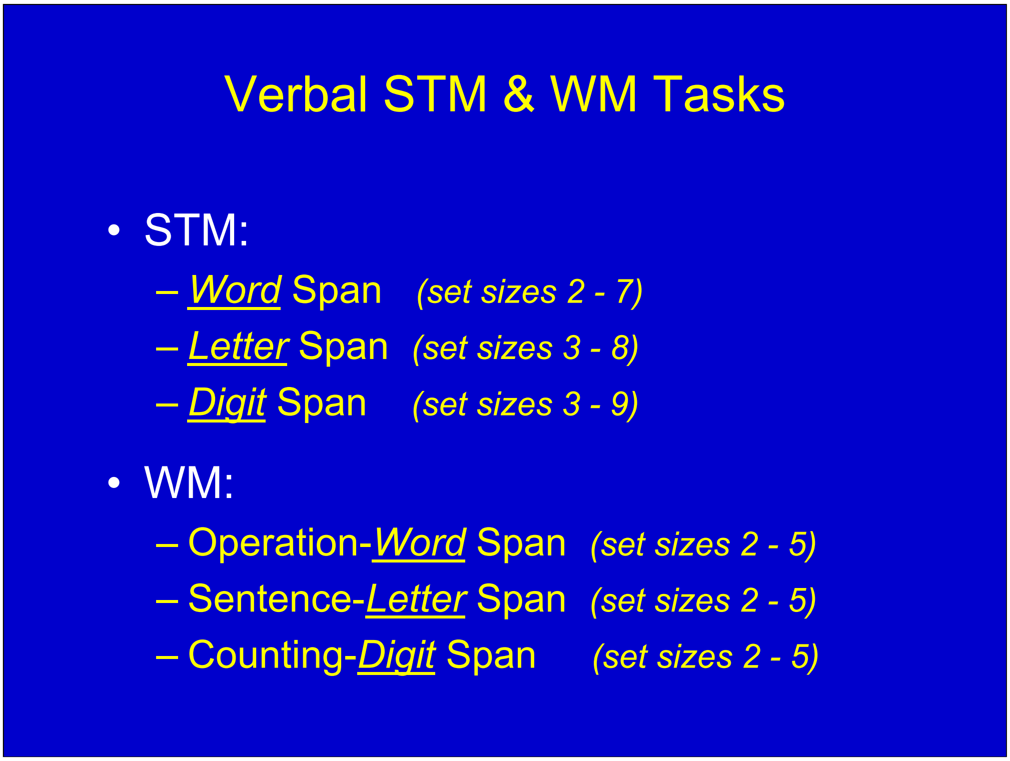
Kane, Hambrick, Tuholski, Wilhelm, Payne & Engle, 2002

- **N = 236**
  - GA Tech, UNCG, SIUE; Atlanta & G'boro community
- **Verbal & Visuo-Spatial STM & WM span**
  - **3** indicators of each
- **Verbal Reasoning, Spatial Visualization, *Gf***
  - **5** indicators each of Verbal & Spatial
  - **3** indicators of *Gf* (Matrix Reasoning)

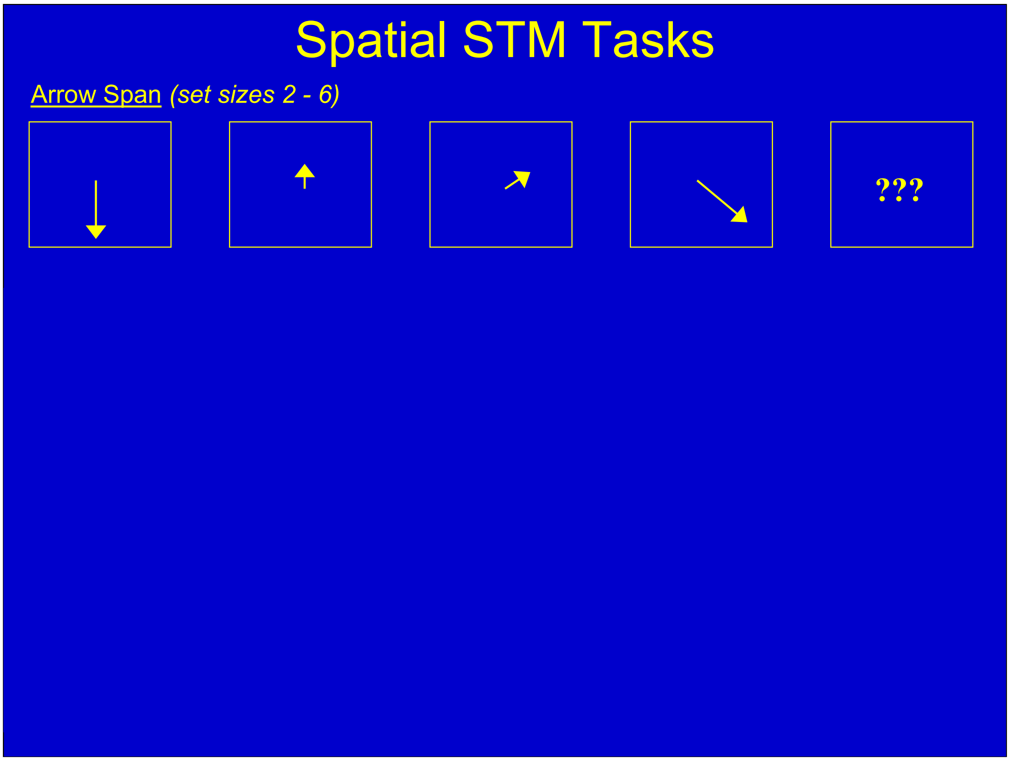
We tested over 200 subjects from different walks of life: Students from selective and comprehensive state universities, and community dwellers from two metro areas.

All subjects completed tests of verbal STM, verbal WM, spatial STM, and spatial WM. Stimuli were presented visually and responses were written.

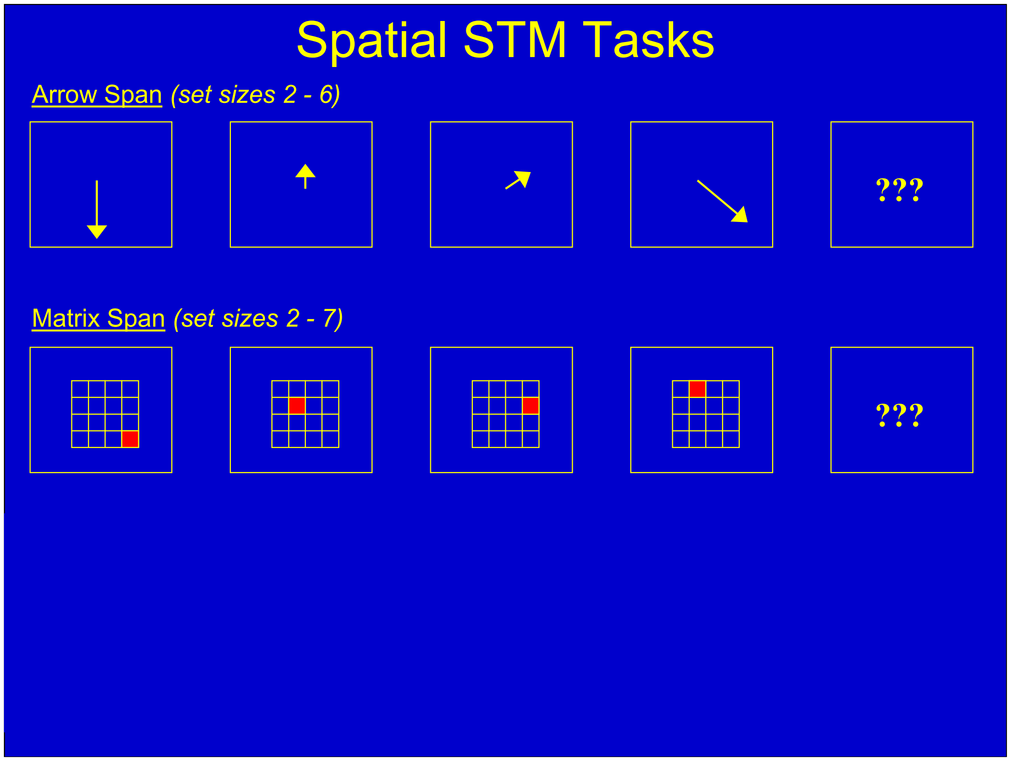
We used these memory measures to predict performance on measures of verbal reasoning, spatial visualization and general fluid intelligence.



