The structure of working memory and how it relates to intelligence in children

David Giofrè[1], Irene C. Mammarella[2], Cesare Cornoldi[1]

[1] Department of General Psychology, University of Padova, Italy

[2] Department of Developmental and Social Psychology, University of Padova, Italy

Correspondence concerning this article should be addressed to:

David Giofrè

Department of General Psychology

University of Padova (Italy)

via Venezia 8 – 35131 – Padova - Italy

E-mail: david.giofre@gmail.com

Abstract

This study explored the structure of working memory, and its relationship with intelligence in 176 typically-developing children in the 4th and 5th grades at school. Different measures of working memory (WM), and intelligence (*g*) were administered. Confirmatory factor analyses showed that WM involves an attentional control system and storage aspects that rely on domain-specific verbal (STM-V) and visuospatial (STM-VS) resources. The structural equation models showed that WM predicts a large portion (66%) of the variance in *g,* confirming that the two constructs are separable but closely related in young children. Findings also showed that only WM and STM-VS are significantly related to *g,* while the contribution of STM-V is moderate. Theoretical implications for the relationship between WM and *g* are discussed.

Keywords: children; general cognitive ability; intelligence; working memory; WM; short-term memory; structural equation modelling

Highlights:

The tripartite model of working memory fits well in children. Working memory predicts 66% of the variance in children's intelligence. Short-term visuospatial memory also explains a large portion of the variance in children's intelligence.

1. **Introduction**

Working memory (WM) is a limited-capacity system that enables information to be temporarily stored and manipulated (Baddeley, 2000). It is involved in complex cognitive tasks such as reading comprehension (Borella et al., 2010, Carretti et al., 2009 and Daneman and Merikle, 1996) and arithmetical problem solving (Passolunghi and Mammarella, 2010, Passolunghi and Mammarella, 2012 and Passolunghi and Pazzaglia, 2004). Intelligence is the ability to reason, plan, solve problems, think abstractly, understand complex ideas, learn quickly, and learn from experience (Gottfredson, 1997).

Various models of WM have been suggested. We will discuss them here with reference to the different models presented in the current study. The most classical model (here called tripartite) was originally proposed by Baddeley and Hitch (1974). In this model the central executive (or working memory) is responsible for controlling the resources and monitoring information-processing across informational domains. In addition, the storage of information is mediated by two domain-specific slave systems (or short-term memory, STM), i.e., the phonological loop (used for the temporary storage of verbal information), and the visuospatial sketchpad (specialized in recalling visual and spatial representations). This model has met with a broad consensus (Baddeley, 2012), and further developments of the model (Baddeley, 2000) have maintained the distinction between a modality-independent component and modality-dependent verbal and visuospatial components of STM.

An alternative approach (modality-dependent model) does not include the distinction between short-term memory and WM. The model is based only on the assumption that WM is supported by two separate sets of domain-specific resources for handling verbal and visuospatial information (e.g., Shah & Miyake, 1996), each of which would be independently capable of manipulating the information and keeping it active (i.e., readily accessible). Research on adults supports this distinction (Friedman & Miyake, 2000).

A different approach (modality-independent model) distinguishes between a storage component (typically characterized as a STM component) and a processing component, and suggests that WM processing capacity is limited by controlled attention (Engle, Tuholski, Laughlin, & Conway, 1999). Working memory tasks are considered the result of the joint activity of the storage and processing functions (e.g., Engle et al., 1999). This model and the tripartite Baddeley and Hitch (1974) model share the distinction between a central component for coordinating ongoing information processing (called controlled attention and central executive, respectively) and the component(s) for storing information in subsystems. The hypothesis that different components can be distinguished within WM has met with criticism, however. In particular, other authors have argued that STM and WM are hardly distinguishable (e.g., Martínez et al., 2011) and suggested a unitary model of WM, especially in the case of children (e.g., Pascual-Leone, 1970). Whether or not WM and STM reflect the same or different factors is still being debated (e.g., Colom, Rebollo, Abad, & Shih, 2006).

Regarding the structure of WM in children, it is not clear to what extent models proposed for adults can be applied to children too. As already mentioned, some authors favour a unitary view (Pascual-Leone, 1970), some (e.g., Engel De Abreu, Conway, & Gathercole, 2010) support a distinction between STM and WM (i.e., a modality-independent model), and others (e.g., Cornoldi and Vecchi, 2003 and Mammarella et al., 2008) have suggested that WM is even more articulated. Finally, Alloway and colleagues (Alloway, Gathercole, & Pickering, 2006) claimed that the tripartite model (Baddeley & Hitch, 1974) is the most appropriate across various age ranges.

Understanding the structure of WM is crucial when it comes to examining the relationship between WM and intelligence, in both adults and children. Research indicates that WM and intelligence are separable but closely-related constructs (Engle et al., 1999). For instance, a meta-analysis showed a correlation of $r = .48$ between WM and intelligence (Ackerman, Beier, & Boyle, 2005), though the correlation between latent variables is typically higher, $r = .72$ (Kane, Hambrick, & Conway, 2005). This incomplete overlap suggests that the two constructs are not isomorphic

(Conway, Kane, & Engle, 2003) and that the relationship between them needs to be further

elucidated.

In particular, research on children has produced less robust evidence concerning the

relationship between intelligence and WM. It has been argued, for example, that WM, not

intelligence, is the best predictor of literacy and numeracy (Alloway & Alloway, 2010), and that

child prodigies may have only a moderately high level of intelligence, but perform extremely well

in WM (Ruthsatz & Urbach, 2012). Such evidence further supports the conviction that WM and

intelligence are separable, but more evidence is needed to confirm this.

