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How Are Visuospatial Working Memory, Executive Functioning, and Spatial Abilities Related? A Latent-Variable Analysis

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This study examined the relationships among visuospatial working memory (WM) executive functioning, and spatial abilities. One hundred sixty-seven participants performed visuospatial short-term memory (STM) and WM span tasks, executive functioning tasks, and a set of paper-and-pencil tests of spatial abilities that load on 3 correlated but distinguishable factors (Spatial Visualization, Spatial Relations, and Perceptual Speed). Confirmatory factor analysis results indicated that, in the visuospatial domain, processing-and-storage WM tasks and storage-oriented STM tasks equally implicate executive functioning and are not clearly distinguishable. These results provide a contrast with existing evidence from the verbal domain and support the proposal that the visuospatial sketchpad may be closely tied to the central executive. Further, structural equation modeling results supported the prediction that, whereas they all implicate some degree of visuospatial storage, the 3 spatial ability factors differ in the degree of executive involvement (highest for Spatial Visualization and lowest for Perceptual Speed). Such results highlight the usefulness of a WM perspective in characterizing the nature of cognitive abilities and, more generally, human intelligence.

One's ability to temporarily maintain relevant information in mind has long been considered an indicator of one's intellectual capabilities (Jacobs, 1887). The fact that many widely used intelligence test batteries, such as the Wechsler Adult Intelligence Scale—Revised (Wechsler, 1981), include measures of temporary, short-term storage capacity, such as forward and backward digit spans, illustrates this point. Theoretical and empirical attempts to relate temporary storage capacity and cognitive abilities have gained momentum during the past 20 years or so, in part because of the development of complex working memory (WM) span measures that require participants to maintain target memory items while performing an additional processing task. In the case of the reading span test (Daneman & Carpenter, 1980), for example, participants read sentences aloud or sometimes verify the truthfulness of those sentences (the processing requirement) while trying to remember the last word of each sentence for later recall (the storage requirement). Similarly, other complex span tasks, such as the operation span (Turner & Engle, 1989) and counting span (Case, Kurland, & Goldberg, 1982) tasks, require concurrent arithmetic processing and counting, respectively, in addition to the maintenance of target words or digits.

These storage-plus-processing WM span tasks have had an important influence in the field, because they predict participants' performance on various cognitive ability and intelligence tests better than do simpler, more traditional measures of memory storage such as digit and word spans (Daneman & Merikle, 1996; Engle, Tuholski, Laughlin, & Conway, 1999). In fact, a strong relationship between complex span measures and cognitive abilities has led some researchers to propose that WM capacity may be the crucial underpinning (or at least an important component) of the well-known psychometric concept of general intelligence, or *g*, particularly its fluid aspects (e.g., Engle, Kane, & Tuholski, 1999; Kyllonen, 1996).

In the present study, we extend this line of research to the domains of visuospatial WM and spatial abilities to examine two issues that so far have not received much empirical and theoretical investigation. The first issue concerns the relationship between simple storage-oriented span measures and complex processing-plus-storage span measures. As is reviewed in more detail shortly, existing evidence suggests that complex span tasks tap something significantly more (e.g., executive functioning) than what is tapped

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by simple storage-oriented tasks, but such evidence comes almost exclusively from studies using verbal and numerical tasks that heavily depend on the maintenance of verbal–phonological representations. In this study, we evaluated the extent to which the conclusion from the verbal domain can be generalized to the visuospatial domain. The second issue concerns the relationship between WM and spatial abilities. Specifically, we focused on three major psychometric spatial ability factors identified in factor analytic studies (Spatial Visualization, Spatial Relations, and Visuospatial Perceptual Speed) and attempted to specify the commonalities and differences among those subfactors from a WM perspective.

Simple and Complex Span Measures: To What Extent Are They Separable?

The first goal of the present study was to examine the relationship between simple storage-oriented tasks and more complex storage-plus-processing tasks in the visuospatial domain. For simplicity (and to follow the convention of the field), we hereinafter refer to simple storage-oriented span tasks with no explicit concurrent processing requirement as *short-term memory* (STM) span tasks and to complex span tasks that involve not only a storage requirement but also an explicit concurrent processing requirement as *WM* span tasks. According to this classification, traditional verbal span measures such as digit and word spans are considered STM span tasks, whereas more complex span measures such as reading and operation spans are considered WM span tasks.

The results of previous individual-differences studies, conducted primarily in the verbal domain, provide strong support for the view that, although they correlate moderately with each other, STM and WM span tasks are not identical. This separability in the verbal domain is supported by various correlational studies. For example, WM span tasks (e.g., reading and operation spans) tend to be better than traditional STM span tasks (e.g., digit and word spans) in predicting performance on complex verbally oriented cognitive tasks, such as reading comprehension, that also require concurrent processing and storage (Daneman & Carpenter, 1980; Turner & Engle, 1989). A recent meta-analysis of 77 individual-differences studies confirmed this general pattern, demonstrating that WM span tasks can indeed predict reading comprehension performance significantly better than traditional STM span tasks, although the correlation between reading comprehension and STM spans still tends to be significant (Daneman & Merikle, 1996).

Another line of evidence for the nonequivalence of verbal STM and WM span tasks comes from a recent study conducted by Engle, Tuholski, et al. (1999). They examined the relationship between verbal–numerical STM and WM spans as well as their relations to general fluid intelligence at the level of latent variables (the variance shared by the multiple exemplar tasks for each construct), rather than at the level of manifest variables (individual tasks). The main finding was that although STM and WM span tasks correlate moderately with each other ($r = .68$) at the level of latent variables, they showed a clear separability and hence could not be considered the same. The nature of this separability is illuminated by the additional finding that the WM span tasks were able to predict performance on general fluid intelligence tests even after the common variance associated with the STM span tasks was partialed out, whereas the STM span tasks were no longer significantly related to general fluid intelligence after the common variance associated with the WM span tasks was partialed out. These results, which were closely replicated in a more recent latent-variable study (Conway, Cowan, Bunting, Therriault, & Minkoff, in press), suggest that WM span tasks tap something extra that is not tapped by STM span tasks, at least in the verbal domain.

To explain these findings, Engle, Tuholski, et al. (1999) proposed that a major difference between STM and WM span tasks may be a differential involvement of what they called *controlled attention,* which they argue is a domain-free, limited attentional capacity for performing controlled processing or sustaining focus on task-relevant information (such as goal information) in the face of interfering or distracting stimuli. According to their proposal, WM capacity equals STM capacity plus controlled attention ability. In other words, STM and WM span tasks are similar in that both require temporary storage of information, but they differ in that WM span tasks require a lot of controlled attention, whereas STM span tasks do not (STM span tasks probably require some controlled attention, but not as much as WM span tasks). This proposal highlights two important aspects of WM span tasks, which are proposed to be the main sources of extra demand on controlled attention: (a) Participants must engage in effortful coordination of concurrent processing and storage requirements (i.e., dual tasking), and (b) the nature of the concurrent processing requirement is such that it interferes with the storage requirement (e.g., in the case of the reading span task, reading sentences aloud necessarily generates irrelevant phonological representations and thereby interferes with the maintenance of target words).

Note that, although the terminology is different, this controlled attention framework is highly compatible with Baddeley's (1986; Baddeley & Logie, 1999) multicomponent model of WM. This model postulates two subsystems specialized for the temporary maintenance of domain-specific information (i.e., the phonological loop for verbal–phonological information and the visuospatial sketchpad for visuospatial information) and a central, general-purpose control structure, termed the *central executive,* that is responsible for regulating and controlling information within the WM system and performing various so-called executive functions. Within this framework, Engle, Tuholski, et al.'s (1999) proposal is essentially equivalent to saying that, in the case of verbally oriented tasks, STM capacity is primarily determined by the capacity of the phonological loop, whereas WM capacity is determined jointly by the capacity of the phonological loop and the efficiency of central executive functioning. From this perspective, the commonality between STM and WM span tasks can be attributed primarily to the use of the phonological loop (i.e., shared storage requirement), whereas the main difference between them can be attributed to a much greater involvement of central executive functioning in WM span tasks.

Because the Engle, Tuholski, et al. (1999) study did not include independent measures of controlled attention, the nonequivalence of STM and WM span tasks in that study cannot unequivocally be attributed to the differential involvement of controlled attention. Nevertheless, the differential patterns of correlations between STM and WM span tasks and general fluid intelligence that Engle, Tuholski, et al. reported, as well as the two executive-demanding characteristics of WM span tasks pointed out earlier, are certainly consistent with the proposal that WM = STM + controlled attention. In addition, subsequent research has also demonstrated that performance on a WM span task (operation span) can reliably predict performance on various cognitive tasks (such as the antisaccade task) that require deliberate, controlled processing in the face of distracting information but do not necessarily impose heavy storage demands (Kane, Bleckley, Conway, & Engle, 2001; Tuholski, Engle, & Baylis, 2001). Such findings suggest that, in the verbal domain, controlled attention ability may indeed be one important—though probably not the only—aspect of what makes the predictive power of WM span tasks greater than that of STM span tasks.

One central issue we addressed in this study was the extent to which this nonequivalence of STM and WM span tasks found for the verbal domain can be generalized to the visuospatial domain. Although there is currently no direct evidence regarding this issue, some tantalizing findings suggest that the results for the verbal domain may not completely generalize.

One line of evidence for this potential asymmetry comes from individual-differences studies of spatial STM and WM span tasks. For example, Shah and Miyake (1996) administered a simple spatial STM span task (keeping track of spatial orientations indicated by arrows) and a more complex spatial WM span task (keeping track of spatial orientations while performing mental rotation), along with a set of spatial ability (spatial visualization) tests. Contrary to their original prediction based on the findings from the verbal domain, Shah and Miyake found that, at least at the level of zero-order correlations, the STM span task predicted performance on the spatial ability tests as well as the WM span task did. Although they lack comparable WM span tasks, other individual-differences studies have also yielded relatively high correlations between spatial STM span tasks and spatial ability test scores (e.g., Ichikawa, 1983; Juhel, 1991), which tend to be more robust than the ones between verbal STM span tasks and reading comprehension scores.

Another line of evidence for the asymmetry between the verbal and visuospatial domains comes from studies of dual-task interference, conducted primarily within the framework of Baddeley's (1986) multicomponent model. The verbal domain has a widely used secondary task that can selectively disrupt the operation of the phonological loop. This articulatory suppression task, which requires participants to say familiar words or phrases over and over (e.g., "the, the, the . . . "), has been shown to exert highly selective effects on tasks that involve the maintenance and processing of phonological information without disrupting the operations of the central executive or the visuospatial sketchpad much (Baddeley, 1986). In contrast, the visuospatial domain lacks such a well-established dual-task procedure, particularly for the spatial aspect. Although spatial tapping (tapping the four corners of an imaginary square sequentially with an index finger) has often been used as an interference task for the visuospatial sketchpad (Logie, 1995), it seems to implicate executive functioning to a larger extent than does articulatory suppression (Hegarty, Shah, & Miyake, 2000). Quinn and McConnell (1996) recently developed the irrelevant picture paradigm that can fairly selectively disrupt the maintenance of visual information, but no task is currently available that can disrupt the maintenance of spatial information without disrupting central executive functioning as well.

These findings have led some researchers to suggest a much stronger tie between the visuospatial sketchpad and the central executive than between the phonological loop and the central executive (e.g., Baddeley, 1996b; Quinn, 1988; Quinn & McConnell, 1996). For example, Baddeley (1996b) suggested that it is likely that "many uses of visual imagery are somewhat less practiced or automatic than the phonological coding that occurs for verbal information, and consequently tasks using the sketchpad often seem to place heavier demands on the central executive" (p. 13470). More recently, Baddeley and his colleagues argued in the context of a vigilance study that maintaining a mental representation of even a single visual stimulus (e.g., a line of varying length) over several seconds can be effortful and places demands on the central executive (Baddeley, Cocchini, Della Sala, Logie, & Spinnler, 1999). Reflecting such a close tie between the visuospatial sketchpad and the central executive, some researchers have even gone so far as to suggest that it might not be necessary to postulate a visuospatial subsystem separate from the central executive (Phillips & Christie, 1977b).

Thus, despite the paucity of direct evidence, there is a fair amount of circumstantial evidence suggesting that, in the visuospatial domain, not only complex WM span tasks but also simpler STM span tasks may heavily implicate central executive functioning or controlled attention. Thus, the distinction between the WM and STM span tasks may not be as clear-cut as in the verbal domain. We tested these hypotheses with latent-variable analyses.

WM and Spatial Abilities: How Do They Relate?