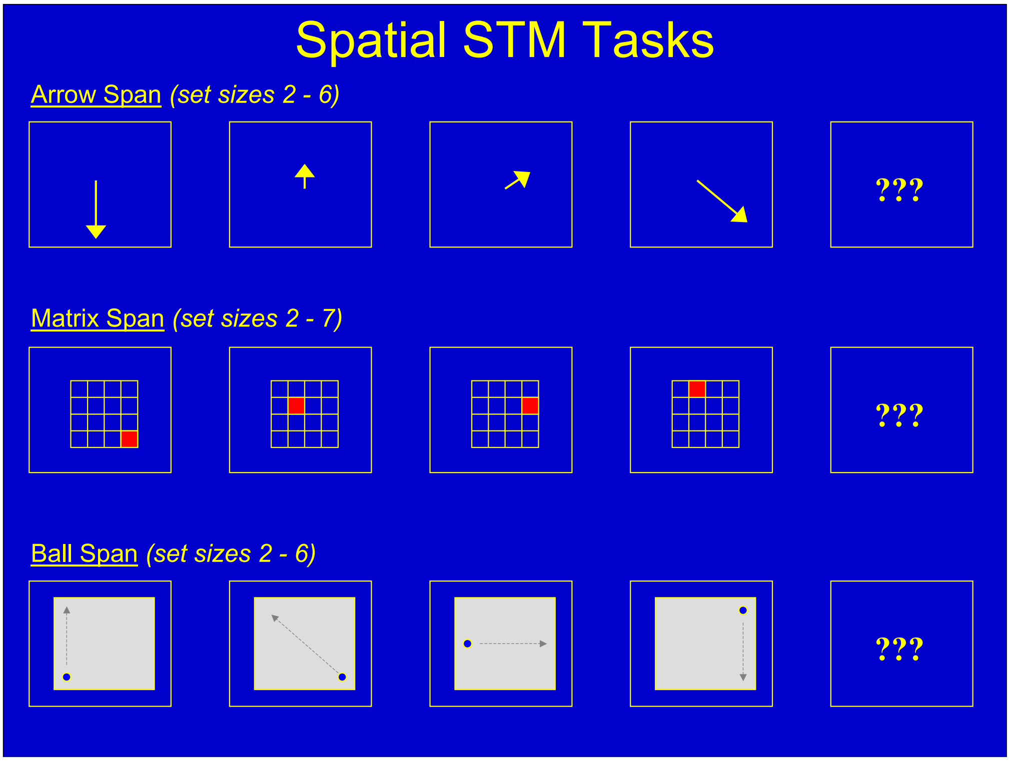
All the verbal memory tasks required subjects to recall sequences of words, letters, or digits. We created WM versions of these tasks by adding an unrelated verbal processing component such as verifying equations, judging sentences, and counting dots.



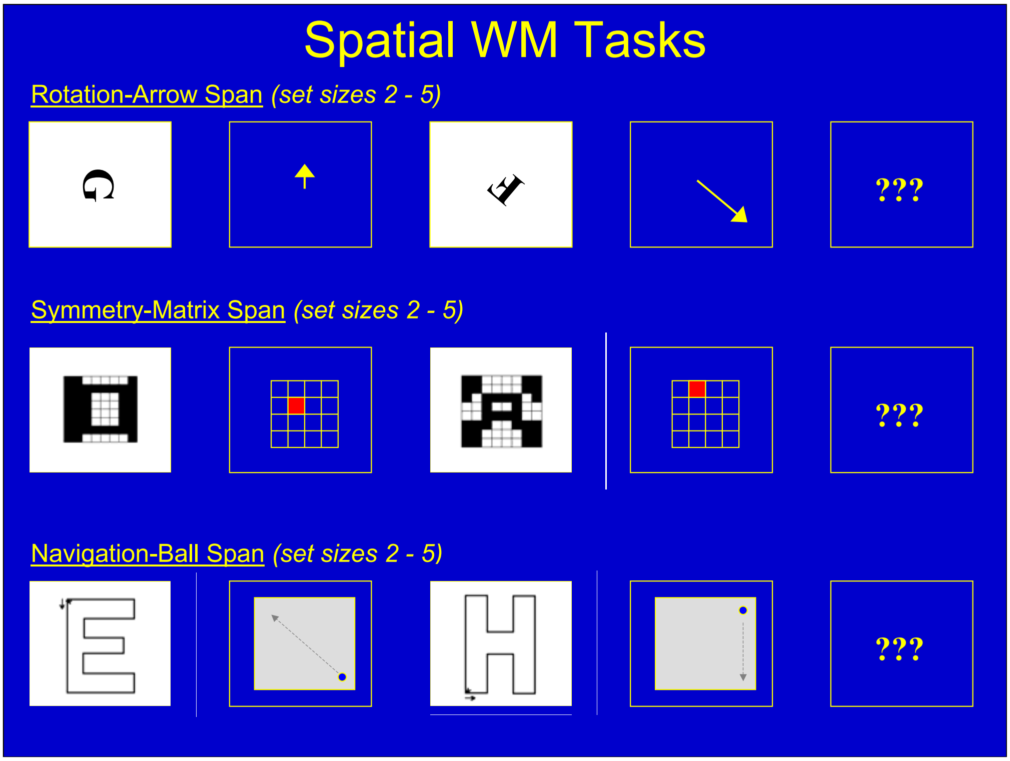
The spatial STM tasks all required subjects to reproduce sequences of visuo-spatial stimuli. The Arrow Span task presented short or long arrows pointing in one of 8 directions from center. At recall, subjects drew the sequence of arrows in correct serial order.



The Matrix Span task presented a sequence of red squares appearing in a 4 x 4 matrix. At recall, subjects marked the locations of the red squares in correct serial order.



The Ball Span task presented a sequence of balls appearing in one of 8 locations around the perimeter of a box, each moving to the opposite side of the box over the course of 1 second. At recall, subjects drew the sequence of ball paths in correct serial order.



To create WM versions of these tasks, we interleaved an interfering spatial-processing task. The Rotation-Arrow task required subjects to mentally rotate letters and decide whether they were normal or mirror-reversed. Subjects recalled the sequence of arrows.

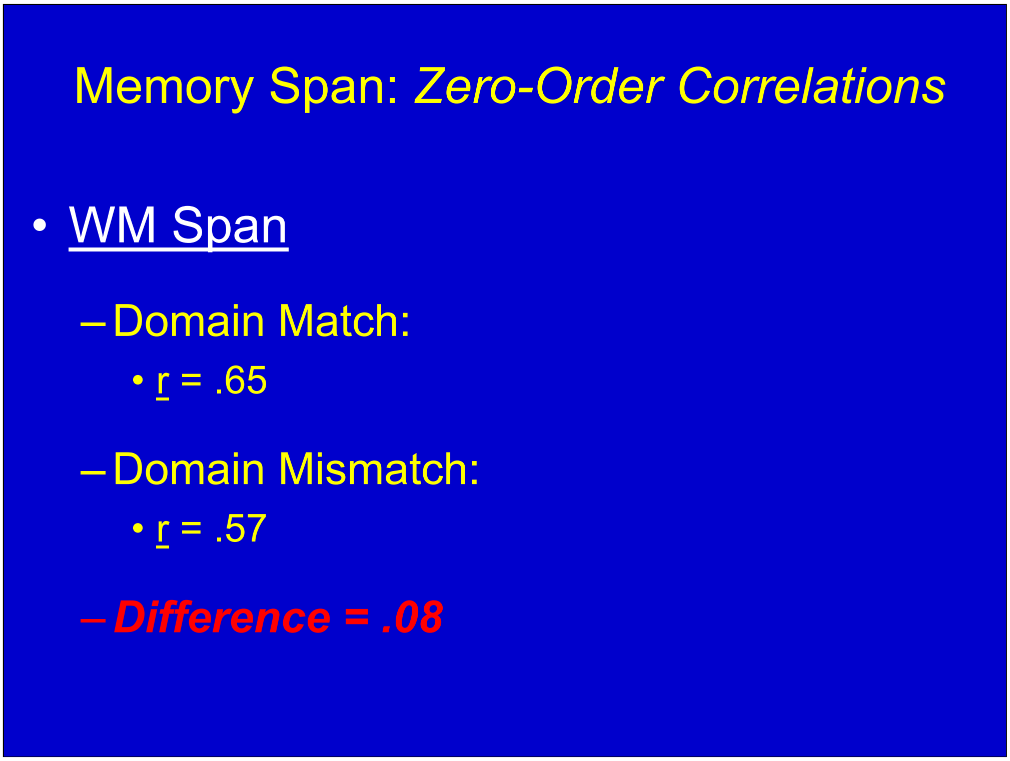
The Symmetry-Matrix task required subjects to judge whether a black & white pattern was symmetrical along its vertical axis. Subjects recalled the sequence of red-square locations.

The Navigation-Ball task presented subjects with a version of the Brooks task. Subjects saw a block letter E or H with a star in one corner and an arrow pointing along one edge. Subjects mentally navigated along the corners of the letter and said aloud whether each corner, in turn, was at the extreme top or bottom of the letter, or not. Subjects recalled the sequence of ball paths.

Gf / Reasoning Tasks

- **Verbal Reasoning**
  - **Comprehension, Analogies, Syllogisms**
- **Spatial Visualization**
  - **Mental paper-folding, 3-D rotation**
- ***Gf*** **/ “Decontextualized” Reasoning**
  - **Figural matrix reasoning**

On the reasoning side, we included standardized verbal, visuo-spatial, and fluid intelligence tests. Verbal tasks included reading comprehension, analogies, syllogisms, and remote-associates tasks. Spatial tasks involved mental paper folding and rotation of 3-dimensional forms. Domain-free tests of fluid intelligence were matrix completion tasks with figural stimuli, such as the Ravens Progressive Matrices.



As a preliminary, informal test of the domain-generality of WM capacity, we examined the mean correlations among the WM tasks that matched versus mismatched in domain. As you can see, the mean correlation for matches was quite high, and the correlation for mismatches was only slightly lower.