In addition, studies on the relationship between STM, WM and intelligence in children

often have their limitations. Firstly, only one task (e.g., Raven) has often been used to assess

intelligence, whereas performance in different measures (preferably using different formats)

should be considered to reduce the specific effects of a given test and treat intelligence as a

latent construct (Süß & Beauducel, 2005). Secondly, not all studies have distinguished

between (verbal and spatial) STM and WM, making it impossible to compare the different

models used. Thirdly, the results of many studies may have been biased by the use of the

absolute credit score for WM tasks: this score only considers the number of trials completed

perfectly, whereas it might be better to take partial recall into account too in the most difficult

trials to reflect the maximum level of performance a person may reach when WM is engaged

in highly-demanding tasks. The absolute credit score is appropriate in clinical settings, while

the partial credit score is more reliable and appropriate in correlational studies (Conway et al.,

2005, Friedman and Miyake, 2005 and Unsworth and Engle, 2007), as it results in higher

correlations with criterion measures than does the absolute credit score method.The scoring

procedure seems to be particularly important when testing different models of WM. In adults

at least, the partial credit score, taking into account also the performance in the most difficult

longest lists, may emphasize the role of STM in explaining human intelligence (Unsworth &

Engle, 2007). In fact, the correlation between WM and intelligence does not change as a

function of list length but the correlation between simple STM and intelligence does change. Indeed, the partial credit score contains the same information as the absolute credit score method plus additional information from items on lists that were not perfectly recalled. Importantly, STM and WM, at least in adults, seem to equivalently predict higher order cognitive abilities when the variability from long list lengths is considered (Unsworth & Engle, 2007).

The fact that STM and WM are predicting intelligence to the same extent, at least in adults, is consistent with the claim advanced by some researchers that STM accounts for the relationship between WM and intelligence (Chuderski, Taraday, Nęcka, & Smoleń, 2012; Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008; Colom, Abad, Rebollo, & Shih, 2005; Krumm et al., 2009). However, this claim has been questioned both in general and, in particular, in the developmental literature (e.g., Engel De Abreu et al., 2010).

Be that as it may, further light needs to be shed on the relationship between STM, WM and intelligence in children. There is some evidence of the WM component having a stronger relationship with intelligence than the STM components. This impression has been influenced by original work provided by Engle and co-authors of the residual variance in WM reflecting controlled processing (once the STM component has been partialled out), which is uniquely linked to general fluid intelligence (Engle et al., 1999). To give an example, Engel de Abreu and co-authors (2010) studied young children, and found WM, STM and fluid intelligence related but separate constructs, and WM was the best predictor of intelligence. Conversely, Hornung et al. reported (2011), again in a study on young children, that once the storage component had been taken into account, only STM explained a significant portion of the variance in intelligence. Further studies are therefore needed to clarify the pattern of the relationships between these constructs.

In the present research, we explored the nature of the relationship between STM, WM and intelligence. These aspects were examined in 4th- and 5th-graders because their ages represent important transitions associated with wide mind reorganisations and, therefore, are particularly

appropriate for emphasizing the relationship between different aspects of WM and intelligence (see Demetriou, et al., 2013). In particular, we examined: i) different models of WM in children, using confirmatory factor analyses (CFA); ii) the relationship between WM and intelligence, and the strength of their association, using structural equation modelling (SEM).

Our first aim was to use CFA to elucidate the structure of WM in children by comparing the following models (see also Fig. 1): (1) a unitary model, considering WM as a single construct (Pascual-Leone, 1970); (2) a modality-dependent model, distinguishing between a visuospatial and a verbal component, without distinguishing between STM and WM (Shah & Miyake, 1996); (3) a modality-independent model, distinguishing between WM and STM, without distinguishing between content domains (Engle, et al., 1999); (4) a tripartite model, expanded to include a distinction between two STM components (verbal *vs.* spatial), and including a WM component (Baddeley, 1986).

The second aim of our study was to test the relationship between WM and intelligence using a SEM approach. We tested the best-fitting model obtained by comparing the above-mentioned models (which proved to be the tripartite model), examining whether short-term memory – in its verbal (STM-V) and visuospatial (STM-VS) components – and WM carry a similar weight, irrespective of the demands of the memory tasks administered, in terms of the processes and presentation format involved in predicting intelligence. Previous findings in children on this issue are unclear: some studies suggest that, when the variance that WM and STM have in common is controlled, only the residual WM factor reveals a significant link with intelligence (Engel De Abreu et al., 2010); other research indicates that the relationship between WM and intelligence is explained primarily by STM (Hornung et al., 2011). In addition, some authors have argued that both storage and executive processes in the WM system can independently predict intelligence (Tillman, Nyberg, & Bohlin, 2008), but well-controlled WM processes have a higher predictive power in typically-developing children than poorly-controlled STM processes (Cornoldi, Giofrè, Calgaro, & Stupiggia, 2013). The inclusion of both verbal and visuospatial STM tasks in our study also gave us

an opportunity to test whether the latter are more closely related to intelligence than the former (as suggested by Kane et al., 2004).

To sum up, the purpose of the present study was to investigate: *i)* whether it would be more appropriate to see children's WM as separable into different components than as a single factor; and *ii)* which WM component is more closely related to intelligence.

2. Method

2.1. Participants

We collected data for 183 children, but 7 of them had extremely low scores on the Raven's Coloured progressive matrices (below the 5th percentile of the Italian norms, Belacchi, Scalisi, Cannoni, & Cornoldi, 2008) and were excluded from further analyses. A total of 176 typically-developing children (96 males, 80 females; $M_{age} = 9.27$, SD = .719) in 4th and 5th grade at school were thus included in the final sample.

2.2. Materials

2.2.1. Intelligence

Coloured progressive matrices (CPM*; Raven, Raven, & Court, 1998).* We selected the CPM (coloured progressive matrices) instead of the classical SPM (standard progressive matrices) because the CPM were standardized quite recently (Belacchi et al., 2008), also on data obtained in the age group considered in the present study, whereas the SPM standardization is very old and did not include the age group considered here. The CPM have good psychometric properties and loading on the *g*-factor (Belacchi et al., 2008; Raven et al., 1998). In fact, the two versions of the matrices should be substantially equivalent. The children were asked to complete a geometrical figure by choosing the missing piece from among 6 possible solutions. The patterns gradually became more difficult. The test consisted of 36 items divided into three sets of 12 (A, AB, and B). The score corresponded to the sum of the correct answers.