The second goal of the present study was to specify the relations between WM and traditional psychometric spatial abilities. More specifically, we focused on three frequently mentioned subfactors (Spatial Visualization, Spatial Relations, and Visuospatial Perceptual Speed) and specified how they relate to measures of visuospatial STM, WM, and executive functioning. The factors we focused on are three of the five major spatial ability factors identified by Carroll (1993) in his reanalysis of previous factor analytic studies (the other two factors are Closure Speed and Closure Flexibility, which are discussed in the General Discussion section). We chose these factors because they are relatively robust (Carroll, 1993; Lohman, 1988), and because the results of previous studies (Hegarty et al., 2000; Shah & Miyake, 1996) as well as our own task analyses suggested that they may differ in terms of the demand they place on the WM system, particularly its executive component.

The most extensively studied factor from a cognitive psychological perspective is the Spatial Visualization factor (Carpenter & Just, 1986). Psychometric tests that load on this factor "reflect processes of apprehending, encoding, and mentally manipulating spatial forms" (Carroll, 1993, p. 309) and require a complex sequence of mental manipulations. Specific tests that often define this factor include the Paper Folding Test (Ekstrom, French, Harman, & Derman, 1976) and the Space Relations Test (Bennet, Seashore, & Wesman, 1972), both of which were used in this study and are illustrated in Figure 1A. Although the items in the figure are relatively simple, the items in the actual tests (particularly later items) are more complex and require extensive "involvement of executive assembly and control processes that structure and analyze the problem, assemble a strategy of attack on it, monitor the performance process, and adapt these strategies as performance proceeds" (Marshalek, Lohman, & Snow, 1983, p. 124).

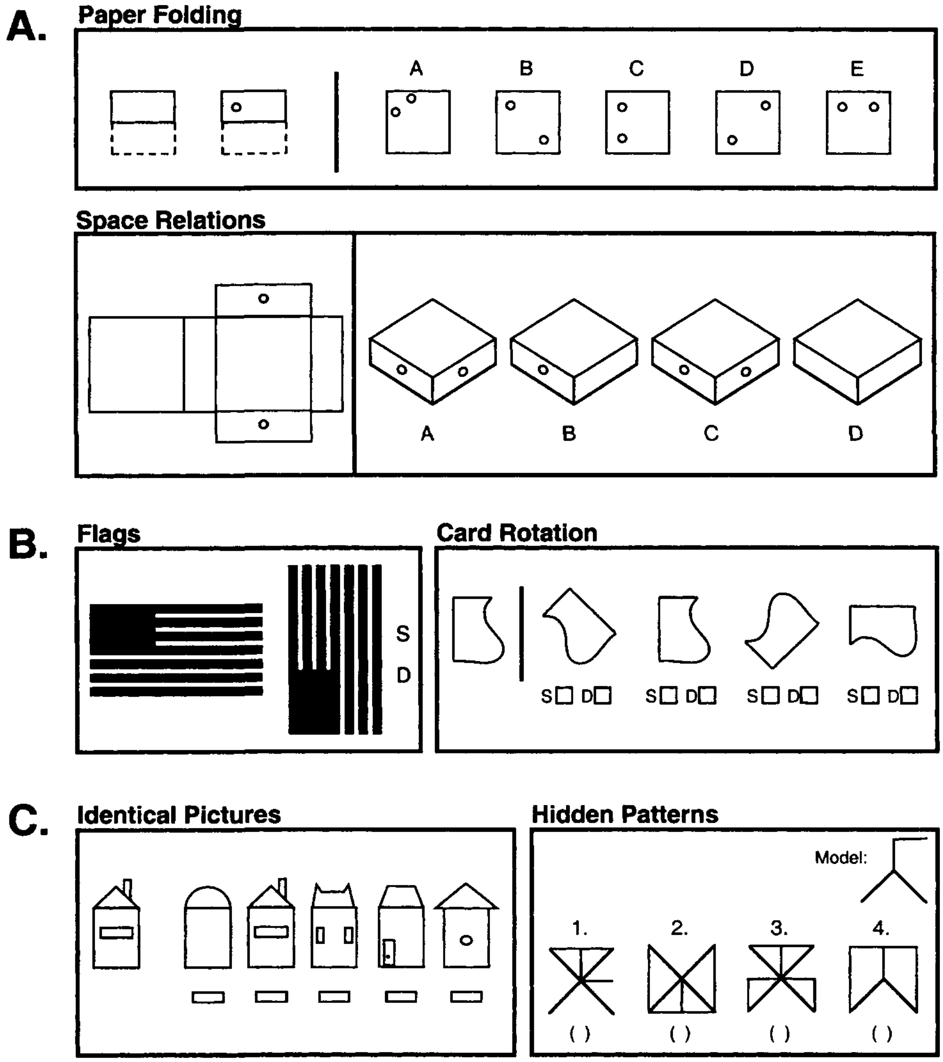

Figure 1. The six spatial ability tests used in the study. A: The two spatial visualization tests. The Paper Folding Test depicts a piece of paper being folded and a hole being punched in it; the participants must select the item in the right panel that depicts what the paper would look like if unfolded. Similarly, for the Space Relations Test, the participants must pick which of the figures in the right panel depicts what the pattern in the left panel would look like if folded. B: The two spatial relations tests. For the Flags Test, the participants must indicate whether the two flags are the same (S; i.e., one can be slid around so that it is identical to the other) or different (D). Similarly, the Card Rotation Test requires the participants to indicate whether each figure in the right panel is the same as the one on the far left. C: The two visuospatial perceptual speed tests. The Identical Pictures Test requires the participants to select from the five alternatives the picture that is identical to the one on the far left. For the Hidden Patterns Test, the participants are shown the model figure at the top of each page (the same "model" figure throughout the task) and must then indicate whether each figure on the page contains the model figure. The items from the Paper Folding Test, the Card Rotation Test, the Identical Pictures Test, and the Hidden Patterns Test are from "Kit of Factor-Referenced Cognitive Tests," by R. B. Ekstrom, J. W. French, H. H. Harman, and D. Derman, 1976, Princeton, NJ: Educational Testing Service. Copyright 1992 by the Educational Testing Service. Reprinted with permission. The Space Relations Test item is from "Differential Aptitude Tests (5th ed.): Space Relations, Form T," by G. K. Bennet, H. G. Seashore, and A. G. Wesman, 1972, New York: Psychological Corporation. Copyright 1990 by The Psychological Corporation, a Harcourt Assessment Company. Adapted with permission. The Flags Test item is from "Factorial Studies of Intelligence," by L. L. Thurstone and T. G. Thurstone, 1941, Chicago: University of Chicago Press. Copyright 1941 by the University of Chicago Press. Adapted with permission.

The second target factor is the Spatial Relations factor (also called Speeded Rotation). Tests that load on this factor are similar to spatial visualization tests in that they also require mental transformations but differ in that they involve manipulations (usually planar rotations) of two-dimensional objects that can be completed in a single step and in that they tend to emphasize speed (Carroll, 1993). Two of the representative tests for this factor are the Card Rotation Test (Ekstrom et al., 1976) and the Flags Test (Thurstone & Thurstone, 1941), illustrated in Figure 1B, both of which require a same–different judgment for each rotated pattern. Given that the amount of mental transformation that has to be performed for each test item is relatively small, this factor essentially represents "the ability to solve simple rotation problems quickly" (Lohman, 1988, p. 187).

The third target factor is the Visuospatial Perceptual Speed factor (or simply Perceptual Speed). Tests that load highly on this factor assess individual differences in the speed or efficiency with which one can make relatively simple perceptual judgments. Perhaps the most representative test for this factor is the Identical Pictures Test (Ekstrom et al., 1976), illustrated in Figure 1C, which requires quickly identifying which of five alternative patterns is identical to a model pattern. We also used the Hidden Patterns Test (Ekstrom et al., 1976; see Figure 1C), which requires quickly deciding whether a simple target pattern is present in a more complex pattern.[1] As these examples illustrate, tests that load on this factor involve no spatial transformations and primarily require rapid matching of visual patterns (Carroll, 1993).

Note that these three factors are moderately correlated with one another. In fact, depending on the tasks included in the analysis, some factor analytic studies have failed to find a clear distinction between the Spatial Visualization and Spatial Relations factors (Carroll, 1993; Lohman, 1988). Similarly, depending on the complexity of the materials, tests that are typically classified under the Closure Flexibility factor can sometimes load on the Spatial Visualization factor or on the Perceptual Speed factor (Lohman, 1988). Such findings suggest that the three target factors should be regarded as separable but correlated constructs, rather than completely independent ones.

What underlies the similarity and separability of the three spatial ability factors? The proposal we evaluated in this study focused on the demand these spatial ability tests place on the WM system, particularly the visuospatial and executive components. Regarding the visuospatial component, all three factors seem to require at least some degree of temporary visuospatial maintenance. The importance of maintaining intermediate results is apparent for Spatial Visualization tests that involve multiple steps of spatial transformations. Spatial Relations tests also seem to implicate temporary storage of visuospatial representations because performing a spatial transformation (e.g., mental rotation) requires that a target figure be mentally represented so that the transformation process can operate on that internal representation and so that the resulting rotated representation can be compared against the comparison figure. Even the simplest Perceptual Speed tests require a brief retention of target figures, because visual comparisons often cannot take place in a single eye fixation and thereby require some form of temporary visuospatial storage across fixations. For these reasons, we predict that all three spatial ability factors require some degree of visuospatial storage. Given that the maintenance of even a simple visuospatial representation may implicate central executive functioning (Baddeley et al., 1999), however, the visuospatial storage involved in the performance of these spatial ability tests may not reflect a "pure" storage capacity of the visuospatial sketchpad and may instead reflect a "virtual" capacity strongly supplemented by executive functioning or controlled attention.

As for the executive component, we propose that the three spatial ability factors place differential demands on executive functioning, with the Spatial Visualization factor imposing the highest demand and the Perceptual Speed factor placing the lowest demand. We predict this rank ordering for a number of reasons. First, Spatial Visualization tests require a sequence of spatial transformations and thereby necessitate the management of task-specific goals and subgoals as well as the scheduling and coordination of different cognitive processes (Lohman, 1996; Marshalek et al., 1983). Second, performing mental transformations seems to require a strong resistance to perceptual interference from the test stimuli. As the example problems in Figure 1 make clear, Spatial Visualization tests (and, to a lesser extent, Spatial Relations tests) require that mental transformations be executed in the presence of external visual stimuli. Because the internally maintained representation is likely to be much weaker than the external visual representation printed on the test booklet, it seems necessary to keep the internal representation accurate as well as highly active in the face of interference from the external visual stimuli. Although they are unlikely to be the only reasons, these considerations suggest that the more mental transformation the task requires, the more demanding it should be of central executive functioning.[2]

We should emphasize that, although we predict the least executive involvement for the Perceptual Speed factor, a considerable amount of executive functioning may still be required for performance on Perceptual Speed tests. First, even though extensive goal management may not be needed, Perceptual Speed tests still require keeping the task goal active during performance. In addition,

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[1] The Hidden Patterns Test is often considered a representative task for the Closure Flexibility factor, rather than the Perceptual Speed factor. Despite this fact, we chose the Hidden Patterns Test as a Perceptual Speed measure for two reasons. First, other available perceptual speed tests tended to have distinct verbal–numerical aspects (e.g., comparing two strings of numbers), leaving more room for verbally oriented strategies. More important, tests of closure flexibility have been known to load on the Perceptual Speed factor when the complexity of the materials is low (Lohman, 1988). The Hidden Patterns Test is one of the simplest tests for closure flexibility and hence could be construed as a Perceptual Speed test. In fact, the results of our analyses do not suggest any signs of misfit, further justifying the inclusion of the Hidden Patterns Test as a Perceptual Speed measure.

[2] This proposal does not mean that we believe that the executive component of WM is directly responsible for performing spatial transformations. In line with recent proposals (Baddeley, 1996a; Engle, Tuholski, et al., 1999; Miyake, Friedman, et al., 2000), we consider executive functions a set of general-purpose control processes and do not wish to include domain-specific processes such as mental rotation or mental folding as part of executive functioning. However, given that spatial transformations are not highly practiced skills for most people and that, as we argue here, more spatial transformations essentially mean more goal management, more multitasking, more interference, and so on, performing spatial transformations can indirectly implicate executive functioning. Thus, it may be difficult to clearly differentiate this proposal from one in which the central executive is directly responsible for spatial transformations.

as the examples in Figure 1C illustrate, Perceptual Speed tests contain a fair amount of distracting information, such as similar-looking patterns in the case of the Identical Pictures Test and distracting lines in the case of the Hidden Patterns Test, hence requiring some degree of deliberate, controlled processing. In fact, these executive-demanding characteristics are also shared by the Spatial Visualization and Spatial Relations tests. Thus, at least some degree of executive functioning is expected even for the simplest Perceptual Speed factor.