Memory Span: *Zero-Order Correlations*

- WM Span
  - Domain Match:
    - r = .65
  - Domain Mismatch:
    - r = .57
  - ***Difference = .08***
- STM Span
  - Domain Match:
    - r = .68
  - Domain Mismatch:
    - r = .42
  - ***Difference = .26***

Correlations among domain-matching STM tasks were also high, but correlations among the mismatching tasks were much lower. Thus, verbal and spatial STM appear to be more distinguishable than are verbal and spatial WM.

EFA: *Principal-Axis, Promax Rotation*

Measure	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
OperSpan	-.07	**.73**	.25	.08	-.21	.08
ReadSpan	.00	**.68**	.22	.05	-.18	.09
CounSpan	-.10	**.76**	.06	-.05	.04	-.05
NavgSpan	.18	**.88**	-.17	-.13	.05	-.05
SymmSpan	.07	**.54**	.04	.05	**.33**	-.11
RotaSpan	.03	**.65**	-.10	.06	.28	.01
WordSpan	-.10	.03	**.73**	.06	.07	.08
LettSpan	.13	-.09	**.89**	-.06	.16	-.07
DigtSpan	-.03	.06	**.78**	-.03	.06	.01
BallSpan	.12	.16	.08	.02	**.51**	.04
ArroSpan	-.04	.23	-.00	.03	**.51**	.26
MatxSpan	.10	.04	.15	.00	**.69**	-.05
Inference	-.05	-.09	.06	**.76**	.23	-.07
Analogy	.07	-.05	-.07	**.70**	-.01	.22
ReadComp	.03	.07	-.04	**.87**	-.03	-.05
RemoAsso	.12	-.09	.06	.22	-.21	**.40**
Syllogsm	**.51**	-.06	.17	.22	-.21	-.01
SpacRela	**.72**	.00	-.10	.03	.06	.17
RotaBlox	**.75**	.06	-.04	-.04	-.01	.02
SurfDevp	**.65**	-.01	.04	-.01	.01	.18
FormBord	**.79**	.10	-.04	.12	.08	-.23
PaprFold	**.79**	-.05	.07	-.09	.04	.05
RAPM	**.30**	-.04	-.09	-.02	.12	**.54**
WASI	.19	-.05	.05	.04	.15	**.47**
BETAIII	.07	.06	.03	-.03	.06	**.66**
% Variance	*.45*	*.10*	*.07*	*.04*	*.03*	*.03*

We next conducted an exploratory factor analysis on all of our tasks, to see whether each task loaded consistently with its putative construct. Most importantly, *all 6* WM tasks, the verbal and visuo-spatial, loaded onto a single common factor, another indication of the domain generality of WM capacity.

EFA: *Principal-Axis, Promax Rotation*

	Measure	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
	OperSpan	-.07	**.73**	.25	.08	-.21	.08
	ReadSpan	.00	**.68**	.22	.05	-.18	.09
	CounSpan	-.10	**.76**	.06	-.05	.04	-.05
	NavgSpan	.18	**.88**	-.17	-.13	.05	-.05
	SymmSpan	.07	**.54**	.04	.05	**.33**	-.11
	RotaSpan	.03	**.65**	-.10	.06	.28	.01
	WordSpan	-.10	.03	**.73**	.06	.07	.08
V	**LettSpan**	.13	-.09	**.89**	-.06	.16	-.07
	DigtSpan	-.03	.06	**.78**	-.03	.06	.01
	BallSpan	.12	.16	.08	.02	**.51**	.04
S	**ArroSpan**	-.04	.23	-.00	.03	**.51**	.26
	MatxSpan	.10	.04	.15	.00	**.69**	-.05
	Inference	-.05	-.09	.06	**.76**	.23	-.07
	Analogy	.07	-.05	-.07	**.70**	-.01	.22
	ReadComp	.03	.07	-.04	**.87**	-.03	-.05
	RemoAsso	.12	-.09	.06	.22	-.21	**.40**
	Syllogsm	**.51**	-.06	.17	.22	-.21	-.01
	SpacRela	**.72**	.00	-.10	.03	.06	.17
	RotaBlox	**.75**	.06	-.04	-.04	-.01	.02
	SurfDevp	**.65**	-.01	.04	-.01	.01	.18
	FormBord	**.79**	.10	-.04	.12	.08	-.23
	PaprFold	**.79**	-.05	.07	-.09	.04	.05
	RAPM	**.30**	-.04	-.09	-.02	.12	**.54**
	WASI	.19	-.05	.05	.04	.15	**.47**
	BETAIII	.07	.06	.03	-.03	.06	**.66**
	% Variance	*.45*	*.10*	*.07*	*.04*	*.03*	*.03*

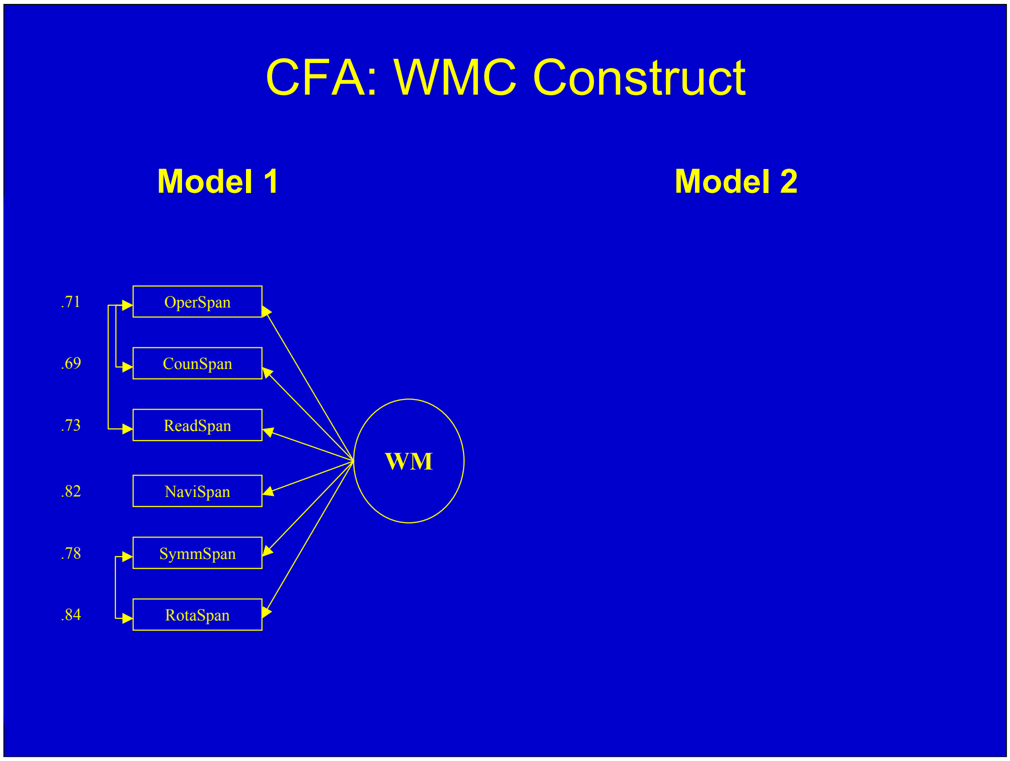
Note, in contrast, that *two* STM factors emerged, split along stimulus-domain lines. The verbal and spatial tasks loaded quite unambiguously on separate factors.