Primary mental ability, reasoning (PMA-R; Thurstone & Thurstone, 1963). This task assesses the ability to discover rules and apply them to verbal reasoning. It is a written test in which the children had to choose which word in a set of four was the odd one out, e.g. *cow, dog, cat, cap* (the answer is *cap*). There was only one correct answer. The test included 25 sets of words and children were allowed 11 minutes to complete it. The score was the sum of the correct answers.

Primary mental ability, verbal meaning (PMA-V; Thurstone & Thurstone, 1963). In this written test, the children had to choose a synonym for a given word from among four options, e.g. *small*: (a) *slow*, (b) *cold*; (c) *simple*; (d) *tiny* (the answer is *tiny*). There was only one correct answer. The test included 30 items and had to be completed within 12 minutes. The score was the sum of the correct answers.

2.2.2. **Working memory tasks**

Simple span tasks (syllable span task, SSPAN; and digit span task, DSPAN). These tasks examined short-term memory abilities involving the passive storage and recall of information (Cornoldi & Vecchi, 2000, 2003; Swanson, 1993). Syllables/digits were presented verbally at a rate of 1 item per second, proceeding from the shortest series to the longest (from 2 to 6 items). There was no time limit for recalling the syllables or digits in the same, forward order. The score was the number of digits/syllables accurately recalled in the right order.

Matrices span tasks (derived from Hornung et al., 2011). Short-term visuospatial storage capacity was assessed by means of two location span tasks. The children had to memorize and recall the positions of blue cells that appeared briefly (for 1 second) in different positions on the screen. After a series of blue cells had been presented, the children used the mouse to click on the locations where they had seen a blue cell appear. The number of blue cells presented in each series ranged from 2 to 6. There were two different conditions: in the first, the targets appeared and disappeared in a visible (4 × 4) grid in the centre of the screen (*matrices span task, grid [MSTG]*); in the second, the targets appeared and disappeared on a plain black screen with no grid (*matrices

span task, no grid [MSTNG]). The score was the number of cells accurately reproduced in the right order.

Categorization working memory span (CWMS; Borella, Carretti, & De Beni, 2008; De Beni, Palladino, Pazzaglia, & Cornoldi, 1998). The material consisted of a number of word lists containing four words of high-medium frequency. The word lists were organized into sets containing word lists of different length (i.e., from two to five words to recall). The children were asked to read each word aloud and to press the space bar when there was an animal noun. After completing each set, they had to recall the last word in each list, in the right order of presentation. The score was the number of accurately recalled words.

Listening span test (LST; Daneman & Carpenter, 1980; Palladino, 2005). The children listened to sets of sentences arranged into sets of different length (containing from 2 to 5 sentences) and they had to say whether each sentence was true or false. After each set, the children had to recall the last word in each sentence, in the order in which it was presented. The score was the number of accurately recalled words.

Visual pattern test, active (VPTA; Mammarella et al., 2006 and Mammarella et al., 2013). This task tests the ability to maintain and process spatial information simultaneously presented on a computer screen. Eighteen matrices, adapted from the Visual Pattern test (Della Sala, Gray, Baddeley, & Wilson, 1997), of increasing size (the smallest with 4 squares and 2 cells filled, the largest with 14 squares and 7 cells filled) contained a different number of cells to remember (from 2 to 7). After the matrices had been shown for 3 seconds, they disappeared and the children were presented with a blank test matrix on which they were asked to reproduce the pattern of the previously-seen cells by clicking in the cells corresponding to the same positions but one row lower down (the bottom row in the presentation matrix was always empty). The score was the number of accurately placed cells.

2.3. Procedure

The selection of the tasks was based on agreements with the schools participating in the study. In particular, the tasks were administered as part of a broad study on the relationship between cognitive structures and academic achievement.

The children were tested in two phases, one involving a group session in their classroom that lasted approximately 1 h, the other in individual sessions lasting approximately 90 min, in a quiet room away from the classroom.

During the group session, the intelligence tests were administered in a fixed order (CPM, PMA-V, PMA-R). At the individual sessions, the WM tasks were also administered in a fixed order as follows: (1) syllable span task; (2) matrix span task, grid; (3) visual pattern test, active; (4) categorization working memory span; (5) digit span task; (6) matrix span task, no-grid; (7) listening span task. At the individual sessions, all tasks were presented on a 15-inch laptop and were programmed using E-prime 2 software. Each task began with two training trials followed by the simplest level of the task, and the complexity then gradually increased thereafter, using three trials for each level of complexity. The partial credit score was used for scoring purposes (see Conway et al., 2005).

3. Results

3.1. Statistical analysis

The assumption of multivariate normality and linearity was tested using the PRELIS package and all the CFA and SEM analyses were estimated with the LISREL 8.80 software (Jöreskog & Sörbom, 2002, 2006).

Individual scores from any variable that were more than three standard deviations from the mean were defined as univariate outliers. Six values - three PMA reasoning, one digit span task, and one listening span test, 0.3% of the total - were found to be univariate outliers according to this criterion, and were replaced with a value corresponding to 3 standard deviations from the appropriate mean (Tabachnick & Fidell, 2007).

No multivariate outliers were found (Mahalanobis distance; $p < .001$). The measure of relative multivariate kurtosis was 1.018. This value is considered relatively small, so the estimation method that we chose (maximum likelihood) is robust against several types of violation of the multivariate normality assumption (Bollen, 1989).

Model fit was assessed using various indices following the criteria suggested by Hu and Bentler (1999). In particular, a model was judged to have a good fit if it had: a non-significant χ^2_M goodness-of-fit statistic; a root mean square error of approximation (*RMSEA*) nearing .06; a standardized root mean square residual (*SRMR*) = .08; a non-normed fit index (*NNFI*) and a comparative fit index (*CFI*) = .96. The Akaike information criterion (*AIC*) was used to compare the fit of non-nested models. To take the children's different ages into account, a partial correlation analysis was conducted with age in months partialled out (Alloway et al., 2006). Partial correlations were used in all the analyses. Descriptive statistics, correlations, partial correlations, and Cronbach's alphas are presented in Table 1.