The Present Study

We examined the theoretical issues outlined above with analysis of latent variables. The latent-variable approach has several advantages over the use of zero-order correlations or multiple regression. Because latent variables are what is shared among multiple tasks used to tap the same construct, idiosyncratic task requirements have less influence on the estimates of the interconstruct relations. In addition, because the measurement error for each task is not part of the latent variable, the latent variable provides a more reliable and accurate measure of the intended construct than do the individual tasks; thus, individual task measurement error and reliability have less influence on the results. For these reasons, latent-variable analysis provides a more powerful method for examining the issues addressed here.

Task Selection

We selected two representative tasks or tests for each target latent variable. We have already outlined the six psychometric tests (see Figure 1) used to tap the three spatial ability factors, Spatial Visualization, Spatial Relations, and Perceptual Speed. For the Visuospatial WM and STM variables, we chose the tasks on the basis of previous research. The two WM span tasks chosen, illustrated in Figure 2A, are the letter rotation task (Shah & Miyake, 1996) and the dot matrix task (Law, Morrin, & Pellegrino, 1995), both of which involve visuospatial storage (spatial orientations and dot locations, respectively) with a concurrent visuospatial processing requirement (mental rotation or verification of spatial matrix equations). The two STM span tasks, illustrated in Figure 2B, are the dot memory task (Ichikawa, 1983) and the Corsi blocks task (Milner, 1971). They are both widely used tasks, and, in particular, the latter task has served as a popular neuropsychological assessment tool (Berch, Krikorian, & Huha, 1998). These STM span tasks require the maintenance of spatial information (dot configurations and location sequences, respectively) but do not involve any explicit concurrent processing requirement.

With respect to the Executive Functioning variable, the issues of what the central executive does (or what controlled attention is) and how it is organized are currently under debate, and there is no widely accepted view at this point (Baddeley, 1996a; Miyake, Friedman, et al., 2000). Thus, it is difficult to select a set of tasks to best assess executive functioning purely in terms of existing theories. A pragmatic strategy we adopted was to rely on tasks frequently used as executive tasks. We chose two complex tasks: the Tower of Hanoi and random number generation.

The Tower of Hanoi task (as well as its variant the Tower of London task) has been widely used as an executive task related to planning and goal management in both cognitive (Carpenter, Just, & Shell, 1990; Simon, 1975) and neuropsychological (Goel & Grafman, 1995; Shallice, 1988) studies. Because administering this task without any restrictions may encourage simple perceptual strategies that may not implicate executive functioning much (Goel & Grafman, 1995; Miyake, Friedman, et al., 2000), we asked participants to use the *goal recursion* strategy, a strategy considered to maximize the involvement of executive functioning. To use this strategy effectively, participants must set up a hierarchy of goals and constantly monitor their place in the hierarchy to keep the correct goals active and shift between goals within the hierarchy when appropriate (Carpenter et al., 1990). Carpenter et al. reported a high correlation ($r = .77$) between performance on Tower of Hanoi problems solved with this strategy and the Raven Progressive Matrices test, a prevalent test of general fluid intelligence considered to place heavy demand on executive functioning or controlled attention (Engle, Tuholski, et al., 1999).

The second executive task, random number generation, is perhaps the task most frequently used to tap executive functioning within the framework of Baddeley's (1986) model of working memory. In dual-task studies, random number generation has been used as a secondary task that disrupts the operations of the central executive, and recent studies have begun to specify exactly what executive processes are implicated in performance on this task (Baddeley, Emslie, Kolodny, & Duncan, 1998; Miyake, Friedman, et al., 2000; Towse, 1998). A point of agreement emerging from these studies is that random number generation taps multiple executive processes. For example, while performing this task, participants must develop a retrieval strategy, keep that strategy active and monitor it for its effectiveness, and constantly shift strategies to avoid repeating previously used sequences (Baddeley, 1996a). This requirement to activate and monitor goals has often been linked to executive functioning as well as *g* (Duncan, Emslie, Williams, Johnson, & Freer, 1996).

Thus, both of these tasks require participants to activate and keep track of a series of goals and subgoals. More important, for both tasks, this goal management must take place in the face of distracting or conflicting information. In the case of the Tower of Hanoi task, so-called conflict moves—moves that are necessary but on the surface seem in conflict with the end goal (e.g., moves that temporarily block the goal peg)—present a major challenge (Goel & Grafman, 1995). Such moves create a conflict within participants between the internally maintained goal representations that suggest one move and the external, perceptual representations of the current disk configuration that suggest a different move. Participants who fail to keep the goal representations highly active in the face of such conflict opt for the incorrect, perceptually based moves, leading to more errors and longer solution times. In the case of random number generation, the source of conflict is internal and comes from the fact that certain well-learned number sequences, such as counting up (e.g., 1 followed by 2) and down (e.g., 6 followed by 5), can be much more automatically activated than other sequences. This means that producing a seemingly random sequence of numbers requires resisting possible intrusions from such easily accessible stereotyped sequences (Baddeley, 1996a; Baddeley et al., 1998), and, hence, a failure to continuously monitor retrieval strategies and shift them when appropriate should lead to the production of more stereotyped sequences than would be the case for a truly random sequence. In fact, the overrepresentation of counting responses is a consistent finding with this task

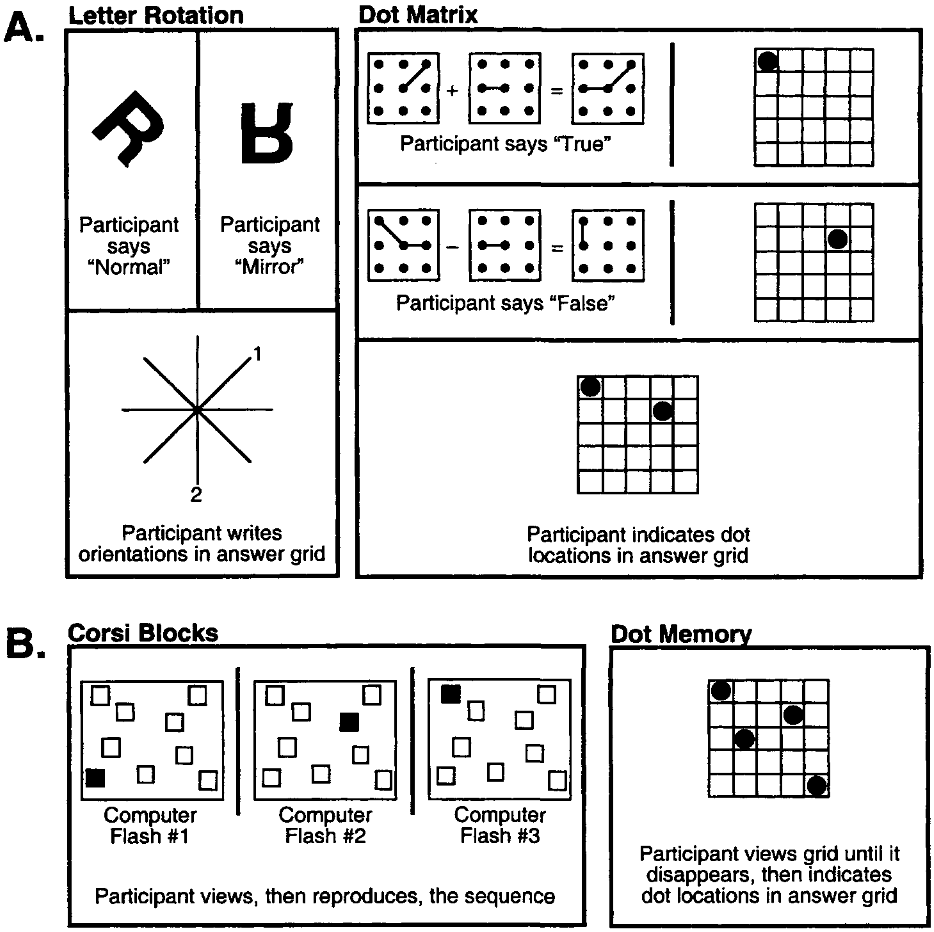

Figure 2. The visuospatial working memory (WM) and short-term memory (STM) tasks used in the study. A: The two WM tasks. For the letter rotation task, participants see a series of pictures of a letter rotated in different orientations and say whether each is normal or mirror imaged; after all the letters, they indicate in an answer grid where the top of each letter was located. For the dot matrix task, participants view a matrix equation and verify whether it is true or false, after which they view a grid with a dot inside it. After a series of such equations and grids, they indicate in an answer grid where the dots from all the grids were located. B: The two STM tasks. For the Corsi blocks task, participants are shown a set of blocks (drawn as white boxes on a computer screen) and are asked to remember the order in which the blocks were "tapped" (shown as changing color). After a sequence of "taps," participants repeat the order by clicking on the boxes with the mouse. The dot memory task requires participants to briefly view a grid with dots inside of it until it disappears, after which they indicate the dot locations in an answer grid.

(Towse, 1998), and substantial individual differences exist for this dimension (Miyake, Friedman, et al., 2000).

As this discussion explicates, although the primary reason for choosing the Tower of Hanoi and random number generation tasks for the Executive Functioning variable was their prevalent use as executive tasks, they both assess the ability to actively maintain goals or other task-relevant information in the presence of externally driven or internally driven conflicts. Note that this ability closely resembles the concept of controlled attention as proposed by Engle and his colleagues (Engle, Kane, & Tuholski, 1999; Engle, Tuholski, et al., 1999). In addition, for each task, we chose the dependent measure that we believed would best tap the individual differences in this shared ability (see the *Method* section for details). Given that the Tower of Hanoi task is based on a visual display, whereas random number generation is primarily verbal in nature, the latent variable for Executive Functioning (i.e., the variance shared by these two tasks) should be a reasonable measure of domain-general central executive functioning or controlled attention.

Logic of the Analyses

The first goal of the study was to specify the degree to which complex WM span tasks and simpler STM span tasks are related to executive functioning in the visuospatial domain. Given the strong tie between the visuospatial sketchpad and the central executive previously suggested, we tested the strong hypothesis that Executive Functioning is as closely related to Visuospatial

STM tasks as to Visuospatial WM tasks. In addition, we also tested the hypothesis that this similar involvement of Executive Functioning in both Visuospatial WM and STM tasks may make these two constructs essentially indistinguishable.

We examined these issues using confirmatory factor analysis (CFA). The logic behind the CFAs is as follows. The starting point is a three-factor model in which the Executive Functioning, Visuospatial WM, and Visuospatial STM variables were hypothesized to be separable but correlated, with the correlations providing an estimation of the degree to which the three target constructs are related. This three-factor model constitutes the least restrictive and, hence, least parsimonious model for the three latent variables. We then imposed on this three-factor model a series of restrictions that represent the hypotheses of interest. Specifically, to test the hypothesis that Executive Functioning is as strongly involved in Visuospatial STM tasks as it is in Visuospatial WM tasks, we constrained the correlation between Executive Functioning and Visuospatial STM to be equal to the one between Executive Functioning and Visuospatial WM. If the resulting model did not significantly worsen the fit to the data, then the restricted (i.e., more parsimonious) model would be preferred, and these two correlations would be considered virtually equal. To test the hypothesis that the Visuospatial STM and WM tasks are tapping the same construct, we tested a model that constrains their correlation to be 1.0 (i.e., a perfect correlation). If this model did not significantly worsen the fit, these two constructs would be considered essentially the same.

The second goal of the study was to examine how the visuospatial and executive aspects of the WM system contribute to predictions of three target spatial abilities. The main prediction was that the degree of contribution of Executive Functioning is largest for the Spatial Visualization factor and smallest for the Perceptual Speed factor. We did not have specific predictions for the relative degree of contribution of the visuospatial component to the three spatial abilities, except that it should be involved in all three abilities. We tested these predictions with structural equation modeling (SEM). Specifically, the model we tested has latent variables that tap the executive and visuospatial aspects of WM predicting the three spatial abilities simultaneously. We compared the path coefficients from the WM constructs to the spatial ability factors, using specific constraints to statistically test our predictions. For example, if Executive Functioning is contributing significantly more to the Spatial Visualization factor than to the Perceptual Speed factor, then constraining these parameters to be equal should significantly worsen the model fit.

Method

Participants

The participants were 167 undergraduate students from the University of Colorado at Boulder who participated to partially fulfill a course requirement. Two additional participants also took part, but their data for some of the tasks were not complete because of technical problems. Thus, their data were not included in the analyses reported below.