CFA: WMC Construct

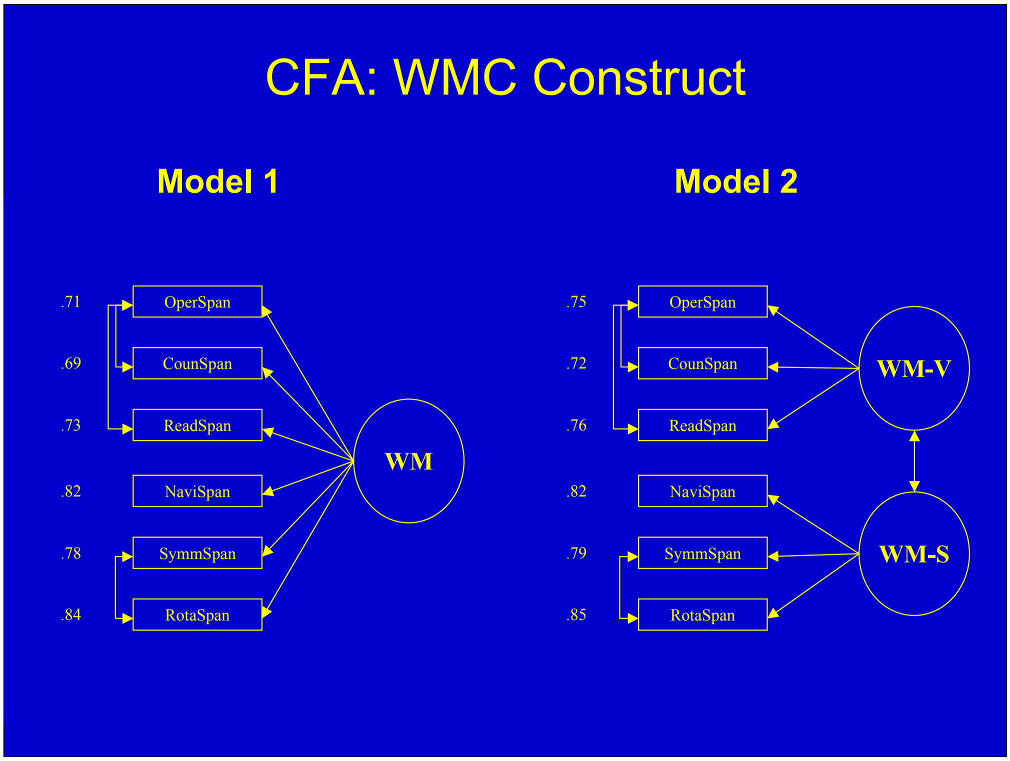
Model 1

Model 2

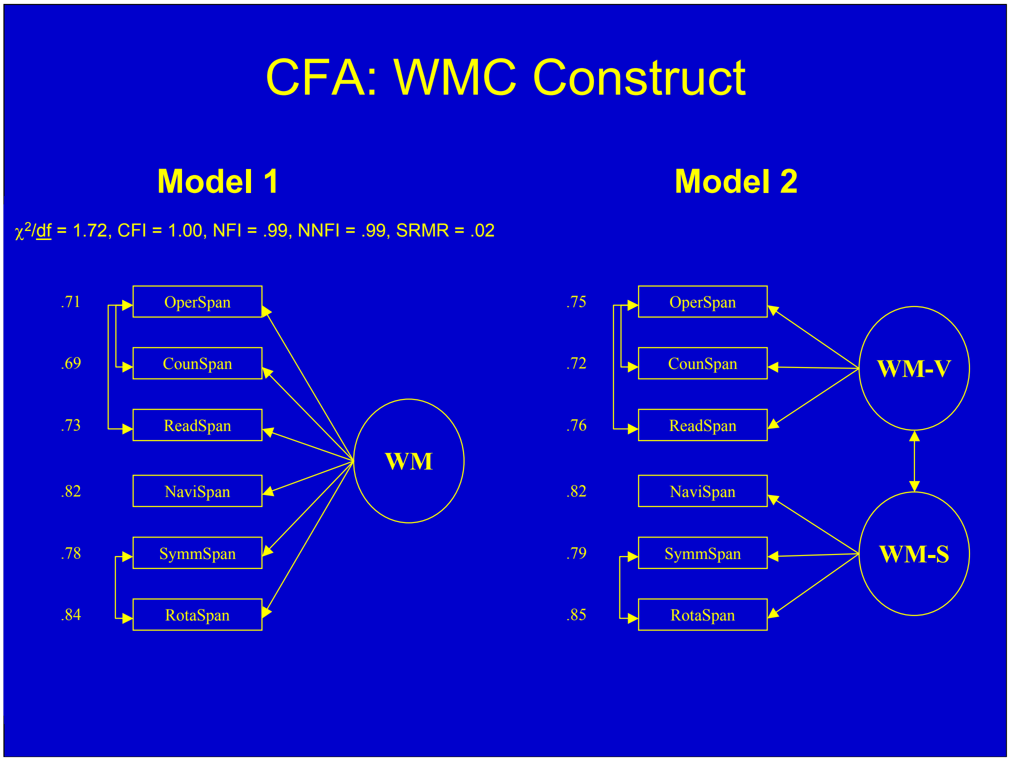
Our main test of the generality of WM capacity was a series of confirmatory factor analyses. Here we statistically compared the relative fits of two models for the data...



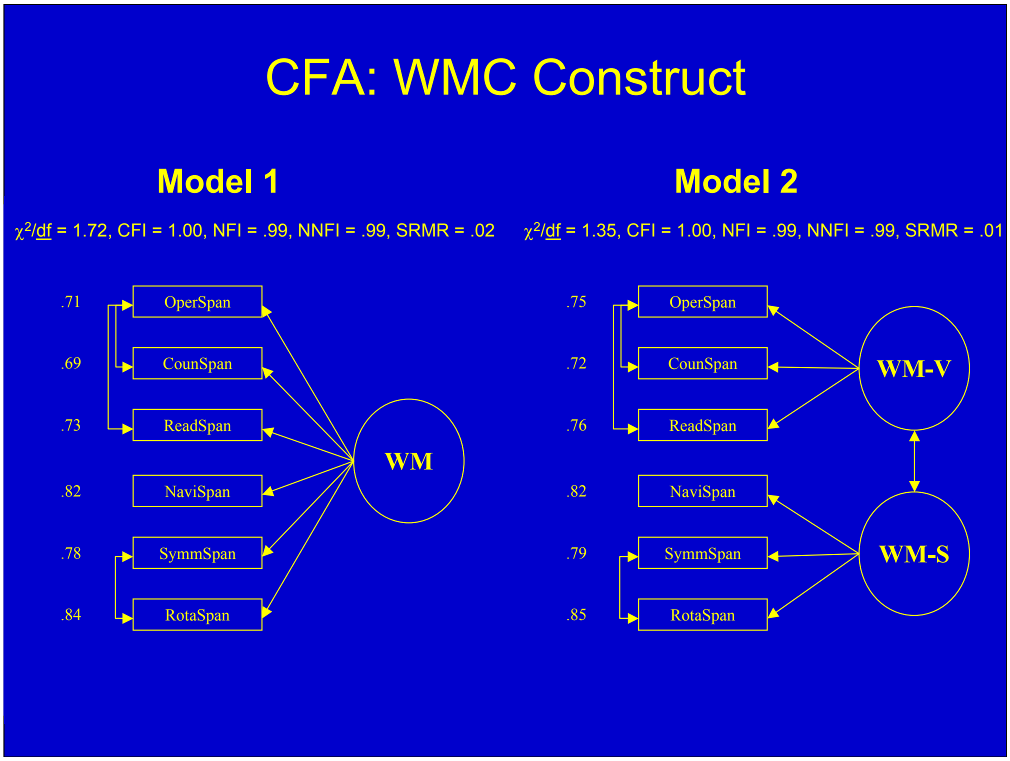
... A single WM factor comprised of all 6 tasks…



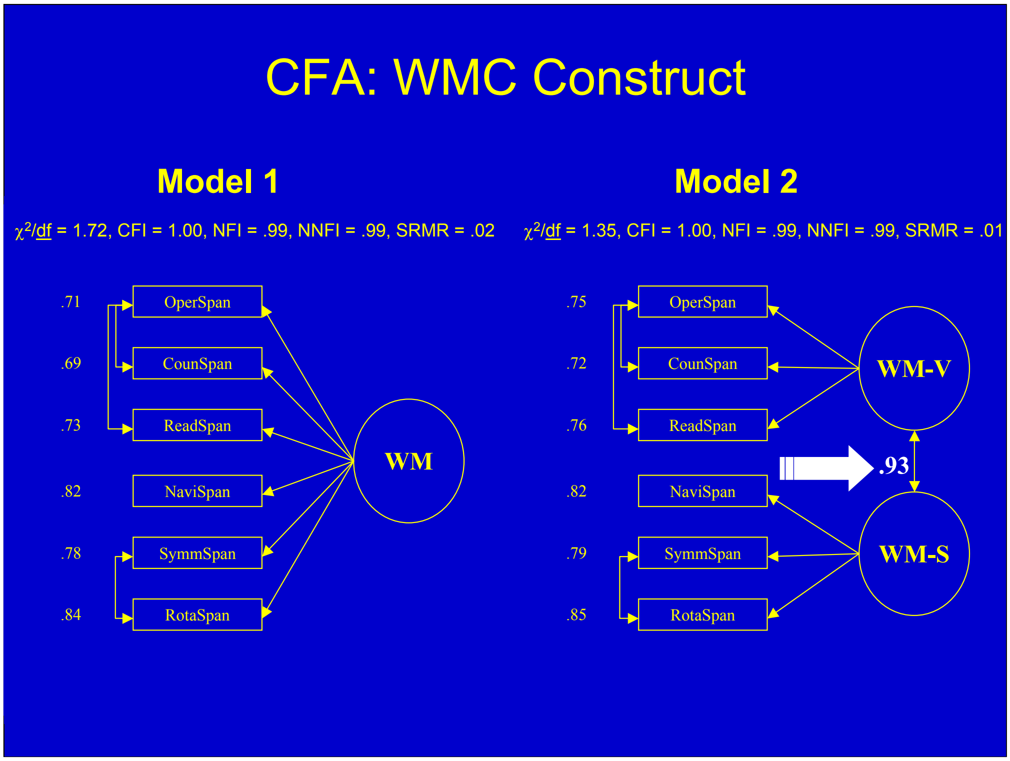
... Versus a two-factor model with separate but correlated verbal and spatial WMs.