<div align="center">Table 1 About here</div>

3.1.1. WM models

We compared a series of models.

Model 1 investigated a single WM factor in children (unitary model; Fig. 1); it provided a poor fit with the data (Table 2).

Model 2 investigated two distinct verbal and spatial factors (modality-dependent model; Fig. 1), and provided a poor fit with the data (Table 2).

Model 3 investigated two distinct STM and WM factors (modality-independent model; Fig. 1); and provided a poor fit with the data (Table 2). We attempted to improve the model's fit by excluding a test (i.e., MSTNG) from the analysis.

Model 3b investigated two distinct STM and WM factors with three indicators for factor (modality-independent model; Fig. 1). This model was considered because STM and WM were more balanced in this way: there were three indicators, i.e., two verbal and one spatial task for each

factor. The fit improved, but this model did not provide a fit as good as Model 4 (i.e., a significant

chi-square, RMSEA = .08, and NNFI < 96; Table 2).

Model 4 tested two STM factors (verbal [- V], and visuospatial [- VS]) and one WM factor

(tripartite model; Fig. 1). It fitted well with the data and proved better than the other models (Table

2), suggesting that the structure of children's WM may be well represented by combining two STM

components (one verbal and one spatial) with a WM component (Baddeley & Hitch, 1974).

Figure 1 about here

Table 2 about here

3.1.2. WM and intelligence models

We used a two-step modelling approach (Kline, 2011). In the first step, Model 5, we estimated a

CFA measurement model testing the relationship between STM-V, STM-VS, WM and *g* (Fig. 2).

The fit of this model was good (Table 2).

Since the fit of Model 5 was good, we tested the fit of alternative SEM models in the second

step. In Model 6, STM-V, STM-VS, WM (correlated with one another) were considered as

exogenous, or independent factors, and *g* was considered as the endogenous, or dependent factor (

Fig. 3). The overall fit of the model was good (Table 2), and 65% of the variance in *g* was

predicted. Notably, only STM-VS and WM were significantly related to *g*, while STM-V had a non-

significant negative effect on *g*. [1]

Figure 3 about here

We also tested an alternative model, Model 7a, in which both STM-V and STM-VS were

regressed on WM and *g* was regressed on STM-V, STM-VS, and WM (Fig. 4). This model,

provided a very good fit to the data, better than the previous model (Table 2), and showed that WM

is directly and indirectly related to *g*. Intriguingly, although the relation between *g* and STM-VS is

lower than the *g*-STM-V relation, the path from STM-V to *g* is not significant (ß = - .38, *SE* = .22, *z* = - 1.711, 95% CI [- .82, .06]), compared to the path from STM-VS to *g* (ß = .30, *SE* = .11, *z* = 2.78, 95% CI [.09, .51]).[1] This model explained 66% of the *g* variance, so it was judged to fit well with the data and proved better than the other models (Table 2).

To shed light on the non-significant negative relation between STM-V and *g* we tested other equivalent/nested models. In the case of Model 7b, we eliminated the direct effect of WM on *g* (Fig. 5). This model provided a not entirely satisfactory fit to the data (Table 2). Since Model 7b was nested to 7a, we also calculated the chi-square difference, which indicated that Model 7a had a better fit than Model 8b ($\chi_D[1] = 18.63$, *p* < .001). The variance explained in *g* also dropped to 47%. This result implies that the direct effect of WM, which is not mediated by STM (-V and VS), accounts for about 19% of the *g* variance. In the case of Model 7c, when we restored the direct effect of WM on *g* and removed the direct effect of STM-V on *g*, the explained variance in *g* diminished (from 66% to 56%), confirming that STM-V predicts a portion of the *g* variance even though the relationship between STM-V and *g* is not significant. Importantly, Model 7c had a good fit, even better than Model 7a ($\chi_D[1] = 4.18$, *p* = .041), except for the significant chi-square.

In the case of Model 7d, to test whether STM-V predicts a significant portion of the *g* variance, we regressed STM-V on WM and correlated STM-V and *g* residuals (Fig. 5). This model is equivalent to Model 7a, so the two models have the same fit (Table 2). Here again, the explained variance in *g* in this Model 7d dropped from 66% (as in Model 7a) to 60%. Importantly, the relationship between STM-V and *g* was weaker. Conversely, the STM-V and *g* relation only accounted for about 4% of the variance once the contribution of WM was partialled out.

Figure 5 about here

To sum up: i) STM-VS is significantly related to *g,* and this result is consistent in all the models tested; ii) the effect of STM-V on *g* is not large; iii) WM directly explains a large portion of the *g* variance.

3.2. Additional analysis

We decided to test the final model (7a) using the same number (i.e., two) and the same types (i.e., one verbal and one spatial) of indicators for each factor. This was necessary because it might be argued that the pattern of the relationship could have been influenced by an imperfect balance in the number/types of indicators for each factor. We therefore eliminated one task (i.e., the CWMS, which was less reliable than the LST; Table 1) from the WM factor. The models provided a good fit to the data and the results were similar to those in Model 7a (Table 2; Model A1). In fact, the relationship between *g* and STM-V was negative, and not significant (β = -.35; 95% CI [-.94, .23]), whereas the path from STM-VS to *g* was positive and significant (β = .30; 95% CI [.05, .55]); this confirmed the results obtained in Model 7a after balancing the number and types of indicators for each factor. In addition, the direct effect of WM on *g* was high (β = .82), as was the total explained variance in *g* (i.e., 61%). The SEM analyses (Models 6-7a) conducted using this particular model generated a pattern of results similar to the pattern obtained with previous models.