Administered Tasks

All participants completed a total of 12 tasks: two Executive Functioning tasks, two Visuospatial WM tasks, two Visuospatial STM tasks, and a set of psychometric tests of spatial abilities (two tests for each spatial ability subfactor). All of the tasks were performed using paper and pencil or Power Macintosh 7200 computers.

Executive Functioning tasks. The computerized Tower of Hanoi task presented a series of five problems, starting with a three-disk problem and progressing to a seven-disk problem, and recorded each move made by a participant and the amount of time it took. The task required moving towers one disk at a time, without placing a larger disk onto a smaller one. The starting and goal pegs were varied for each problem so that the problems with fewer disks would not be subsets of the problems with more disks. To discourage participants from using simple perceptual strategies that may not place much executive demand, we required them to use the goal recursion strategy that necessitates extensive goal management. Participants were given instructions regarding the goal recursion strategy (see Carpenter et al., 1990, for details) until they could satisfactorily explain the procedure back to the experimenter. They were also closely monitored (with extra instructions if necessary) during the two practice trials (a two-disk problem and a three-disk problem) so that they had a complete understanding of this strategy by the end of the practice. Illegal moves as well as legal moves that did not follow the solution specified by the goal recursion strategy were not allowed, as the computer beeped and immediately replaced improperly placed disks.

The random number generation task required participants to say a series of numbers aloud, one every 800 ms, with the goal of making the sequence as random as possible. A computer program generated a series of beeps to pace the responses, and participants were instructed to use only the numbers 1 to 9, to say a number on every beep, and not to skip beeps. Prior to the administration of the task, participants were given, as an illustration of the concept of randomness, the analogy of picking a number out of a hat and putting it back before picking another. After this instruction, they completed a short practice series of about 10 beeps, after which the actual task began. The first 100 valid responses for each participant were used to assess the randomness of the produced sequence.

Visuospatial WM tasks. In the letter rotation task (illustrated in Figure 2A), each trial consisted of the sequential presentation of a set of the same capital letter (*F, J, L, P,* or *R*), each of which appeared on a computer screen either normal or mirror imaged and rotated in one of seven possible orientations (multiples of 45°, except the upright orientation). The participant's task was to say aloud whether each letter was normal or mirror imaged as quickly and as accurately as possible and remember its spatial orientation (i.e., where the top of each letter was pointing). Participants were given a maximum of 3 s to verbally respond "Normal" or "Mirror," and the experimenter pressed a key to display the subsequent letter immediately after the participant's oral response. After each set, the participant turned to an answer sheet with a series of grids and marked down numbers corresponding to the positions of the tops of the presented letters in the correct serial order. There were three practice trials with two letters each, after which sets progressively increased in size from two to five letters for a total of 20 sets, 5 of each size.

In the dot matrix task, the main requirement was to verify a matrix equation while simultaneously remembering a dot location in a 5 × 5 grid. Each trial contained a set of to-be-verified matrix equations followed by a 5 × 5 grid containing one dot. In the matrix equation display, a simple addition or subtraction equation was presented in the manner illustrated in Figure 2A. Participants were given a maximum of 4.5 s to verbally verify each equation by saying "True" or "False." Immediately after their oral response, the experimenter pressed a key, and the computer then displayed a dot grid for 1,500 ms. After a sequence of between two and five equation–grid pairs, participants recalled, in any order, which grid spaces had contained dots. There were three practice trials with two equations and two dots each, after which sets progressively increased in size from two to five equations and dots for a total of 20 sets, 5 of each size.

Visuospatial STM tasks. In the computerized version of the Corsi blocks test (illustrated in Figure 2B), participants were shown a set of blocks (drawn as white boxes) and asked to remember the order in which they were "tapped" (shown as changing color). One box at a time turned black for 650 ms each, a duration short enough to discourage the use of idiosyncratic coding strategies. Also, on the basis of our pilot testing, we used five similar but different configurations of blocks (changed on each trial) to discourage participants from using numerical coding of box locations. Immediately after a sequence of "taps," participants repeated the order by clicking on the boxes with the mouse. Once the sequence of flashing boxes was complete, they had unlimited time to respond. There were three practice trials with three taps each, after which the sequences progressed in length from three to eight taps for a total of 30 trials, with 5 trials at each set size.

In the dot memory task, participants saw a 5 × 5 grid for 750 ms on each trial. Each grid had between two and seven spaces containing dots as illustrated in Figure 2B. After the grid presentation, participants recalled, on an answer sheet, the locations that contained dots. On the basis of Ichikawa's (1981) work, we tried to avoid dot configurations that formed systematic patterns. We also selected brief enough presentation durations (750 ms) to discourage idiosyncratic coding strategies. There were three practice trials with two dots each, after which the trials progressively increased in difficulty from two to seven dots. There were 30 trials in total for this task, 5 at each difficulty level.

In addition to these computerized tasks, participants also completed six psychometric tests of spatial ability. We used the standard instructions for all six tests but reduced the time limits to prevent possible ceiling effects for some of the tasks. All tests included written instructions as well as illustrative examples or practice problems.

Tests of Spatial Visualization. The Paper Folding Test, illustrated in Figure 1A, required participants to mentally fold a piece of paper, imagine a hole punched through the folded paper, and judge what the paper would look like when unfolded. Participants responded by choosing one of five alternatives. The items progressed in difficulty, with the most complex items requiring three folds that were sometimes nonsymmetrical. Participants had 2.5 min to work on each of two subsections, which had 10 items each. In the Space Relations Test, participants were asked to mentally fold a piece of paper (like the one shown in Figure 1A) along the creases to create a three-dimensional object. They responded by selecting the correct drawing of the resulting object from four alternatives and were given 12 min to solve 60 items.

Tests of Spatial Relations. The Flags Test required participants to determine whether or not a pair of American flags (drawn in black and white, without stars, as shown in Figure 1B) were the same when rotated on the page. There were 48 items in the test, and the time limit was 1.5 min. The Card Rotation Test, illustrated also in Figure 1B, required participants to view a two-dimensional target figure and indicate which of the test figures were planar rotations of the target figure (as opposed to mirror images) as quickly and as accurately as possible. There were 10 rows of eight test figures in each of two subsections, and participants had 2 min for each subsection.

Tests of Visuospatial Perceptual Speed. The Identical Pictures Test, illustrated in Figure 1C, required participants to view a target figure and judge which one of five alternative figures was identical to the target figure as quickly and as accurately as possible. There were 48 items in each of the two subsections, and the time limit was 1 min for each subsection. In the Hidden Patterns Test, participants were shown a simple criterion or model pattern (see Figure 1C). Then, for a series of slightly more complex test patterns, they were to determine whether the criterion pattern was embedded in each test pattern. There were 200 items in each of the two subsections (the criterion pattern remained the same throughout the entire test), and the time limit was 1.5 min for each subsection.

General Procedure

Testing took place in two sessions, administered individually during a 10-day period (for a total of approximately 3 hr). The order of task administration was fixed for all participants to minimize any measurement error due to a participant by order interaction. The tasks administered in Session 1 (in order) were the Paper Folding Test, the Flags Test, the Space Relations Test, the Card Rotation Test, and the random number generation task. Those administered in Session 2 were the Identical Pictures Test, the letter rotation task, the dot memory task, the Tower of Hanoi task, the Corsi blocks task, the dot matrix task, and the Hidden Patterns Test.

Preliminary Data Analyses

Data scoring. The dependent measure for the Tower of Hanoi task was the total time taken for all five problems, including the time taken for erroneous moves. This measure was selected because it was considered to tap both the speed and accuracy of executing the goal recursion strategy, thereby best reflecting the consequence of failing to manage the goals and subgoals (i.e., erroneous moves and longer solution times). For the analysis of random number generation performance, we first obtained 14 "randomness" indices[3] using the RgCalc program (Towse & Neil, 1998) and reduced the data with a principal-components analysis (we used an oblique promax rotation to allow the factors to correlate). We used the factor scores from the first rotated principal component as the dependent measure for the random number generation task because the indices that were particularly sensitive to the tendency to produce stereotyped counting responses (i.e., a failure to monitor retrieval strategies and shift them when appropriate) loaded highly on that factor.

For the four Visuospatial WM and STM span tasks, the dependent measures were the total number of items correctly recalled (for the letter rotation and Corsi blocks tasks, the total number of items correctly recalled in the correct serial position). The six psychometric tests of spatial abilities were all scored by giving 1 point per correct answer and subtracting a fraction of a point for each error (in proportion to the number of alternatives minus one for each item) to correct for guessing.

Data screening. Because the multivariate techniques used in this study (i.e., CFA and SEM) assume multivariate normal distributions and are sensitive to extreme outliers, careful screening is recommended (Kline, 1998). For this reason, we trimmed the data using the following procedure: For each variable, any observations with values that exceeded 3 standard deviations from the mean were set to values that were 3 standard deviations from the mean. We chose this fairly conservative trimming procedure so that we could retain extreme observations without those observations having adverse effects on the distributions or undue influence on the covariances. For the 12 manifest variables used in the CFA and SEM analyses, this trimming procedure affected only 0.5% of the observations across all 12 variables (no more than 1.8% for any one variable).[4] This trimming procedure resulted in satisfactory distributions for all 12 variables used in the CFA and SEM models, as the skewness and kurtosis statistics summarized in Table 1 indicate. In addition, Mardia's (1970) multivariate kurtosis for all 12 variables was 5.01 ($p > .10$), indicating

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[3] The randomness indices used were: Total Adjacency, Runs, Turning Point Index, Evans' Random Number Generation Index (RNGI), Coupon, Mean Repetition Gap (RG), Redundancy, and Phi2 through Phi7 (for more information about these indices, see Towse & Neil, 1998). Guttman's Null-Score Quotient was excluded because it was redundant with RNGI, $r(165) = .96$. Median RG and Mode RG were also excluded because they essentially measured the same thing as Mean RG but had nonnormal distributions. Consistent with the previous results (Miyake, Friedman, et al., 2000; Towse & Neil, 1998), the measures that loaded highly on the first rotated principal component were RNGI, Runs, Turning Point Index, and Total Adjacency (loadings > .75).

[4] We also applied this procedure to the 14 randomness indices before conducting a principal-components analysis; 1.5% of the observations across the 14 variables were affected (no more than 4.2% for any one variable).

Table 1
Descriptive Statistics for the Dependent Measures (N = 167)

Task	*M*	*SD*	Range	Skewness	Kurtosis	Reliability
Tower of Hanoi	14.96	4.76	6.26–29.79	0.88	0.47	N/A
RNG	−0.01	0.98	−1.92–3.00	0.73	0.70	N/A
Letter rotation	34.16	10.28	14–64	0.34	−0.27	.82[a]
Dot matrix	36.57	7.21	21–58	0.35	0.06	.79[a]
Corsi blocks	116.28	16.82	63–157	−0.59	0.77	.85[a]
Dot memory	87.36	13.28	47–121	−0.51	0.50	.83[a]
Paper folding	11.12	4.14	0.50–20.00	−0.24	−0.29	.75[b]
Space relations	26.44	10.45	1.33–51.67	0.04	−0.59	.94[b]
Card rotation	78.09	19.63	19–130	0.14	−0.02	.80[b]
Flags	20.06	8.44	3–45	0.58	−0.18	.91[b]
Identical pictures	53.72	8.46	30–77	0.18	0.04	.86[b]
Hidden patterns	106.94	25.70	29–171	−0.59	0.95	.88[b]

Note. For all variables except Tower of Hanoi (where values given are solution times in minutes) and RNG, higher numbers indicate better performance. N/A = not available; RNG = random number generation factor scores.

[a] Reliability based on Cronbach's alpha. [b] Reliability based on split-half method (odd–even or Part 1–Part 2) adjusted by Spearman–Brown prophecy formula.

adequate multivariate normality. Thus, no observations were removed from the analyses reported below.

Descriptive statistics. Descriptive statistics for each task are presented in Table 1. Higher values for the Tower of Hanoi task and the random number generation task indicate worse performance (i.e., longer solution times and more deviation from randomness, respectively). For all other measures, higher numbers indicate better performance. In addition to skewness and kurtosis, Table 1 also summarizes the reliability estimates for the measures used in this study. The estimates for the WM and STM tasks were derived by computing Cronbach's alpha, following the procedure used by Turner and Engle (1989). The estimates for the psychometric tests were derived from the split-half correlations (based on correlations between two subsections or correlations between even-numbered and odd-numbered items), adjusted by the Spearman–Brown prophecy formula. All measures for which we were able to calculate the estimates had satisfactory internal reliabilities.