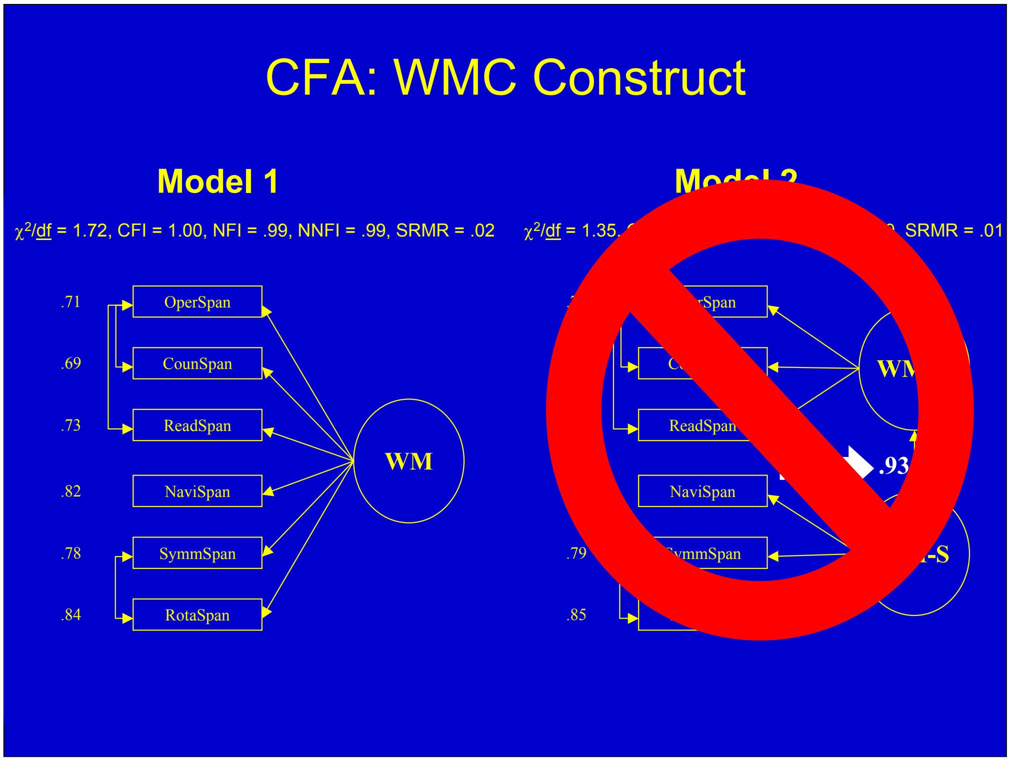
In fact, both models provided good fits to the data…



…And, critically, the two-factor model did <u>*not*</u> significantly improve the fit over the single-factor model.



This isn't too surprising, given that the correlation between the verbal and spatial WM factors was .93.



At least among the verbal and spatial tasks we studied, then, WM capacity may be considered a domain-general construct.

Latent Variable Studies: Verbal x Visuo-spatial WM

Unitary WM

- Ackerman et al. (in press)
- Kyllonen (1993)
- Law et al. (1995)
- Oberauer et al. (in press)
- Salthouse (1995)
- Swanson (1996)

Our findings are consistent with other recent work using latent-variable procedures with verbal and visuo-spatial WM tasks. Several studies have found a single unitary factor to account for the data.

Latent Variable Studies: Verbal x Visuo-spatial WM

Unitary WM

- Ackerman et al. (in press)
- Kyllonen (1993)
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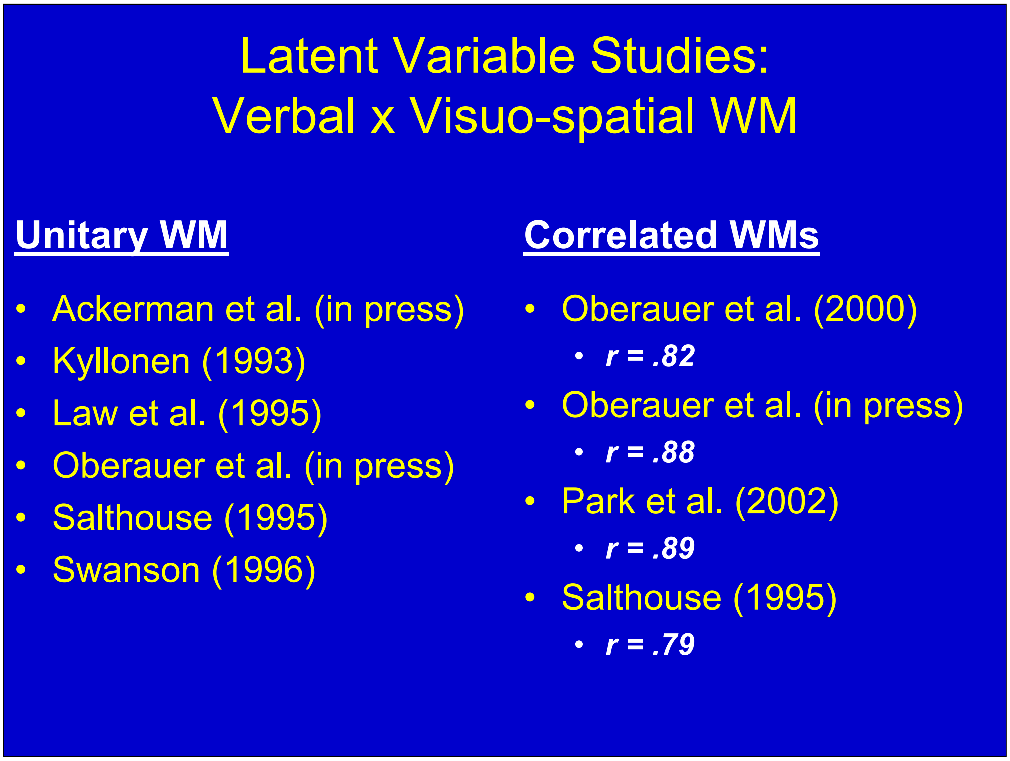
- Oberauer et al. (in press)
- Salthouse (1995)
- Swanson (1996)

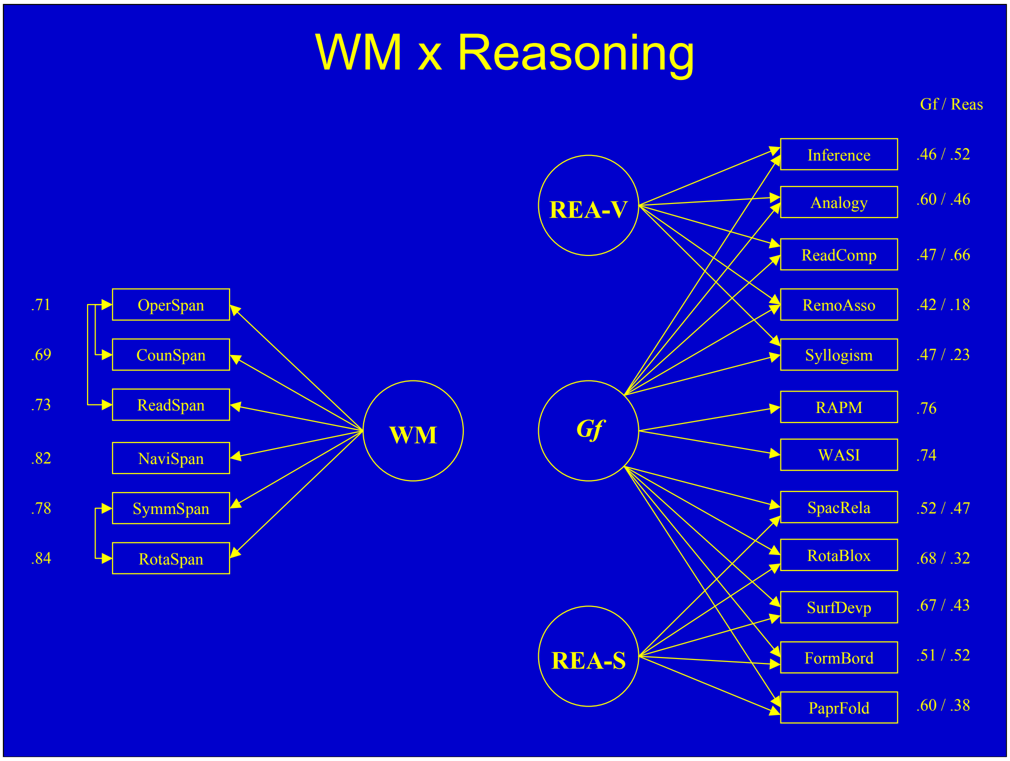
Correlated WMs

- Oberauer et al. (2000)
- Oberauer et al. (in press)
- Park et al. (2002)
- Salthouse (1995)

And, while other studies have found verbal and spatial WM capacity to be separable...