4. Discussion

The purpose of the present study was to investigate the structure of WM and the relationship between WM and intelligence in 4th- and 5th-grade children. In particular, we examined: *i)* whether children's WM could be seen as a single factor, or separated into different components; and *ii)* which WM component is more closely related to intelligence. Concerning the first issue, many different models have been proposed that differ according to whether they are unitary or articulated, whether they distinguish between different modalities and/or between a storage STM component and a processing WM component. The main results of the present study indicate that our data fitted poorly with a unitary WM model, and

with two-factor models that were either modality-dependent (distinguishing between visuospatial and verbal components [see Shah & Miyake, 1996]) or modality-independent (distinguishing between STM and WM [e.g., Engle et al., 1999]). Our findings indicate that children's WM can be well represented by three components, consistently with the tripartite model, which distinguishes between a WM component and two storage components relying on domain-specific verbal and visuospatial resources. This result is consistent with previous research on populations of developmental age (e.g., Alloway, Gathercole, Kirkwood, & Elliott, 2009; Alloway et al., 2006).

As for the second issue, we investigated whether the division into three factors postulated in the tripartite WM model could describe the relationship between WM and intelligence. We found visuospatial STM (STM-VS) and the WM components significantly related to intelligence. This result is consistent with the observation that STM-VS (typically involving unfamiliar situations) predicts a unique portion of the variance not explained by active WM (Kane et al., 2004), whereas the verbal component (i.e., STM-V) (typically involving more familiar material) is less relevant. Our results also confirm that WM predicts a substantial portion of the g variance even when the effect of STM is taken into account (Conway, Getz, & Engel De Abreu, 2011).

Unlike previous research (e.g., Kane et al., 2004), our findings cannot be attributed to our g factor being biased towards spatial abilities because two of the three measures of intelligence used in our study were verbal (i.e., vocabulary and reasoning). The less clear relationship between intelligence and verbal STM tasks seems to have at least two reasons: i) the simple rote repetition of familiar material, tested in the verbal short-term memory tasks, might have little to do with fluid intelligence (Engle et al., 1999); (ii) the age bracket (8–10 years old) considered in the present study is characterised both by a transition from iconic to symbolic (verbal) working memory, and this might introduce important individual differences, and by a robust relationship between WM and intelligence (Demetriou et al.,

2013). The relationship between STM-V was therefore large but not significant because of the high variability, which can be explained by the above-mentioned marked individual differences.

The present study showed a relationship between WM and *g*. Unlike the close relationship between WM and intelligence seen in adults (e.g., Engle et al., 1999; Kane et al., 2004), previous research on children provided unclear evidence on the strength of the relationship between intelligence and WM. In some cases, it was only modest (e.g., Engel De Abreu et al., 2010), while in others (e.g., Demetriou et al., 2013) WM and *g* shared a substantial portion of the variance, in agreement with our results, in which it was particularly high (about 66%).

Although it contains some insightful findings, the present study has some limitations. First, we only considered 4th- and 5th-graders and so, although previous studies have suggested that the overall structure of WM remains much the same in children of different ages (Alloway et al., 2006), our findings may not be generalizable to samples of younger or older children. In fact, previous research has also shown that verbal and visuospatial WM follow a different developmental trajectory (Gathercole, 1998), and that the relationship between WM and *g* may change as a child grows up (see also Demetriou et al., 2013). The importance of the developmental perspective is further supported by the specific finding of a negative relationship between verbal STM and intelligence, not seen in the adult literature, which seems more compatible with the view that attributes importance to the passage from the iconic to the symbolic stage in children (Bruner, Olver, & Greenfield, 1966) and to other developmental changes observed in children too (see also Demetriou et al., 2013).

A second limitation of the present study concerns the number and the choice of tasks. To comply with the school's requirements, we were obliged to restrict the number of tasks administered and our choice was particularly appropriate for testing the classical tripartite model and the

treatment of intelligence as a single factor. It may be that a different choice of tasks could better support the other models.

In fact, we used a relatively limited set of measures to investigate children's WM, i.e. two verbal short-term, two visuospatial short-term, and three working memory tasks. This did not allow for any testing of alternative three-factor models of WM, or any distinction between verbal and visuospatial working memory. The choice of tasks used in this study was initially based on the standard WM model generally applied to developmental samples. It is common knowledge that visuospatial short-term memory and visuospatial working memory are strongly correlated to each other (Kane et al., 2004; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001). The literature on children also provides evidence of the links between the central executive domain-general processing construct and the domain-specific constructs (and the visuospatial one in particular) being higher in younger children, meaning that younger children draw more on executive resources (or controlled attention) than older children (e.g., Alloway et al., 2006; Cowan et al., 2005). Nevertheless, further studies should test other WM models, particularly to distinguish not only between verbal and spatial STM, but also between verbal and spatial WM components.

We also considered g as a unitary construct. In fact, the feasibility of differentiating between fluid (gF) and crystallised intelligence (gC) in children has been considered (e.g., Brydges, Reid, Fox, & Anderson, 2012), but also questioned (Johnson & Bouchard, 2005). We opted not to draw this distinction for two reasons: first, because tasks considered gC tasks in adults might also be closely related to gF in children; second, because distinguishing between gF and gC would have been difficult considering their relationship with the verbal and visuospatial components of WM due to the fact that gF tasks is traditionally measured by means of visual/spatial tasks, and gC tasks is measured using verbal ones. The relationship between verbal and visuospatial memory components and fluid/crystallised intelligence might therefore have been biased by the content of these visual and verbal tasks, respectively. Hence the need for future research to address this issue,

particularly by administering a variety of intelligence measures involving *gF* and *gC,* and considering different models of intelligence.

To sum up, the present study found, in 4th- and 5th-grade children, that the WM structure best fitting our data is characterized by a central component and two STM domain-specific storage components, devoted to retaining verbal information in one and spatial information in the other. As for the relationship between WM and intelligence, the WM component and STM-VS do significantly predict intelligence, while STM-V does not. Finally, our findings also confirm a large body of evidence to indicate that WM is strongly related to intelligence.