Statistical Procedure

The CFA and SEM analyses were performed with the AMOS program (Arbuckle, 1999). This program uses maximum-likelihood estimation to derive the specified parameters based on the covariance matrix. Because there is no clear consensus as to the best fit indices for the evaluation of structural models, we followed the recommendation of Hu and Bentler (1998) and evaluated the fit of each model with multiple indices. Specifically, we selected commonly used indices—the χ^2 and χ^2/df statistics—and supplemented them with indices that have been found to be most sensitive to model misspecification without being overly sensitive to sample size (Hu & Bentler, 1998): the standardized root-mean-square residual (SRMR) and Bentler's comparative fit index (CFI).

The most common fit index is the χ^2 statistic, which measures the "badness of fit" of the model compared with a saturated model. Because this statistic measures the degree to which the covariances predicted by the specified model differ from the observed covariances, a small value indicates no statistically meaningful difference between the predicted and observed covariances, suggesting a satisfactory fit. However, the χ^2 statistic is correlated with sample size and, consequently, as sample sizes increase, "the χ^2 statistic may be significant even though differences between observed and model-implied covariances are slight" (Kline, 1998, p. 128). For this reason, many researchers have advocated the use of the χ^2/df statistic, with $\chi^2/df < 2$ indicating a good fit (Byrne, 1989). The SRMR is the square root of the averaged squared residuals or differences between observed and predicted covariances. Thus, lower SRMR values indicate a closer fit, with values less than .08 indicating a fair fit to the data, and values less than .05 indicating a good fit (Hu & Bentler, 1998). For CFI, higher values indicate better fit, because it quantifies the extent to which the model is better than a baseline model (e.g., one with all covariances set to zero). Hu and Bentler advocated a CFI cutoff of .95 as an indication of a good fit.

To examine whether one model was significantly better than another, we performed χ^2 difference tests on "nested" models. These tests entail subtracting the χ^2 for the full model from the χ^2 for a nested, restricted model with fewer free parameters (degrees of freedom are calculated with an analogous subtraction). If the resulting $\Delta\chi^2$ is significant, then the fuller model provides a significantly better fit. For all analyses reported in this article, we used an alpha level of .05.

Results and Discussion

The zero-order intercorrelations between the measures are summarized in Table 2. For ease of interpretation, the directionality of the dependent measures for the two Executive Functioning tasks (i.e., the Tower of Hanoi and random number generation tasks) was adjusted for all analyses so that larger numbers always indicated better performance. As the table clearly shows, the 12 measures tended to correlate with one another, with the pair of tasks chosen to tap the same latent variable generally showing higher correlations. Although the correlation between the two Executive Functioning tasks (.26) was somewhat lower than the other within-construct correlations, zero-order correlations of this magnitude (often .30 or less) are common among executive tasks, partly because these complex tasks often involve a good deal of variance related to nonexecutive processes as well as measurement error (for further discussions, see Miyake, Emerson, & Friedman, 2000; Rabbitt, 1997). Latent-variable analysis is particularly helpful in this situation because the analysis statistically extracts the common variance between the tasks chosen to tap executive functioning, thereby separating the variance due to executive processes from the considerable variance due to nonexecutive task requirements and measurement error (Miyake, Emerson, & Friedman, 2000).

Table 2
Intercorrelations Between Dependent Measures (N = 167)

Variable	1	2	3	4	5	6	7	8	9	10	11	12
1. Tower of Hanoi	—											
2. RNG	.26	—										
3. Letter rotation	.26	.17	—									
4. Dot matrix	.24	.24	.51	—								
5. Corsi blocks	.32	.13	.36	.42	—							
6. Dot memory	.26	.08	.39	.53	.48	—						
7. Paper folding	.42	.22	.49	.38	.25	.45	—					
8. Space relations	.44	.21	.42	.31	.23	.40	.71	—				
9. Card rotation	.34	.22	.22	.32	.33	.33	.40	.51	—			
10. Flags	.33	.17	.25	.28	.36	.33	.45	.58	.67	—		
11. Identical pictures	.15	.21	.16	.24	.21	.26	.31	.35	.22	.30	—	
12. Hidden patterns	.27	.21	.30	.39	.39	.36	.36	.34	.33	.39	.40	—

Note. The directionalities of the Tower of Hanoi and RNG scores were reversed so that higher scores indicate better performance for all tasks. All correlations greater than or equal to .16 were significant at the .05 level. RNG = random number generation factor scores.

To What Extent Are Visuospatial STM and WM Tasks Separable?

The first goal of this study was to specify the extent to which the storage-oriented STM span tasks and the storage-and-processing WM span tasks measure the same underlying construct in the visuospatial domain. Of particular interest was the hypothesis that, in contrast to the verbal domain, WM and STM tasks may implicate central executive functioning or controlled attention equally strongly in the visuospatial domain. We performed a series of CFAs to address these issues.

The first step was to estimate the full, three-factor model that assumes some degree of separability among all three latent variables (i.e., Executive Functioning, Visuospatial WM, and Visuospatial STM). The estimated model, which provided the basis for later hypothesis testing, is illustrated in Figure 3. The numbers next to the longer straight, single-headed arrows are the standardized factor loadings, and those at the ends of the shorter straight, single-headed arrows represent the squared error terms, which are the unexplained variance for each task attributable to unique aspects of the task as well as measurement error. The numbers next to the curved, double-headed arrows are the estimated intercorrelations between the three latent variables. As shown in the figure, the interfactor correlations were moderate to high, ranging from .55 to .86 (all significantly larger than zero). The fit indices for this model were all quite good, as summarized in Table 3 (Model A_1). In addition to a nonsignificant chi-square, $\chi^2(6, N = 167) = 9.35$, $p > .10$, and a small χ^2/df value of 1.56, the SRMR value of .034 was well below the criterion of .05, and the CFI value of .98 was above the criterion of .95. Thus, all the indices indicated that the current model fit the data well.

After ascertaining that this baseline model provided a good fit to the data, we evaluated whether WM and STM span tasks differed in their relation to executive functioning or controlled attention. As the correlations in Figure 3 indicate, the Executive Functioning variable was almost equally correlated with the Visuospatial WM variable ($r = .55$, with the 95% confidence interval [CI] of .23 to .86) and with the STM variable ($r = .56$, with the 95% CI of .29 to .83), suggesting that, in the visuospatial domain, WM and STM

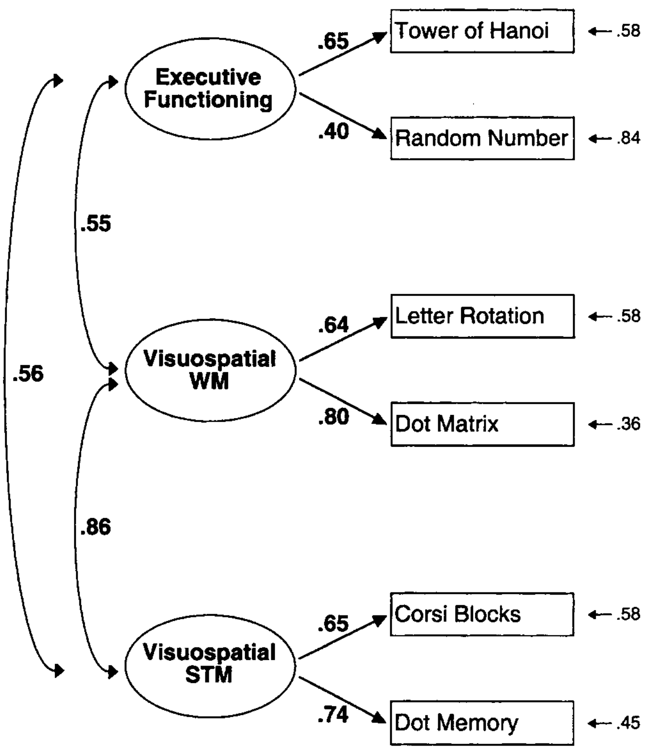

Figure 3. The estimated three-factor model for the three working-memory-related constructs. The longer single-headed arrows have standardized factor loadings next to them. The loadings, all significant at the .05 level, are standardized regression coefficients estimated with maximum-likelihood estimation. The numbers at the ends of the shorter single-headed arrows are squared error terms, which give estimates of the variance for each task that is not accounted for by the latent construct. The curved, double-headed arrows have correlation coefficients next to them and indicate significant correlations between the latent variables. WM = working memory; STM = short-term memory.

Table 3
Fit Indices for the Full Confirmatory Factor Analysis Model and Reduced Models for the Working Memory–Related Constructs (N = 167)

Model	*df*	$\chi^{2\,a}$	χ^2/df^b	SRMR[c]	CFI[d]
A_1 (depicted in Figure 3)	6	9.35	1.56	.034	.98
A_2 (equal correlations from Executive Functioning to WM and STM)	7	9.36	1.34	.034	.99
A_3 (STM–WM correlation = 1.0)	7	12.99	1.86	.038	.97
A_4 (equal correlations from Executive Functioning to WM and STM + STM–WM correlation = 1.0)	8	13.02	1.63	.038	.97

Note. No chi-square values were significant. SRMR = standardized root-mean-square residual; CFI = comparative fit index; WM = working memory; STM = short-term memory.
[a] χ^2 difference tests indicated that Models A_2 through A_4 were not significantly worse than Model A_1. [b] $\chi^2/df < 2$ indicates a good fit. [c] Lower values of SRMR indicate a better fit, with SRMR < .05 indicating a close fit. [d] CFI values above .95 indicate a good fit.

span tasks may not differ in the degree to which they implicate executive functioning. This conclusion was corroborated by a more formal statistical test of this hypothesis. Specifically, we created a model in which these two correlations were constrained to be equal (Model A_2) and pitted it against the full, three-factor model (Model A_1). As expected, this restricted model fit the data just as well as the full model, $\Delta\chi^2(1, N = 167) = 0.01, p > .10$, and the estimate of the magnitude of these correlations constrained to be equal was .56. These results suggest that, although WM span tasks may implicate more executive functioning than STM span tasks in the verbal domain, WM and STM span tasks are equally closely related to executive functioning in the visuospatial domain.

This result, combined with the high correlation between the Visuospatial WM and STM variables ($r = .86$), raises the question of whether Visuospatial WM and STM span tasks should be considered to be measuring the same construct. Consistent with this view, the 95% CI for the correlation between Visuospatial WM and STM was .70 to 1.01, containing 1.0.[5] Moreover, a model that constrained the correlation between the Visuospatial WM and STM variables to 1.0 (Model A_3 in Table 3) provided a fit that was not significantly worse than the full, three-factor model (Model A_1), $\Delta\chi^2(1, N = 167) = 3.64, p < .10$.

Given these findings, a more parsimonious model than the original three-factor model appears to be one in which the two restrictions tested above were simultaneously imposed—not only were the correlation between Executive Functioning and Visuospatial WM and the one between Executive Functioning and Visuospatial STM constrained to be equal, but the correlation between Visuospatial WM and STM was also set to 1.0. As summarized in Table 3, the fit of this reduced model (Model A_4) was quite good and was again statistically no worse than that of the full three-factor model (Model A_1), $\Delta\chi^2(2, N = 167) = 3.67, p > .10$, suggesting that this is indeed a more parsimonious model than the original model. For clarity and simplicity, this new model can be redrawn as the one depicted in Figure 4, in which the Visuospatial WM and Visuospatial STM variables are collapsed into a single latent variable, named the Visuospatial STM–WM variable. This model in Figure 4 is statistically equivalent to the one just described (Model A_4), a fact apparent from the observation that the fit of the model is identical to that of Model A_4, $\chi^2(8, N = 167) = 13.02, p > .10$, $\chi^2/df = 1.63$, SRMR = .038, CFI = .97. Thus, for reasons of parsimony, we use this revised two-factor model as the basis for our subsequent SEM analyses.[6]

Note that the Visuospatial STM–WM variable in Figure 4 does *not* represent a pure capacity of the visuospatial component of WM (or the visuospatial sketchpad). In the case of verbally oriented tasks, what is common between STM and WM span tasks is their shared verbal storage requirement (e.g., the capacity of the phonological loop) that reflects relatively little involvement from executive functioning or controlled attention (Engle, Tuholski, et al., 1999). In the case of visuospatial tasks, however, the common variance among the four Visuospatial STM and WM span tasks (i.e., the Visuospatial STM–WM variable) clearly includes more than simple storage capacity. It reflects substantial central executive involvement, as indicated by the moderate correlation between Executive Functioning and Visuospatial STM–WM ($r = .59$, with the 95% CI of .33 to .85).