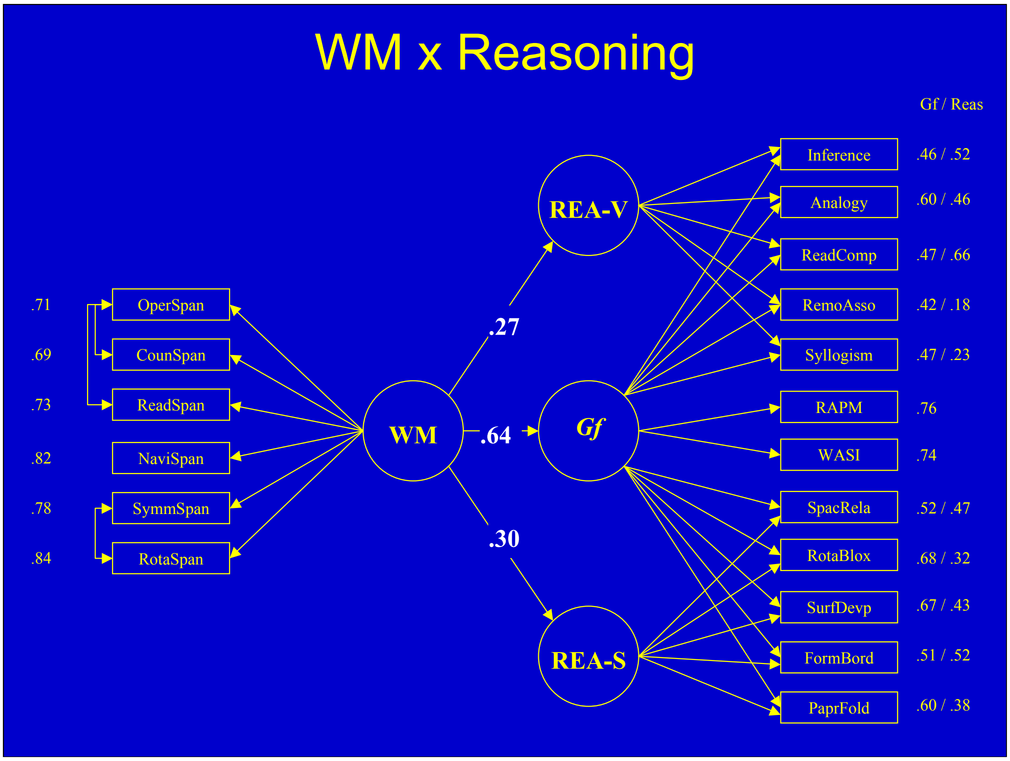


The correlations between them are very high, indicating that, at the very least, verbal and visuo-spatial WM share most of their variance. These findings are obviously inconsistent with a strong, domain-specific view of WM capacity.



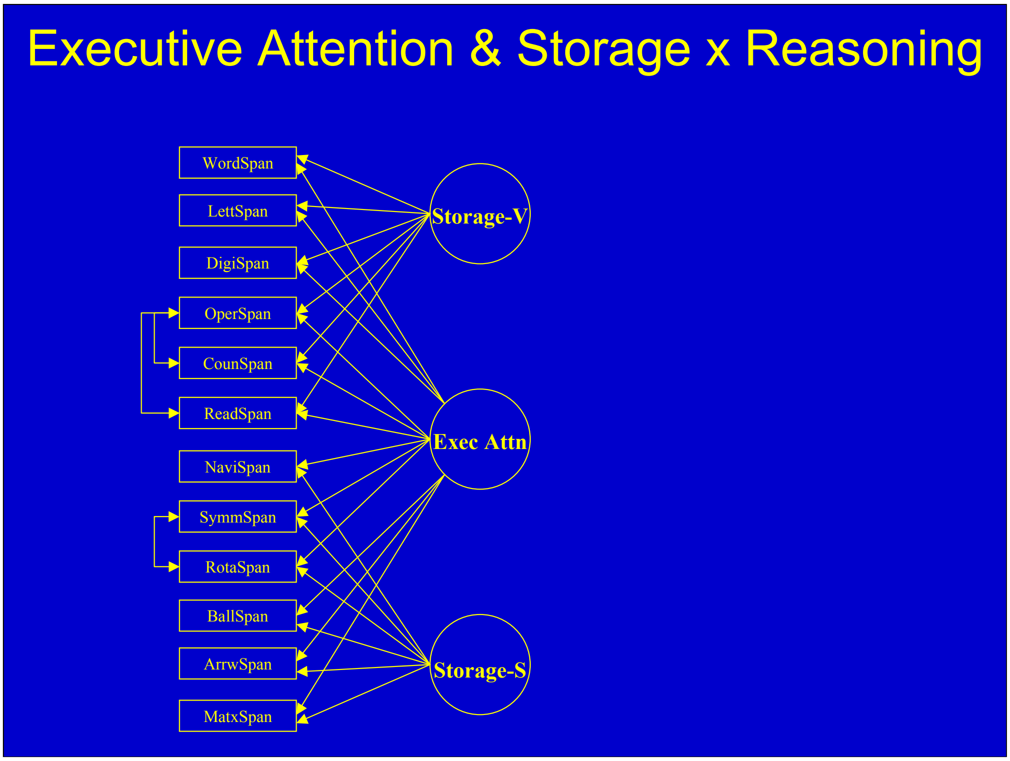
We next explored how well the unitary WM construct predicted general intelligence and domain-specific reasoning. To do so, we modeled the reasoning tasks using a nested structure. All tasks loaded onto a common factor, representing the variance shared across all the verbal, spatial, and matrix tasks. We labeled this common factor, *Gf*.

In addition, all the verbal tasks loaded onto a residual, domain-specific verbal reasoning factor, representing the variance shared by the verbal tasks that was NOT shared by the other tasks. All the spatial tasks loaded onto a residual, domain-specific spatial reasoning factor, representing the variance shared by the spatial tasks that was NOT shared by the other tasks.



Consistent with recent studies using rather different tasks, the correlation between the WM and *Gf* factors was substantial, at about .60. Thus, WM and *Gf* were closely related to one another.

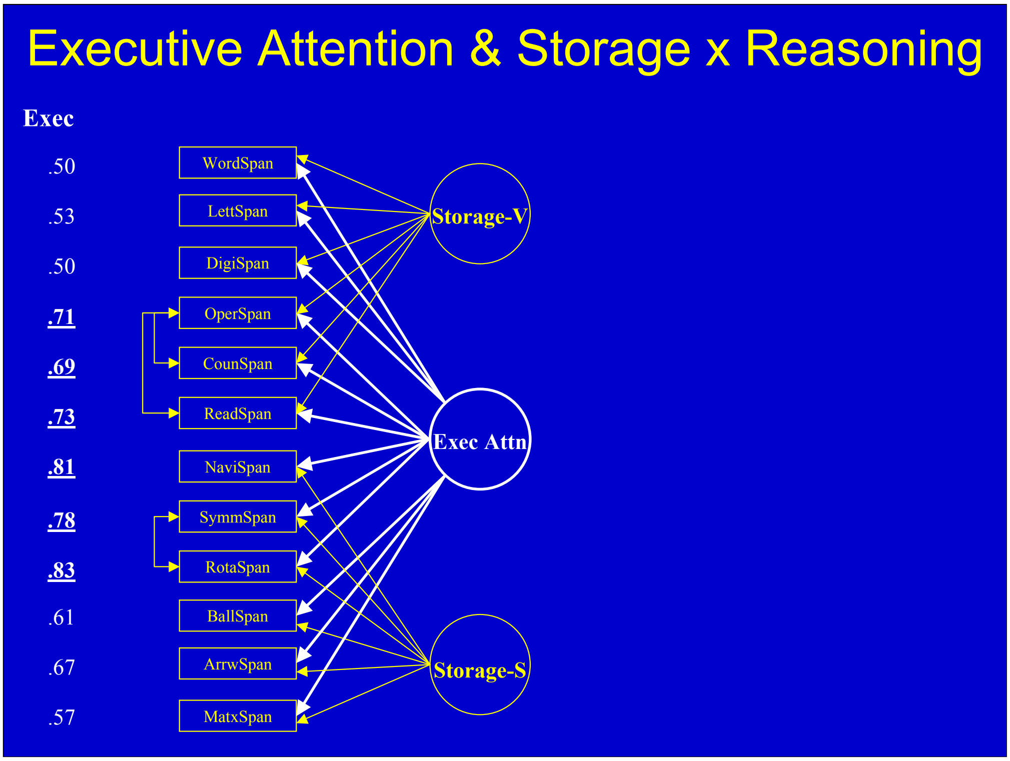
Additionally, the WM factor had significant, and equivalent, correlations with the two domain-specific reasoning factors. So, in addition to predicting general fluid intelligence, WM capacity is related to more domain-specific processes in verbal and visuo-spatial thinking.



In our next set of analyses we attempted to bring STM into the picture, and to examine the predictive power of the executive versus storage components of memory span tasks. Here we assumed that no span task is a pure measure of domain-specific storage or domain-general attention control. Instead, both WM and STM span reflect storage and executive attention to varying degrees.