References

Ackerman, P. L., Beier, M. E., & Boyle, M. O. (2005). Working memory and intelligence: the same or different constructs? *Psychological Bulletin*, *131*(1), 30–60. doi:10.1037/0033-2909.131.1.30

Alloway, T. P., & Alloway, R. G. (2010). Investigating the predictive roles of working memory and IQ in academic attainment. *Journal of Experimental Child Psychology*, *106*(1), 20–9. doi:10.1016/j.jecp.2009.11.003

Alloway, T. P., Gathercole, S. E., Kirkwood, H., & Elliott, J. (2009). The cognitive and behavioral characteristics of children with low working memory. *Child Development*, *80*(2), 606–21. doi:10.1111/j.1467-8624.2009.01282.x

Alloway, T. P., Gathercole, S. E., & Pickering, S. J. (2006). Verbal and visuospatial short-term and working memory in children: are they separable? *Child Development*, *77*(6), 1698–716. doi:10.1111/j.1467-8624.2006.00968.x

Baddeley, A. D. (1986). *Working memory (vol. 11)*. Oxford, England: Oxford University Press.

Baddeley, A. D. (2000). The episodic buffer: a new component of working memory? *Trends in Cognitive Sciences*, *4*(11), 417–423. doi:10.1016/S1364-6613(00)01538-2

Baddeley, A. D. (2012). Working memory: theories, models, and controversies. *Annual review of psychology*, *63*, 1–29. doi:10.1146/annurev-psych-120710-100422

Baddeley, A. D., & Hitch, G. J. (1974). Working Memory. In G. A. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 8, pp. 47–90). New York: Academic Press.

Belacchi, C., Scalisi, T., Cannoni, E., & Cornoldi, C. (2008). *CPM—Coloured progressive matrices standardizzazione Italiana*. Florence, Italy: Giunti O. S.

Bollen, K. A. (1989). *Structural equations with latent variables*. New York, NY: Wiley.

Borella, E., Carretti, B., & De Beni, R. (2008). Working memory and inhibition across the adult life-span. *Acta Psychologica*, *128*(1), 33–44. doi:10.1016/j.actpsy.2007.09.008

Borella, E., Carretti, B., & Pelegrina, S. (2010). The specific role of inhibition in reading comprehension in good and poor comprehenders. *Journal of Learning Disabilities*, *43*(6), 541–52. doi:10.1177/0022219410371676

Bruner, J. S., Olver, R. R., & Greenfield, P. M. (1966). *Studies in cognitive growth*. New York: John Wiley & Sons.

Brydges, C. R., Reid, C. L., Fox, A. M., & Anderson, M. (2012). A unitary executive function predicts intelligence in children. *Intelligence*. doi:10.1016/j.intell.2012.05.006

Carretti, B., Borella, E., Cornoldi, C., & De Beni, R. (2009). Role of working memory in explaining the performance of individuals with specific reading comprehension difficulties: A meta-

analysis. *Learning and Individual Differences*, *19*(2), 246–251. doi:10.1016/j.lindif.2008.10.002

Chuderski, A., Taraday, M., Nęcka, E., & Smoleń, T. (2012). Storage capacity explains fluid intelligence but executive control does not. *Intelligence*, *40*(3), 278–295. doi:10.1016/j.intell.2012.02.010

Colom, R., Abad, F. J., Quiroga, M. Á., Shih, P. C., & Flores-Mendoza, C. (2008). Working memory and intelligence are highly related constructs, but why? *Intelligence*, *36*(6), 584–606. doi:10.1016/j.intell.2008.01.002

Colom, R., Abad, F. J., Rebollo, I., & Shih, P. C. (2005). Memory span and general intelligence: A latent-variable approach. *Intelligence*, *33*(6), 623–642. doi:10.1016/j.intell.2005.05.006

Colom, R., Rebollo, I., Abad, F. J., & Shih, P. C. (2006). Complex span tasks, simple span tasks, and cognitive abilities: A reanalysis of key studies. *Memory & Cognition*, *34*(1), 158–171. doi:10.3758/BF03193395

Conway, A. R. A., Getz, S. J., & Engel De Abreu, P. M. J. (2011). Working memory and fluid intelligence: A multi-mechanism view. In R. J. Sternberg & S. B. Kaufman (Eds.), *The Cambridge Handbook of Intelligence*. Cambridge, UK: Cambridge University Press.

Conway, A. R. A., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin & Review*, *12*(5), 769–786. doi:10.3758/BF03196772

Conway, A. R. A., Kane, M. J., & Engle, R. W. (2003). Working memory capacity and its relation to general intelligence. *Trends in Cognitive Sciences*, *7*(12), 547–552. doi:10.1016/j.tics.2003.10.005

Cornoldi, C., Giofrè, D., Calgaro, G., & Stupiggia, C. (2012). Attentional WM is not necessarily specifically related with fluid intelligence: the case of smart children with ADHD symptoms. *Psychological Research*. doi:10.1007/s00426-012-0446-8

Cornoldi, C., & Vecchi, T. (2000). Mental imagery in blind people: The role of passive and active visuo-spatial processes. In M. Heller (Ed.), *Touch, representation and blindness* (pp. 143–181). Oxford, England: Oxford University Press.

Cornoldi, C., & Vecchi, T. (2003). *Visuo-spatial working memory and individual differences*. Hove: Psychology Pr.

Cowan, N., Elliott, E. M., Scott Saults, J., Morey, C. C., Mattox, S., Hismjatullina, A., & Conway, A. R. A. (2005). On the capacity of attention: its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychology*, *51*(1), 42–100. doi:10.1016/j.cogpsych.2004.12.001

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, *19*(4), 450–466. doi:10.1016/S0022-5371(80)90312-6

Daneman, M., & Merikle, P. M. (1996). Working memory and language comprehension: A meta-analysis. *Psychonomic Bulletin & Review*, *3*(4), 422–433. doi:10.3758/BF03214546

De Beni, R., Palladino, P., Pazzaglia, F., & Cornoldi, C. (1998). Increases in intrusion errors and working memory deficit of poor comprehenders. *The Quarterly Journal of Experimental Psychology*, *51*(2), 305–20. doi:10.1080/713755761

Della Sala, S., Gray, C., Baddeley, A. D., & Wilson, L. (1997). *Visual Patterns Test*. Bury St Edmonds, England: Thames Valley Test Company.