This extensive executive involvement even for the simpler Visuospatial STM span tasks is consistent with the proposal that the visuospatial sketchpad is closely tied to the central executive (Baddeley, 1996b; Quinn, 1988; Quinn & McConnell, 1996) as well as with the suggestion that the maintenance of even a single item may require central executive involvement (Baddeley et al., 1999). The strong executive involvement for the STM span tasks may also reflect a fair amount of strategic processing that seems to take place during the performance of these tasks (Shah & Miyake, 1996). Although we tried to discourage the use of idiosyncratic strategies (see the *Method* section), many participants nonetheless spontaneously reported using strategies to cope with the visuospatial storage demand by, for example, mentally creating a path that links all the "tapped" boxes in order (for the Corsi blocks task) or forming an overall pattern with the presented dots (for the dot memory task). These strategies are not particularly well practiced for most participants, and implementing such effortful strategies likely makes the STM span tasks more than just simple storage

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[5] Although an actual correlation cannot exceed 1.0, the CI is the range that contains the true value of the correlation and hence is hypothetical. Consequently, it can span values greater than 1.0.

[6] For completeness, we also examined other reduced models: models that assume perfect correlations (a) between Executive Functioning and Visuospatial WM, (b) between Executive Functioning and Visuospatial STM, and (c) among all three latent variables. All these models produced significantly worse fits than the original, three-factor model (Model A_1; all *p*s < .05).

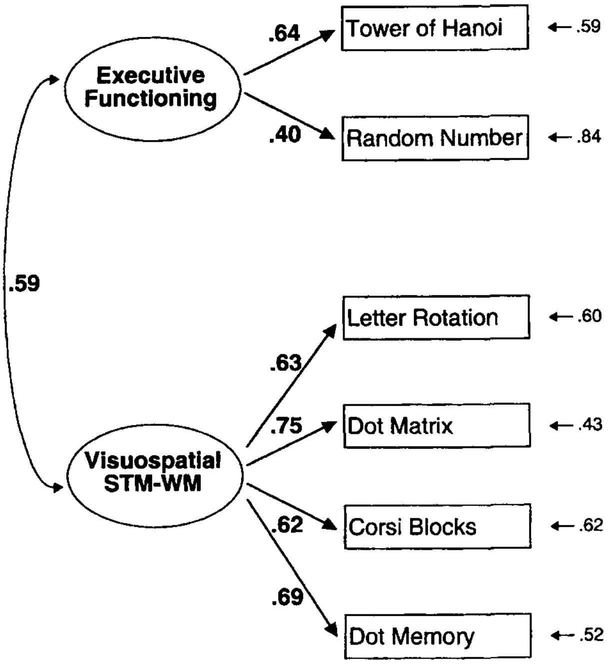

Figure 4. The revised two-factor model for the working-memory-related constructs. The values next to the longer single-headed arrows are standardized factor loadings; the values next to the shorter single-headed arrows are squared error terms; and the values next to the curved, double-headed arrows are correlation coefficients. The model is identical to the model depicted in Figure 3, except that the working memory (WM) and short-term memory (STM) variables have been collapsed into a single variable, as indicated by the fact that the tasks that previously loaded on two separate latent variables in Figure 3 now load on a single latent variable, Visuospatial STM–WM.

tasks. Thus, it might make sense that the Visuospatial STM tasks used in this study were related to Executive Functioning as strongly as were more complex Visuospatial WM tasks, even though the WM span tasks inherently had more executive-demanding characteristics than did the STM span tasks (e.g., explicit dual-tasking requirements, interference from the concurrent processing task).

Although these considerations clearly point to an asymmetry between the verbal and visuospatial domains, the current results based on the Visuospatial STM and WM tasks do not necessarily contradict Engle, Tuholski, et al.'s (1999) "WM = STM + controlled attention" proposal from the verbal domain. In fact, Engle, Tuholski, et al. cautioned about the variability in controlled attention or central executive functioning requirements among various WM and STM span tasks:

> To the extent that STM tasks demand controlled attention, they will also reflect the central executive or WM capacity construct. Further, what is clearly an STM task for some participants might be primarily a WM task for others. This is likely true not just at different levels of development but also among individuals at a given stage of development depending on intellectual abilities and skill in the task. (p. 312)

From this perspective, the difficulty of clearly differentiating STM and WM span tasks in the visuospatial domain may mean that the visuospatial STM span tasks used in the current study demanded a lot of controlled attention or central executive functioning, even for a cognitively restricted sample of young college students, hence virtually measuring what Engle, Tuholski, et al. would consider WM capacity (i.e., STM + controlled attention).

It is important to point out here that our discussions of the CFA results have relied on the findings that the fit of the restricted model in question was not significantly worse than that of the full, three-factor model. In this sense, our conclusions could be construed as being based on the acceptance of null hypotheses, and one could argue that greater statistical power might produce different results. While acknowledging such a possibility, however, we argue that the results presented above are theoretically informative for a number of reasons.

First, although a greater statistical power (e.g., a larger sample size) is likely to lead to the rejection of the statistical hypothesis that the correlation between Visuospatial WM and STM can be constrained to 1.0, the correlation was quite high (r = .86), particularly in comparison to the one found between the verbal WM and STM tasks in the Engle, Tuholski, et al. (1999) study (r = .68). Although no direct comparison can be made between the two studies, the current study had a larger sample size (N = 167) than the Engle, Tuholski, et al. study (N = 133), and the dependent measures we used also had reasonable distributions as well as reliabilities. Thus, in this context, the difficulty of separating the Visuospatial WM and STM variables seems meaningful. Second, our conclusion regarding the equivalent degree of executive involvement for Visuospatial WM and STM tasks is also based on the failure to detect differences between the full, three-factor model and a reduced model, but there, the difference between the two target correlations was virtually absent (.55 and .56, respectively; see Figure 3). Thus, increasing statistical power is unlikely to lead to the rejection of the statistical hypothesis that Visuospatial WM and STM are equally strongly related to Executive Functioning. Finally, these CFA results were predicted a priori on the basis of the existing evidence suggesting a close tie between executive functioning and the maintenance of visuospatial representations. Thus, for these reasons, we believe that the null hypothesis argument does not provide a major threat to our interpretation of the CFA results.

In summary, the results of the CFAs point to two related conclusions. First, in the visuospatial domain, the STM and WM span tasks are equally closely related to central executive functioning or controlled attention. In addition, the variance associated with the WM span tasks and that associated with the STM span tasks are almost identical in the visuospatial domain, suggesting that they may be essentially tapping the same underlying construct. These conclusions provide an interesting contrast to those derived from previous studies based primarily on verbal–numerical WM and STM span tasks.

How Are the Three Spatial Abilities Related to Executive Functioning and Visuospatial Storage?

After establishing the interrelationship among visuospatial WM and STM span tasks and executive functioning and settling on the most parsimonious model for these variables (Figure 4), we addressed the second main question: How are the three spatial ability

Table 4
Fit Indices for the Full Confirmatory Factor Analysis Model and Reduced Models for the Spatial Ability Factors (N = 167)

Model	*df*	χ^2 [a]	χ^2/df [b]	SRMR[c]	CFI[d]
B_1 (depicted in Figure 5)	6	5.49	0.92	.022	1.00
B_2 (one factor; all correlations = 1.0)	9	58.31*	6.48	.071	.86
B_3 (Spatial Visualization–Spatial Relations correlation = 1.0)	7	46.95*	6.71	.059	.89
B_4 (Spatial Visualization–Perceptual Speed correlation = 1.0)	7	19.70*	2.82	.055	.96
B_5 (Spatial Relations–Perceptual Speed correlation = 1.0)	7	19.33*	2.76	.056	.97

Note. SRMR = standardized root-mean-square residual; CFI = comparative fit index.
[a] χ^2 difference tests indicated that Models B_2 through B_5 were significantly worse than Model B_1. [b] $\chi^2/df < 2$ indicates a good fit. [c] Lower values of SRMR indicate a better fit, with SRMR < .05 indicating a close fit. [d] CFI values above .95 indicate a good fit.
$* p < .05$.

factors different in their relationships to the WM-related constructs (i.e., Visuospatial STM–WM and Executive Functioning)?

Before doing so, however, it was necessary to demonstrate that the six psychometric tests we used to capture the three specific spatial abilities indeed showed some separability according to the way we classified the tests. For this purpose, we performed CFAs on the six measures, using the same method described earlier. As summarized in Table 4, the full, three-factor model (Model B_1), illustrated in Figure 5, produced an excellent fit, $\chi^2(6, N = 167) = 5.49, p > .10, \chi^2/df = 0.92$, SRMR = .022, CFI = 1.00.

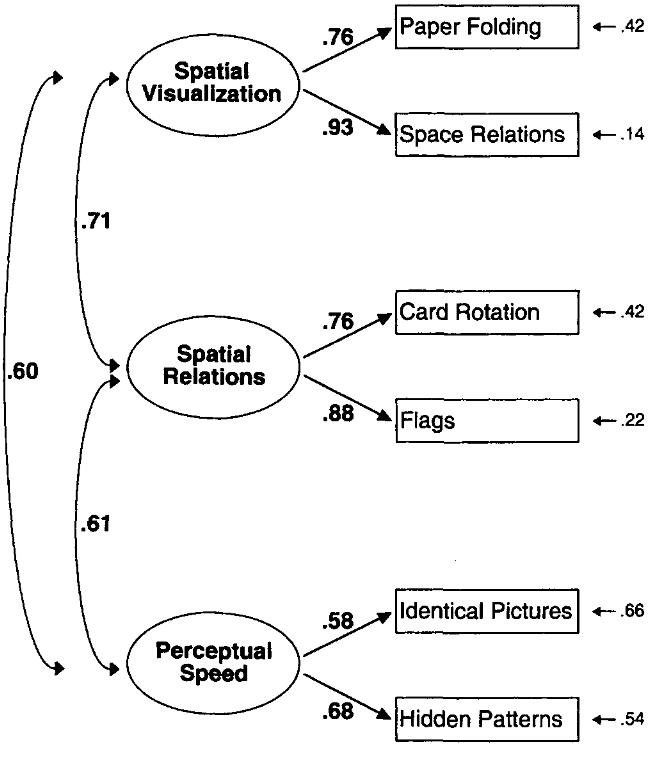

Figure 5. The estimated three-factor model for the spatial ability factors. The values next to the longer single-headed arrows are standardized factor loadings; the values next to the shorter single-headed arrows are squared error terms; and the values next to the curved, double-headed arrows are correlation coefficients. The model depicts three hypothesized spatial abilities (latent variables): Spatial Visualization, Spatial Relations, and Perceptual Speed. All loadings and correlations are significant at the .05 level.

As expected, the estimates of the intercorrelations between the three spatial ability latent variables were moderately high, ranging from .60 to .71, but none of the 95% CIs for the latent-variable correlations contained 1.0 (.59 to .82 for the Spatial Visualization and Spatial Relations factors, .43 to .79 for the Spatial Relations and Perceptual Speed factors, and .41 to .79 for the Spatial Visualization and Perceptual Speed factors). Given these CIs, it is not surprising that the model comparisons with χ^2 difference tests indicated that the full, three-factor model depicted in Figure 5 (Model B_1) provided a significantly better fit than any of the reduced models that assumed perfect correlations between two or all three of the latent variables (Models B_2 to B_5 in Table 4). These results are consistent with the general pattern of results from previous factor analytic studies of spatial abilities and suggest that the three spatial abilities tapped by the six psychometric tests are correlated but separable.

After confirming this point, we used SEM analyses to examine the relationship between the two WM-related constructs (i.e., Executive Functioning and Visuospatial STM–WM) and the spatial ability factors. To do so, we created the model illustrated in Figure 6, which simultaneously estimated the contribution of the two WM-related constructs in predicting each of the three spatial abilities. The model is basically the CFA model depicted in Figure 4 with the addition of the three spatial ability latent variables. Although, for simplicity, the individual tasks used to construct the latent variables are not explicitly represented in Figure 6, they were included in the models tested.[7] The standardized parameter estimates for this model are also provided in Figure 6, and the numbers at the ends of the shorter arrows are squared error terms, which give estimates of the variance for each spatial ability factor that is not accounted for by the Executive Functioning and Visuospatial STM–WM variables. Note that, although the correlation between the Executive Functioning variable and the Visuospatial

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[7] For this and all subsequent SEM models we tested, we allowed all of the factor loadings from the latent variables as well as interfactor correlations to vary (Anderson & Gerbing, 1988). Thus, the estimated parameters could differ somewhat from the values found for the CFA model, but major distortions to the factor structure should not occur unless the model is misspecified. In fact, in all of the SEM models we tested, there was no evidence for qualitative changes in the overall factor structure, and the changes in the parameters were all relatively small and were within the 95% CIs of the respective parameters in the original CFA model illustrated in Figure 4.