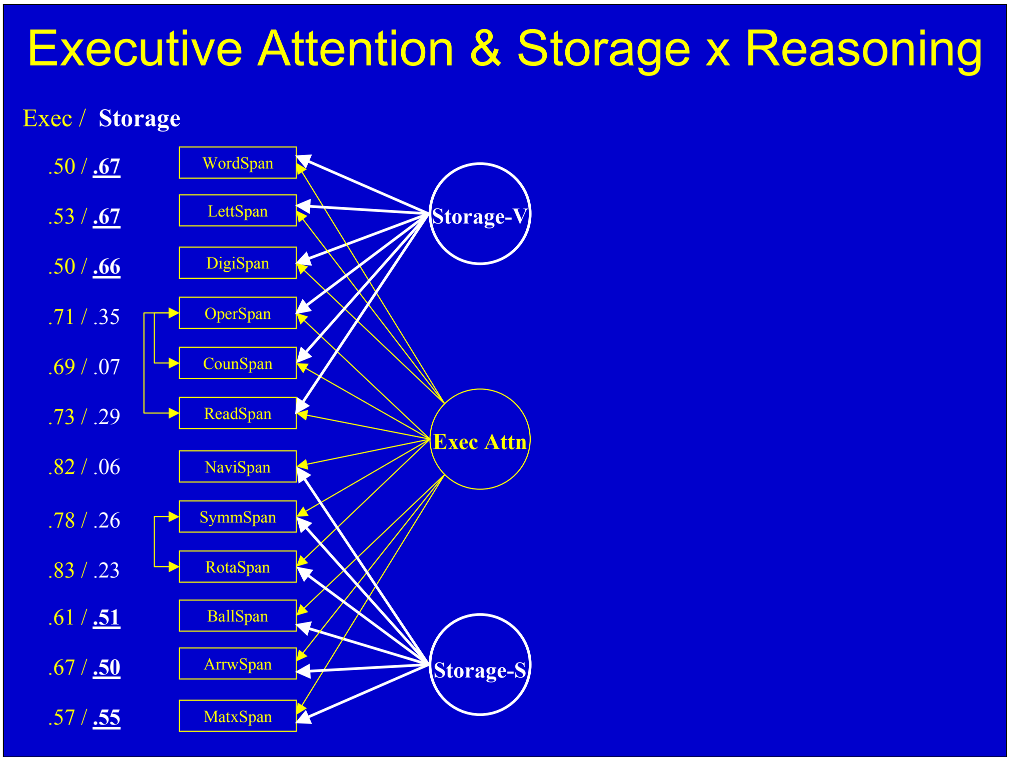
We therefore modeled the memory tasks in a similar manner to the reasoning tasks. All short-term and WM tasks loaded onto a single factor, reflecting the variance common to all the memory tasks; we inferred this common variance to reflect domain-general executive-control processes.

In addition, all the verbal memory tasks loaded onto a residual “verbal storage” factor, and all the spatial memory tasks loaded onto a residual “spatial storage” factor.

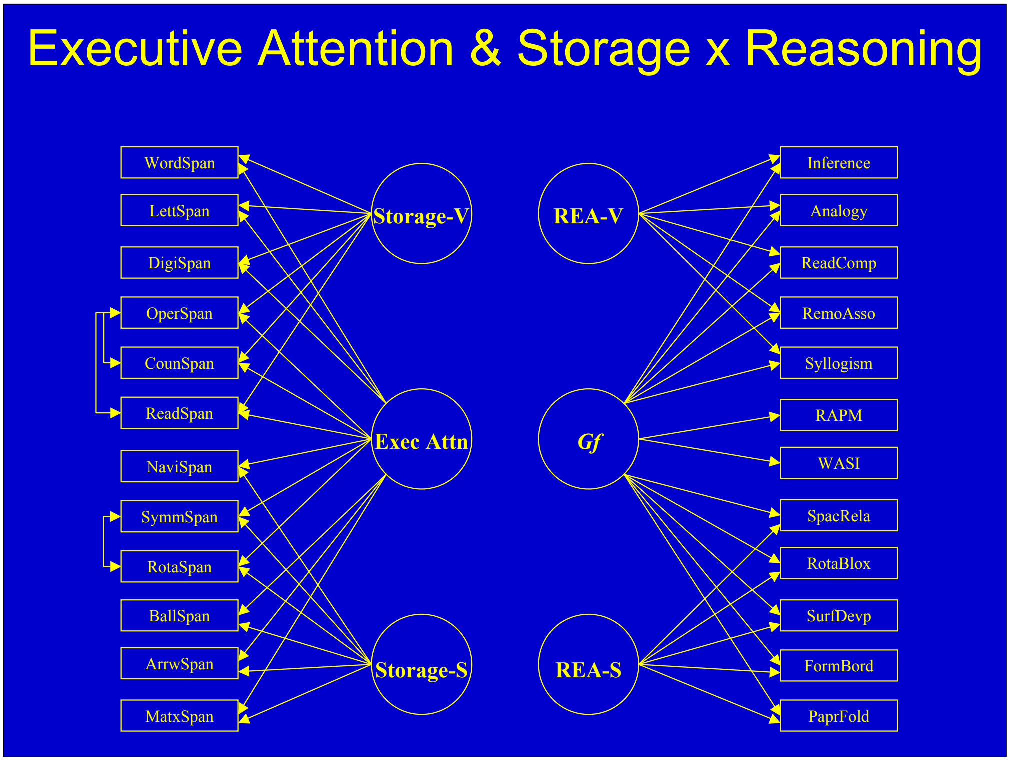


Importantly, the labels we gave to these memory factors were empirically supported by the factor loadings of the tasks.

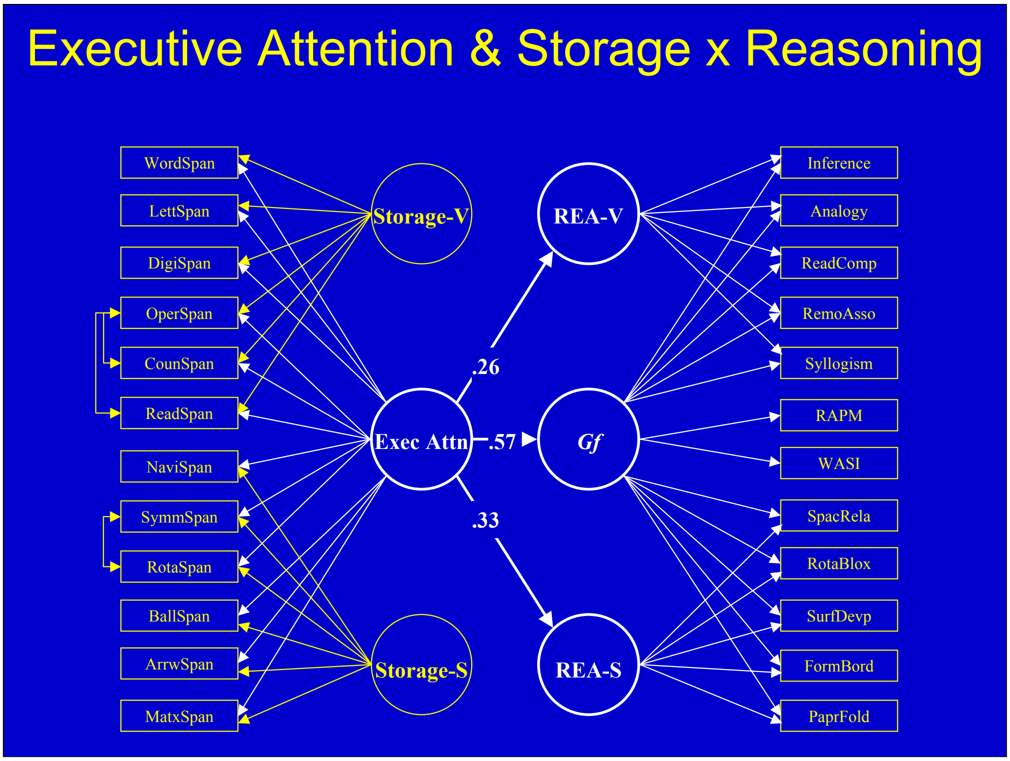
Consider first the Executive Attention factor, where the task loadings are presented to the left. If you examine the verbal tasks, you can see that WM span has higher loadings on this factor than does STM span. Likewise, for the spatial tasks, WM span has higher loadings than does STM span. Although the Executive Attention factor reflects variance common to all the span tasks, it is more heavily weighted to the WM tasks.



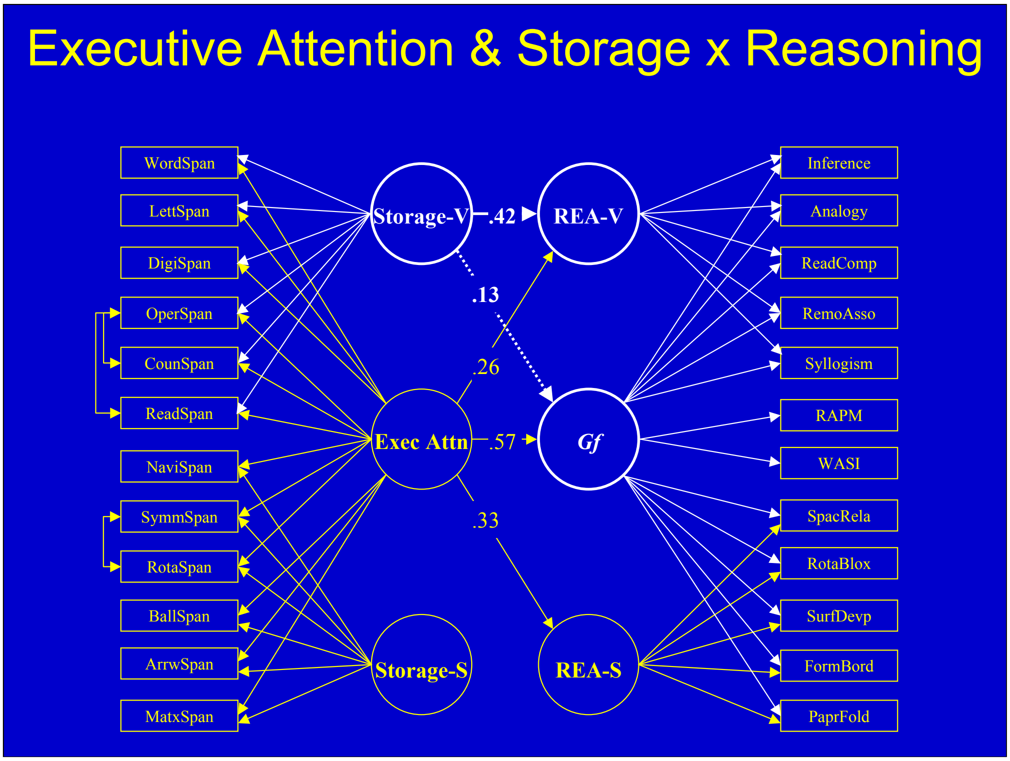
In contrast, if we consider loadings onto the domain-specific storage factors (presented in white), we see that for the verbal tasks, STM span has higher loadings than does WM span. Similarly, for spatial storage, STM span has higher loadings than does WM span. Again, although the storage factors reflect variance common to both short-term and WM tasks, they are more heavily weighted to the simple storage, STM tasks.