Demetriou, A., Spanoudis, G., Shayer, M., Mouyi, A., Kazi, S., & Platsidou, M. (2013). Cycles in speed-working memory-G relations: Towards a developmental–differential theory of the mind. *Intelligence*, *41*(1), 34–50. doi:10.1016/j.intell.2012.10.010

Engel De Abreu, P. M. J., Conway, A. R. A., & Gathercole, S. E. (2010). Working memory and fluid intelligence in young children. *Intelligence*, *38*(6), 552–561. doi:10.1016/j.intell.2010.07.003

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General*, *128*(3), 309–331. doi:10.1037/0096-3445.128.3.309

Friedman, N. P., & Miyake, A. (2000). Differential roles for visuospatial and verbal working memory in situation model construction. *Journal of Experimental Psychology: General*, *129*(1), 61–83. doi:10.1037/0096-3445.129.1.61

Friedman, N. P., & Miyake, A. (2005). Comparison of four scoring methods for the reading span test. *Behavior research methods*, *37*(4), 581–90. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/16629290

Gathercole, S. E. (1998). The Development of Memory. *Journal of Child Psychology and Psychiatry*, *39*(1), 3–27. doi:10.1111/1469-7610.00301

Gottfredson, L. (1997). Mainstream science on intelligence: An editorial with 52 signatories, history, and bibliography. *Intelligence*, *24*(1), 13–23. doi:10.1016/S0160-2896(97)90011-8

Hornung, C., Brunner, M., Reuter, R. A. P., & Martin, R. (2011). Children's working memory: Its structure and relationship to fluid intelligence. *Intelligence*, *39*(4), 210–221. doi:10.1016/j.intell.2011.03.002

Hu, L., & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling*, *6*(1), 1–55. doi:10.1080/10705519909540118

Johnson, W., & Bouchard, T. J. (2005). The structure of human intelligence: It is verbal, perceptual, and image rotation (VPR), not fluid and crystallized. *Intelligence*, *33*(4), 393–416. doi:10.1016/j.intell.2004.12.002

Jöreskog, K. G., & Sörbom, D. (2002). *PRELIS 2 User's reference guide.* (Third Edit.). Lincolnwood, IL: Scientific Software International.

Jöreskog, K. G., & Sörbom, D. (2006). *LISREL for Windows [Computer software]*. Lincolnwood, IL: Scientific Software International.

Kane, M. J., Hambrick, D. Z., & Conway, A. R. A. (2005). Working memory capacity and fluid intelligence are strongly related constructs: comment on Ackerman, Beier, and Boyle (2005). *Psychological Bulletin*, *131*(1), 66–71; author reply 72–5. doi:10.1037/0033-2909.131.1.66

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. W. (2004). The generality of working memory capacity: a latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology: General*, *133*(2), 189–217. doi:10.1037/0096-3445.133.2.189

Kline, R. B. (2011). *Principles and Practice of Structural Equation Modeling* (Third edit.). New York, NY: Guilford Press.

Krumm, S., Schmidt-Atzert, L., Buehner, M., Ziegler, M., Michalczyk, K., & Arrow, K. (2009). Storage and non-storage components of working memory predicting reasoning: A simultaneous examination of a wide range of ability factors. *Intelligence*, *37*(4), 347–364. doi:10.1016/j.intell.2009.02.003

Mammarella, I. C., Cornoldi, C., Pazzaglia, F., Toso, C., Grimoldi, M., & Vio, C. (2006). Evidence for a double dissociation between spatial-simultaneous and spatial-sequential working memory in visuospatial (nonverbal) learning disabled children. *Brain and Cognition*, *62*(1), 58–67. doi:10.1016/j.bandc.2006.03.007

Mammarella, I. C., Giofrè, D., Ferrara, R., & Cornoldi, C. (2013). Intuitive geometry and visuospatial working memory in children showing symptoms of nonverbal learning disabilities. *Child neuropsychology*, *19*(3), 235–49. doi:10.1080/09297049.2011.640931

Mammarella, I. C., Pazzaglia, F., & Cornoldi, C. (2008). Evidence for different components in children's visuospatial working memory. *British Journal of Developmental Psychology*, *26*(3), 337–355. doi:10.1348/026151007X236061

Martínez, K., Burgaleta, M., Román, F. J., Escorial, S., Shih, P. C., Quiroga, M. Á., & Colom, R. (2011). Can fluid intelligence be reduced to "simple" short-term storage? *Intelligence*, *39*(6), 473–480. doi:10.1016/j.intell.2011.09.001

Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P., & Hegarty, M. (2001). How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. *Journal of Experimental Psychology: General*, *130*(4), 621. doi:10.1037//0096-3445.130.4.621

Palladino, P. (2005). Uno strumento per esaminare la memoria di lavoro verbale in bambini di scuola elementare: taratura e validità. *Psicologia Clinica dello Sviluppo*, (25), 129–150. doi:10.1449/20152

Pascual-Leone, J. (1970). A mathematical model for the transition rule in Piaget's developmental stages. *Acta Psychologica*, *32*, 301–345. doi:10.1016/0001-6918(70)90108-3

Passolunghi, M. C., & Mammarella, I. C. (2010). Spatial and visual working memory ability in children with difficulties in arithmetic word problem solving. *European Journal of Cognitive Psychology*, *22*(6), 944–963. doi:10.1080/09541440903091127

Passolunghi, M. C., & Mammarella, I. C. (2012). Selective spatial working memory impairment in a group of children with mathematics learning disabilities and poor problem-solving skills. *Journal of Learning Disabilities*, *45*(4), 342–51. doi:10.1177/0022219411400746

Passolunghi, M. C., & Pazzaglia, F. (2004). Individual differences in memory updating in relation to arithmetic problem solving. *Learning and Individual Differences*, *14*(4), 219–230. doi:10.1016/j.lindif.2004.03.001

Raven, J., Raven, J. C., & Court, J. H. (1998). *Raven manual, Section 2 (Coloured Progressive Matrices)*. Oxford, England: Oxford Psychologist Press.