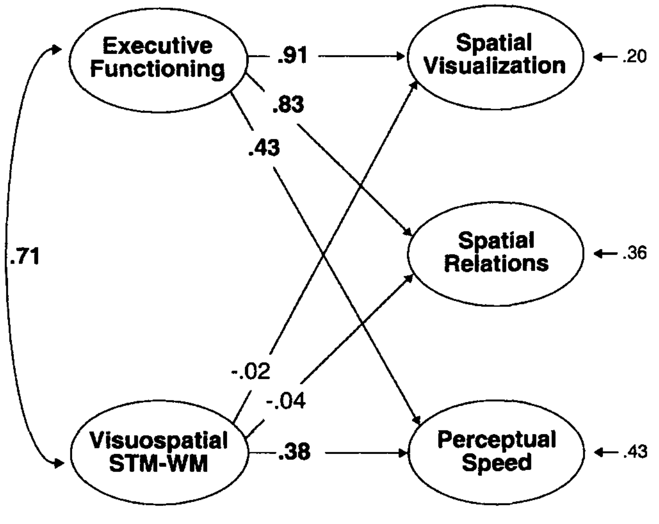

Figure 6. The main structural equation model tested, along with standardized parameter estimates (boldface indicates that the regression coefficients significantly differed from zero). The values next to the longer single-headed arrows are standardized factor loadings; the values next to the shorter single-headed arrows are squared error terms; and the values next to the curved, double-headed arrows are correlation coefficients. The model is basically the confirmatory factor analysis model (see Figure 4), with the addition of the three spatial ability latent variables (see Figure 5). The parameters of interest were the patterns of contributions from the Executive Functioning and Visuospatial short-term memory/working memory (STM–WM) variables to the spatial ability factors. Note that, although for simplicity the tasks that were used to construct the latent variables are not explicitly represented in the figure, they were present in the models tested. The squared error terms give estimates of the variance for each spatial ability factor that is not accounted for by the Executive Functioning and Visuospatial STM–WM variables.

STM–WM variable in this model (r = .71) was somewhat higher than the corresponding correlation (r = .59) in the two-factor CFA model we endorsed (see Figure 4), it was still within the 95% CI for the original correlation (.33 to .85).

The fit indices for this SEM model are presented in Table 5 (Model C_1). Although the overall χ^2 statistic was significant, $\chi^2(47, N = 167) = 76.84$, $p < .05$, the χ^2/df statistic (1.64) was well below the recommended criterion of 2.0, and the other fit indices also indicated a good fit, SRMR = .048 and CFI = .96, suggesting that this SEM model fit the data well overall. We thus used this model as the basis for subsequent model comparisons.

The crucial aspect of the SEM analyses concerned the relationship between the Executive Functioning and Visuospatial STM–WM variables and the three spatial ability variables (Spatial Visualization, Spatial Relations, and Perceptual Speed). We examined this relationship with the standardized path coefficients, also shown in Figure 6 (boldface indicates that the path coefficients are significantly different from zero). Because the model takes into account the correlation between the Executive Functioning variable and the Visuospatial STM–WM variable (.71), the path coefficients to the spatial ability factors are similar to multiple regression coefficients and thus can be interpreted as the contribution of each WM-related variable to the spatial ability factor in question, *controlling for the other variable.*

According to the predictions outlined earlier, Executive Functioning should be most strongly related to Spatial Visualization and least strongly related to Perceptual Speed. Overall, the magnitudes of the standardized path coefficients followed our predictions. The contribution of Executive Functioning was statistically significant for all three spatial abilities and, more important, was highest for the Spatial Visualization factor (.91), followed by the Spatial Relations factor (.83), and then by the Perceptual Speed factor (.43). To formally test whether these path coefficients were indeed significantly declining, we created a restricted model in which the three path coefficients were constrained to be equal to one another.[8] This reduced model (Model C_2 in Table 5) provided a significantly worse fit to the data than the model in Figure 6 (Model C_1) that allowed the three paths to differ, $\Delta\chi^2(2, N = 167) = 12.11$, $p < .05$, indicating that these path coefficients cannot be considered identical. Subsequent pairwise comparisons, in which we compared the full model (Model C_1) with restricted models in which two of the three coefficients were constrained to be equal, revealed that the path from Executive Functioning to Perceptual Speed was significantly lower than the other two paths from Executive Functioning (both $ps < .05$), which did not differ from each other ($p > .10$). Thus, even though the differentiation between the Spatial Visualization factor and the Spatial Relations factor was not completely clear-cut in this analysis, the overall pattern of the data was consistent with the hypothesis that the three spatial abilities differ in the demand they impose on executive functioning, with the demand highest for the Spatial Visualization factor and lowest for the Perceptual Speed factor.

Given that these path coefficients represent the degree of executive involvement not shared with the Visuospatial STM–WM variable and that this variable reflects strong executive involvement, the finding that the path coefficients between the Executive Functioning variable and the spatial ability factors were generally high is intriguing. Such large path coefficients suggest that, in addition to supporting the demanding process of maintaining visuospatial representations, executive functioning also contributes greatly to the performance of these spatial ability tests. Although precisely specifying the nature of this additional executive involvement is beyond the scope of this article, likely possibilities include some factors outlined in the introductory section, such as goal management and resistance to interference from external representations. In addition, being able to sustain one's attention to the task at hand (Baddeley et al., 1999; Engle, Kane, & Tuholski, 1999) and to efficiently select responses (Rowe, Toni, Josephs, Frackowiak, & Passingham, 2000) may also be part of what is reflected in the large path coefficients from Executive Functioning to the spatial ability factors, given that these abilities are clearly involved in the performance of spatial ability tests and also seem to be tapped by the two Executive Functioning tasks.

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[8] This comparison necessitated that the unstandardized coefficients be constrained to be equal. These unstandardized coefficients are affected by the variances of the tasks, and these tasks are on an arbitrary scale. Thus, before testing a model in which these parameters were constrained to be equal, it was necessary to make sure that the unstandardized path coefficients would be on the same scale. To do so, we standardized all of the manifest variables in the model to have a variance of 1.0 before testing the model with these paths constrained to be equal.

Table 5
Fit Indices for the Structural Equation Models Relating Working Memory-Related Constructs and Spatial Abilities (N = 167)

Model	*df*	χ^2 [a]	χ^2/df [b]	SRMR [c]	CFI [d]
C_1 (depicted in Figure 6)	47	76.84*	1.64	.048	.96
C_2 (three path coefficients from Executive Functioning constrained to be equal)	49	88.95*	1.82	.056	.94
C_3 (three path coefficients from Visuospatial STM–WM constrained to be equal)	49	79.70*	1.63	.049	.95
C_4 (spatial ability correlations added)	44	72.95*	1.66	.047	.96

Note. SRMR = standardized root-mean-square residual; CFI = comparative fit index; STM–WM = short-term memory/working memory.
[a] χ^2 difference tests indicated that Model C_2, but not Model C_3, was significantly worse than Model C_1; Model C_4 was not significantly worse than Model C_1. [b] $\chi^2/df < 2$ indicates a good fit. [c] Lower values of SRMR indicate a better fit, with SRMR $< .05$ indicating a close fit. [d] CFI values above .95 indicate a good fit.
* $p < .05$.

With respect to the Visuospatial STM–WM variable, our prediction was that all three spatial ability factors should implicate some degree of visuospatial storage. However, we did not have specific predictions for the rank ordering of the SEM path coefficients because, given the strong executive involvement in visuospatial storage, it was not clear to us how substantially the Visuospatial STM–WM variable, controlling for Executive Functioning, would be related to the spatial abilities. As shown in Figure 6, the path coefficients turned out to be generally small. In fact, the only path coefficient significantly different from zero was the one between Visuospatial STM–WM and Perceptual Speed (.38), and the other two were virtually zero (−.02 for Spatial Visualization and −.04 for Spatial Relations). These three path coefficients did not significantly differ from one another, however: A restricted model in which all three path coefficients were constrained to be equal (Model C_3 in Table 5) was not significantly worse than the model in which they were allowed to differ (Model C_1), $\Delta\chi^2(2, N = 167) = 2.86, p > .10$.

These small path coefficients from Visuospatial STM–WM to the spatial abilities do not mean that short-term storage of visuospatial information is an unimportant part of the spatial abilities. Given that these coefficients represent the contribution of the Visuospatial STM–WM variable that is *unrelated* to Executive Functioning, they instead mean that the visuospatial storage required for the performance on these spatial ability tests may depend strongly (or almost exclusively in the case of spatial visualization and spatial relations tests) on the involvement of executive functioning. From this perspective, it is interesting that the path coefficient from Visuospatial STM–WM to the Perceptual Speed factor was statistically significant (.38). Judging from the fact that perceptual speed tests seem to require brief, bufferlike maintenance of relatively simple shapes that do not require any transformations, this significant path coefficient may mean that there is indeed a passive, short-term visuospatial storage system for simple stimuli that operates in a bufferlike manner, but not as autonomously as its verbal analogue, the phonological loop.

These conclusions were corroborated by the analysis of the simple relationships among the latent variables that do not involve any statistical control. These simple relationships are given by the implied correlations, presented in Table 6. Each implied correlation is the full relationship between each pair of latent variables that is implied by the model in Figure 6, taking into account all of the paths, both direct and indirect, between them. Thus, the implied correlations provide an estimate of the extent to which the Executive Functioning and Visuospatial STM–WM variables are related to the spatial ability factors *without* controlling for the correlation between them.

As shown in Table 6, for the Executive Functioning variable, the implied correlations to Spatial Visualization, Spatial Relations, and Perceptual Speed were .90, .80, and .71, respectively. For the Visuospatial STM–WM variable, they were .63, .54, and .69, respectively. Thus, for the implied correlations involving Executive Functioning, the rank ordering of the correlation magnitudes was consistent with the results based on the path coefficients and with our predictions. Also consistent with our prediction is the observation that the implied correlations between the Visuospatial STM–WM variable and the three spatial ability factors were all moderately high, suggesting that the spatial ability tests indeed involve visuospatial storage. The finding that such moderately strong relationships essentially disappear when Executive Functioning is controlled for, however, reinforces the view that the visuospatial storage required for the performance of spatial ability tests is strongly (or even almost exclusively) tied to executive functioning.

The SEM analyses so far suggest that the two WM-related constructs (i.e., Executive Functioning and Visuospatial STM–WM) can explain the commonalities and differences among the three spatial abilities well. An interesting additional question is to what extent these two latent variables can account for the pattern of intercorrelations between the three spatial ability factors by themselves. To address this question, we compared the SEM model in Figure 6 to one that allowed the error variances of the three spatial abilities to correlate with one another. Notice that, unlike the CFA model depicted in Figure 5, the model in Figure 6 does not incorporate any direct intercorrelations between the three

Table 6
Intercorrelations Between the Latent Variables Implied by the Structural Equation Model in Figure 6

Variable	1	2	3	4	5
1. Executive Functioning	—				
2. Visuospatial STM–WM	.71	—			
3. Spatial Visualization	.90	.63	—		
4. Spatial Relations	.80	.54	.71	—	
5. Perceptual Speed	.71	.69	.63	.55	—

Note. STM–WM = short-term memory/working memory.

spatial ability factors. The lack of such direct correlations means that the model in Figure 6 incorporates the hypothesis that Executive Functioning and Visuospatial STM–WM can completely explain the pattern of intercorrelations between the three spatial ability factors (i.e., that these three spatial ability variables correlate because of their relations to Executive Functioning and Visuospatial STM–WM). In contrast, a model in which the intercorrelations between the error variances of the three spatial abilities are added hypothesizes that these spatial ability variables correlate over and above the correlations implied by their relations to Executive Functioning and Visuospatial STM–WM. Because the fit of this alternative model (Model C_4 in Table 5) was not significantly better than the fit of the original model (Model C_1), $\Delta\chi^2(3, N = 167) = 3.89$, $p > .10$, these additional parameters appear to be unnecessary.

This conclusion was further corroborated by the implied intercorrelations between the three spatial ability latent variables for the model depicted in Figure 6. As listed in Table 6, they were .71 between Spatial Visualization and Spatial Relations, .63 between Spatial Visualization and Perceptual Speed, and .55 between Spatial Relations and Perceptual Speed. These implied correlations are rather close to the actual intercorrelations between the three factors depicted in the CFA model in Figure 5 (.71, .60, and .61, respectively), which suggests that the two WM-related constructs were sufficient to fully explain the pattern of intercorrelations between the three spatial ability factors. These findings further endorse the view that executive functioning and (executive-dependent) visuospatial storage are the essence of the relations among these spatial abilities.