Here we predicted that the Executive Attention factor would predict *Gf*, as well as domain-specific reasoning, but that the domain-specific storage factors would limit their predictive utility to reasoning in the matching domain.

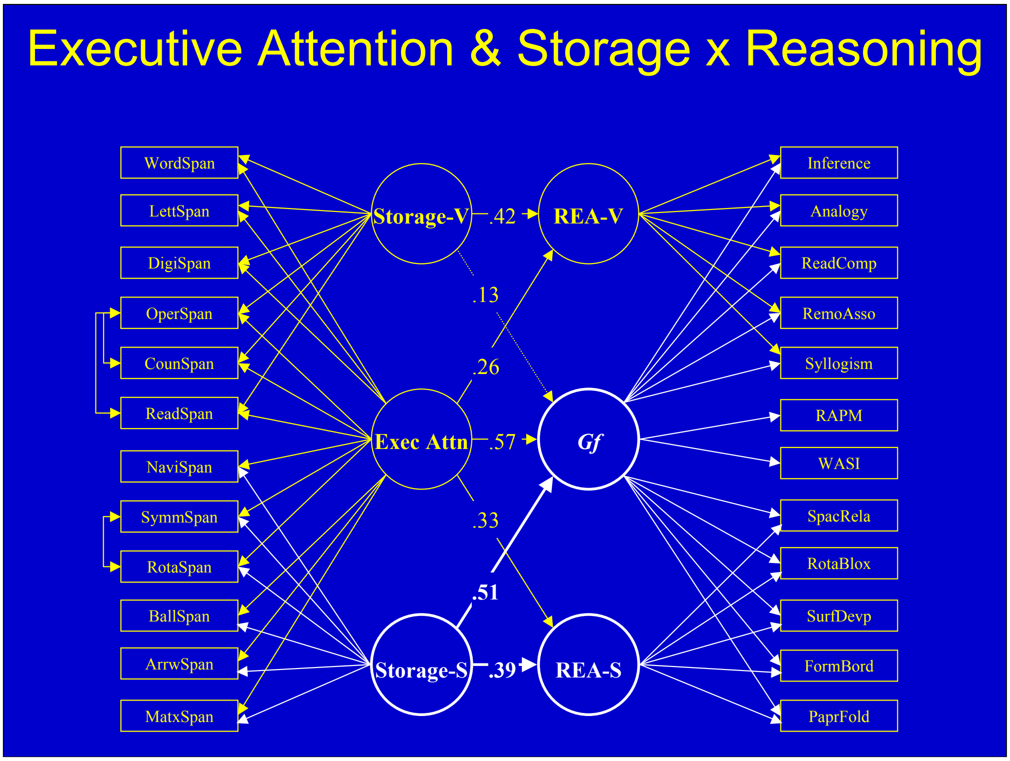


Considering first the Executive Attention factor, we see correlations very similar to those we saw from the unitary WM factor in a previous slide. The correlation with Gf is near .60, and the domain-specific correlations are about .30. The similarity of these correlations to those shown earlier increases our confidence that the "Executive Attention" factor is properly labeled.



The verbal storage construct also behaved as we predicted. Consistent with prior research, verbal STM measures account for unique variance in verbal ability over and above that accounted for by WM.

In addition, and also consistent with recent work, verbal storage shared no unique variance with the general intelligence factor.



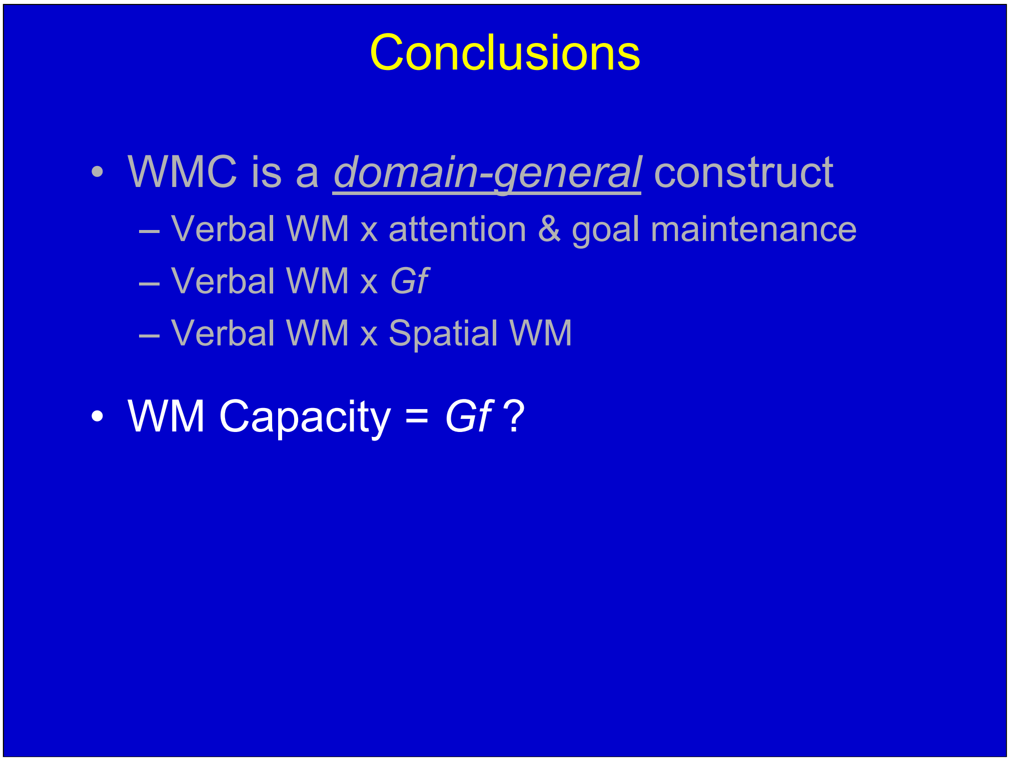
A very different picture emerges from the spatial storage factor. Although it shows a significant correlation with spatial reasoning, its most impressive correlation is with fluid ability. Over and above the variance predicted by Executive Attention, spatial storage accounts for a substantial amount of unique variance in *Gf*.

So, whereas verbal storage is linked only to verbal reasoning, spatial storage taps a more general cognitive capability.

Conclusions

- WMC is a *domain-general* construct
  - Verbal WM x *Gf*
  - Verbal WM x attention & goal maintenance
  - Verbal WM x Spatial WM

Our most important conclusion today is that WM capacity reflects primarily a domain-general construct. Verbal WM tasks correlate strongly with measures of general fluid intelligence, verbal WM tasks predict low-level attention control abilities, and finally, verbal and visuo-spatial WM tasks are functionally indistinguishable.



Is WM capacity the mechanism behind the statistical construct of general fluid intelligence? Although intriguing, the possibility is becoming less likely as we find more examples of the correlation between WM and *Gf* hovering near .60.

The Magic Number .60 ?

- WM x *Gf*: .64
- Exec Attn x *Gf*: .57

In the two analyses reported here, the correlations between the WM capacity and fluid intelligence constructs were .64 and .57.

The Magic Number .60 ?

- WM x *Gf*: .64
- Exec Attn x *Gf*: .57
- Ackerman et al. (in press): .70
- Conway et al. (2002): .60
- Engle et al. (1999): .59
- Süß et al. (2002): .65

Note the limited variability around this estimate in other recent studies. Although perhaps premature for “magical number” status, the consistency of this correlation is impressive.

And, although it’s a substantial correlation, the confidence interval is not likely to include 1. So, at this point it is probably wisest to say that WM capacity is one of perhaps several important mechanisms of general cognitive ability.

Conclusions

- WMC is a *domain-general* construct
  - Verbal WM x attention & goal maintenance
  - Verbal WM x *Gf*
  - Verbal WM x Spatial WM
- WM Capacity = *Gf* ?
- Spatial "STM" ?
  - High loadings on Executive factor in SEM
  - Substantial links to *Gf*

Finally, "short-term memory" tasks involving spatial stimuli appear to be tapping something other than a passive storage buffer. Our spatial STM tasks loaded highly onto the Executive Attention factor and they were strong predictors of *Gf*. As indicated by recent work by Akira Miyake and his colleagues, there is something going on with these putatively "simple" spatial tasks that warrants further research.

Thank you very much.