In summary, the results of the SEM analyses point to three main conclusions regarding the relationship between WM and spatial abilities. First, the three spatial ability factors indeed differed in the degree of executive involvement, with the Spatial Visualization factor showing the highest involvement and the Perceptual Speed factor showing the lowest. Second, all three spatial abilities require a substantial degree of visuospatial storage, but the maintenance of visuospatial representations involved in the performance on these spatial ability tests (particularly the Spatial Visualization and Spatial Relations tests) may be strongly tied to executive functioning or controlled attention. Finally, these relations between the WM-related constructs and the spatial ability factors are substantial. In fact, they are so substantial that, together, the Executive Functioning and Visuospatial STM–WM variables were able to essentially fully explain the pattern of the intercorrelations between the three spatial ability factors. These conclusions all agree with our predictions and suggest that a multicomponent view of WM can provide a useful framework for understanding the commonalities and differences among spatial abilities.

Qualifications for the Current Study

Although the CFA and SEM results we reported are generally clear-cut, we should add a couple of qualifications here. First, the results presented in this article are based on a restricted sample of young college students; thus, they may not be completely generalizable to more cognitively diverse samples, such as those that include noncollege students, young children, and older adults. However, given that cognitively more selective samples (such as the young college student sample in the present study) tend to show lower intercorrelations between different cognitive ability measures (Legree, Pifer, & Grafton, 1996), the main CFA finding of the nonseparability between visuospatial STM and WM span tasks is likely to generalize to more cognitively diverse samples. If anything, more diverse samples would likely reveal an even stronger involvement of executive functioning or controlled attention in the maintenance of visuospatial information.

A second qualification is that, although latent-variable analysis reduces measurement error and minimizes the effects of idiosyncratic aspects of individual tasks, the generalizability of the current results to a different set of tasks and psychometric tests (or even the same set of tasks administered differently) remains to be seen. This point is worth emphasizing, because the current study used only two representative tasks to construct each latent variable and, more important, because there is a considerable variability among various span tasks in the extent to which they require central executive functioning or controlled attention as pointed out earlier (Engle, Tuholski, et al., 1999). Depending on the characteristics of the span tasks used and the skill or ability level of the individual performing the tasks, qualitatively different results might be obtained.

General Discussion

We reported an individual-differences study that examined the relationships among visuospatial storage, executive functioning, and spatial abilities at the level of latent variables. The study had two major goals. The first goal was to examine the relationship between simple storage-oriented STM span tasks and complex storage-plus-processing WM span tasks in the visuospatial domain. The second goal was to specify the similarities and differences among three target spatial ability factors from the perspective of WM, particularly focusing on the visuospatial and executive components of the system. The results of the CFA and SEM analyses provided clear answers with respect to both of these goals.

The Relationship Between STM and WM Tasks

Regarding the first goal, the main finding of the study was that, in the visuospatial domain, STM and WM span tasks were related to executive functioning equally strongly and cannot be clearly differentiated. Although direct statistical comparisons cannot be made, such results provide an interesting contrast to the finding from an analogous latent-variable study from the verbal domain (Engle, Tuholski, et al., 1999) that suggested that STM and WM spans are related but clearly separable constructs in that WM span tasks implicate something significantly more (i.e., controlled attention) than do STM span tasks. This intriguing difference between verbal (phonological) storage and visuospatial storage puts important constraints on models of WM. Given that the evidence for such an asymmetry between the verbal and visuospatial domains has been growing (Baddeley, 1996b; Baddeley et al., 1999; Quinn, 1988; Quinn & McConnell, 1996; Shah & Miyake, 1996), any satisfactory comprehensive theory of WM should specify the nature of this asymmetry and provide an explanation of why such an asymmetry exists.

Although we do not know of any direct empirical testing of these issues, there are a number of possible reasons for this asymmetry between the two domains. One possibility, raised in the introductory section, is that the asymmetry may reflect differences in the extent to which the short-term maintenance of verbal (phonological) materials and visuospatial materials are practiced and automatized. As Baddeley (1996b) suggested, it seems plausible that memorizing dot patterns or a sequence of dot locations is not as practiced as maintaining information in the verbal domain and, hence, has to draw more heavily on executive control mechanisms. The asymmetry may also have to do with the fact that, although there is a well-practiced rehearsal mechanism for verbal–phonological materials (i.e., maintenance rehearsal using the articulatory control process of the phonological loop), no such common rehearsal mechanism seems to exist (or has been identified) for visuospatial materials.

Another related possibility concerns the architectural limitation of the visuospatial system. Specifically, the sheer capacity of the visuospatial sketchpad itself may be so severely limited—even more so than the capacity of the phonological loop (usually said to be the amount of verbal material that can be articulated within 1.5 or 2 s)—that performing any sufficiently complex visuospatial tasks would be impossible without the involvement of executive functioning. Consistent with this view, several studies have estimated the capacity for temporary visuospatial storage to be no more than one item (e.g., Ballard, Hayhoe, & Pelz, 1995; Phillips & Christie, 1977a). Moreover, as mentioned earlier, Baddeley et al. (1999) suggested that temporary maintenance of even a single visuospatial item can impose a considerable demand on the central executive. Given that there is no clear consensus as to what constitutes an "item" for visuospatial information, the validity of these claims regarding the sketchpad capacity is difficult to evaluate at this moment. To the extent that these claims are valid, however, such a severe capacity restriction may explain why the involvement of other WM subsystems (particularly the central executive) is necessary or essential in the maintenance of visuospatial information.

From a methodological standpoint, the results of the current study point to the importance of studying not only the verbal domain but also the visuospatial domain to understand the structure of the WM system as well as the nature of individual differences in WM. Most of the individual-differences studies of WM conducted so far have focused on the verbal domain, relying on one or more widely used verbal and numerical tasks, such as digit span and word span for STM span tasks, and reading span, operation span, and counting span for WM span tasks. As the current study demonstrated, however, the results may not completely generalize to the visuospatial domain. Thus, such an asymmetry between the two domains should serve as an important testing ground for the generality and generalizability of theoretical ideas or principles derived from the work conducted in the verbal domain.

The Relationship Between WM and Spatial Abilities

The second goal of the current study was to specify the similarities and differences among the three target spatial abilities (Spatial Visualization, Spatial Relations, and Perceptual Speed) from the perspective of a multicomponent view of WM. A major finding of the SEM analyses was that, consistent with our prediction, the three spatial ability factors differ in the extent to which they implicate executive functioning or controlled attention, with the executive involvement being the highest for the Spatial Visualization factor and the lowest for the Perceptual Speed factor. The results also suggested that an ability to maintain visuospatial representations is important across all three spatial ability factors, but that the visuospatial storage involved in the performance of those tasks may be strongly (or even almost exclusively for highly complex tasks) dependent on the involvement of executive functioning or controlled attention. Taken together with the finding that the two WM-related constructs were sufficient to fully explain the patterns of intercorrelations between the three spatial ability factors, these SEM results support the proposal that the efficiency of executive functioning (or controlled attention ability) and the ability to maintain visuospatial representations may be essential ingredients of these spatial abilities.

These conclusions shed new light on why spatial ability factors, particularly the Spatial Visualization and Spatial Relations factors, are not completely independent and are usually moderately correlated with one another (Carroll, 1993; Lohman, 1988). These factors are similar (and hence correlated with one another) in the sense that they rely on both executive functioning and visuospatial storage, but they also show some separability because the demands they place on the executive component are systematically different. Thus, depending on the difficulty or complexity levels of the psychometric tests or the ability or skill levels of the test takers, it might not always be possible to clearly distinguish these factors.

In this study, we focused on three major spatial ability factors (i.e., Spatial Visualization, Spatial Relations, and Perceptual Speed) identified in factor analytic studies (Carroll, 1993; Lohman, 1988). The two remaining major factors on Carroll's list are the Closure Flexibility and Closure Speed factors. Both are concerned with the speed of apprehending and identifying a visual pattern, often in the presence of distracting stimuli. In the case of the Closure Flexibility factor, test takers know in advance what the pattern is, whereas in the case of the Closure Speed factor, they do not. These factors were not included in this study, primarily because we did not have specific predictions regarding the contributions of different aspects of WM. We suspect, however, that they may be similar to the other three factors in the sense that they both probably rely on the visuospatial and executive components of WM.

For the Closure Flexibility factor, the necessity of internally maintaining a given pattern seems to require some degree of visuospatial storage, and the need to counteract the distracting stimuli seems to strongly implicate executive functioning. Thus, in our view, this factor is similar to the Spatial Visualization factor when the target pattern is complex and is highly disguised in the test stimuli, even though no spatial transformations have to be performed. Consistent with this proposal, the Hidden Figures Test (Ekstrom et al., 1976), a difficult Closure Flexibility task that requires identifying a complex pattern within an even more complex pattern (much more complex and difficult than the Hidden Patterns Test that we used in the present study), has sometimes been found to load on the Spatial Visualization factor (Lohman, 1988). Moreover, the results of a recent dual-task study also suggest that the executive and visuospatial components of WM are implicated in performance on the Hidden Figures Test (Miyake, Witzki, & Emerson, 2001).

The relationship between the Closure Speed factor and WM is less clear. Tests that load on this factor (such as the Gestalt Completion Test; Ekstrom et al., 1976) usually require test takers to visually identify familiar objects whose representations are highly degraded (e.g., a partly erased drawing of a ship). Given that such tasks do not seem to require the maintenance of a specific visual pattern, the Closure Speed factor may rely on visuospatial storage to a lesser extent than other spatial ability factors. Instead, performance on such tests is likely to be aided by strategic mental searches of possible objects, and hence the contribution of executive functioning may be relatively high. Although speculative (particularly for Closure Speed), these considerations would be consistent with the proposal that what unifies different spatial abilities is the involvement of both the visuospatial and executive components of WM.

This WM interpretation of spatial abilities is highly consistent with both the hierarchical models (e.g., Carroll, 1993) and the nonhierarchical radex models (e.g., Marshalek et al., 1983) of human intelligence, developed within the psychometric tradition. As Marshalek et al. pointed out, both models suggest a complexity continuum along which cognitive tasks can be ordered. In these models, the more complex a task is, the more strongly it tends to be correlated with *g*, and the higher it is placed in the hierarchy (in the hierarchical models) or the closer it is placed to the center of the configuration (in the radex models). For example, in Marshalek et al.'s radex model, various spatial ability tests cluster together into one wedge, separate from verbal and numerical tests. Furthermore, complex spatial visualization tests such as the Paper Folding Test appear near the center of the configuration, whereas much simpler perceptual speed tests such as the Identical Pictures Test appear more toward the periphery. From the perspective of the present SEM results, this complexity continuum nicely corresponds to the degree of central executive involvement, and the clustering of spatial ability tests into one wedge can be interpreted as indicating the involvement of visuospatial storage mechanisms for all spatial ability tests.

Our discussion has focused on one specific aspect of cognitive abilities, namely, spatial ability, but the results from the current study also have an implication for *g* and its psychological basis. Most relevant is the finding that in the SEM model we focused on (see Figure 6), the standardized path coefficients from the Executive Functioning variable to the three spatial ability factors were quite high, particularly for the paths to the Spatial Visualization factor (.91) and to the Spatial Relations factor (.83). This finding is intriguing when considered in the context of the common observation that spatial ability tests are among the best measures of *g* or general fluid intelligence (Lohman, 1996). Given that the path coefficients control for the correlation with the Visuospatial STM–WM variable and hence are not attributable to the maintenance of visuospatial representations, these high path coefficients are consistent with the proposal that the efficiency of domain-general central executive functioning or controlled attention ability may indeed be a crucial underpinning of *g* (Conway et al., in press; Duncan et al., 1996; Engle, Kane, & Tuholski, 1999; Engle, Tuholski, et al., 1999; Kyllonen, 1996).

Concluding Remarks

As this study has illustrated, a multicomponent view of WM provides a useful framework within which to understand the nature of traditional psychometric abilities and, more generally, human intelligence. Kyllonen (1996) articulated the advantages of studying intelligence from the perspective of WM particularly clearly:

> Working memory capacity is not susceptible to the criticism of being a statistical artifact in the manner that *g* is. The working memory capacity construct does not depend on factor analysis for its identification. The working memory system was developed theoretically not as a label for an individual-differences factor, but rather as a construct to explain experimental results in the memory literature. (p. 73)

Given that WM research and intelligence research have interesting parallels (Miyake & Shah, 1999), a better understanding of WM is likely to illuminate the nature of human intelligence and help bring cognitive theories and psychometric theories into closer alignment.

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