Ruthsatz, J., & Urbach, J. B. (2012). Child prodigy: A novel cognitive profile places elevated general intelligence, exceptional working memory and attention to detail at the root of prodigiousness. *Intelligence*, *40*(5), 419–426. doi:10.1016/j.intell.2012.06.002

Shah, P., & Miyake, A. (1996). The separability of working memory resources for spatial thinking and language processing: An individual differences approach. *Journal of Experimental Psychology: General*, *125*(1), 4–27. doi:10.1037/0096-3445.125.1.4

Süß, H. M., & Beauducel, A. (2005). Faceted models of intelligence. In O. Wilhelm & R. W. Engle (Eds.), *Handbook of measuring and understanding intelligence* (pp. 313–332). Thousand Oaks, CA: SAGE Publications.

Swanson, H. L. (1993). Working memory in learning disability subgroups. *Journal of Experimental Child Psychology*, *56*(1), 87–114. doi:10.1006/jecp.1993.1027

Tabachnick, B. G., & Fidell, L. S. (2007). *Using Multivariate Statistics (5th ed.)*. New York, NY: Allyn and Bacon.

Thurstone, L. L., & Thurstone, T. G. (1963). *Primary mental abilities*. Chicago, IL: Science Research.

Tillman, C. M., Nyberg, L., & Bohlin, G. (2008). Working memory components and intelligence in children. *Intelligence*, *36*(5), 394–402. doi:10.1016/j.intell.2007.10.001

Unsworth, N., & Engle, R. W. (2007). On the division of short-term and working memory: an examination of simple and complex span and their relation to higher order abilities. *Psychological Bulletin*, *133*(6), 1038–66. doi:10.1037/0033-2909.133.6.1038

Footnotes

[1] Notably, the path from STM-V to g is higher compared to the pattern from STM-VS to g. It is possible that this is due to the high correlation between STM-V and WM, which tends to increase the standard error, decreasing the precision of the path coefficient estimates. In fact, the 95% CI of the path from STM-V to g is wider that the CI 95% CI of the path from STM-VS and does include the 0.

Table 1

Correlations, means (M), standard deviations (SD), and reliabilities for the measures of g and WM.

	1	2	3	4	5	6	7	8	9	10
g										
1 CPM	1	.431	.432	.251	.132	.290	.313	.309	.226	.330
2 PMA-R	.447	1	.572	.261	.191	.383	.363	.351	.363	.181
3 PMA-V	.446	.618	1	.272	.242	.393	.387	.487	.402	.322
<u>WM</u>										
4 SSPAN	.261	.280	.291	1	.544	.249	.349	.398	.390	.241
5 DSPAN	.139	.200	.246	.546	1	.260	.313	.395	.464	.256
6 MSTG	.300	.397	.404	.258	.264	1	.720	.296	.301	.372
7 MSTNG	.332	.405	.435	.363	.318	.722	1	.302	.268	.288
8 CWMS	.324	.381	.509	.408	.399	.309	.329	1	.550	.292
9 LST	.247	.402	.445	.402	.465	.316	.303	.566	1	.378
10 VPTA	.335	.192	.322	.246	.259	.376	.295	.298	.383	1
M	28.26	16.32	20.73	41.80	46.30	39.50	29.53	26.59	27.43	59.81
SD	4.93	4.03	7.34	8.58	8.08	10.14	10.03	6.59	6.76	11.79
Reliability	.82	.78	.93	.69	.70	.83	.83	.77	.83	.91

Note. Zero order correlation below and partial correlation (controlling for age) above the diagonal; all coefficients $\geq$.148 are significant at .05 level; CPM=coloured progressive matrices; PMA-R=primary verbal abilities, reasoning; PMA-V=primary mental abilities, verbal; *S*SPAN=syllable span; DSPAN=number span; MSTG=matrix span task, grid; MSTNG=matrix span task, no-grid; CWMS=categorization working memory span; LST=listening span task; VPTA=visual pattern test active; Reliability=Cronbach's alpha.

Table 2

Fit indices for different CFA and SEM analysis for WM and WM and g relationship

Model	χ^2_M (df)	p	RMSEA	SRMR	CFI	NNFI	AIC
WM							
(1) CFA	117.57(14)	<.001	.20	.10	.80	.70	141.39
(2) CFA	37.64(13)	<.001	.11	.07	.95	.92	69.08
(3) CFA	93.95(13)	<.001	.20	.12	.84	.75	138.23
(3b) CFA	16.83(08)	=.032	.08	.06	.98	.95	42.41
(4) CFA	17.68(11)	=.088	.06	.04	.99	.98	51.57
WM and g							
(5) CFA	40.16(29)	=.081	.04	.04	.99	.98	89.31
(6) SEM	40.16(29)	=.081	.04	.04	.99	.98	89.31
(7a) SEM	41.34(30)	=.081	.04	.04	.99	.98	88.54
(7b) SEM	59.97(31)	=.001	.07	.06	.97	.96	105.82
(7c) SEM	45.52(31)	=.045	.05	.05	.99	.98	90.70
(7d) SEM	41.34(30)	=.081	.04	.04	.99	.98	88.54
Additional analysis							
(A1) SEM	33.35(22)	=.057	.05	.04	.99	.98	77.93

Note. χ^2_M = model chi-square, *RMSEA* = root mean square error of approximation, *SMSR* = standardized root mean square residuals, *CFI* = comparative fit index, *NNFI* = non-normed fit index, *AIC* = Akaike information criterion.
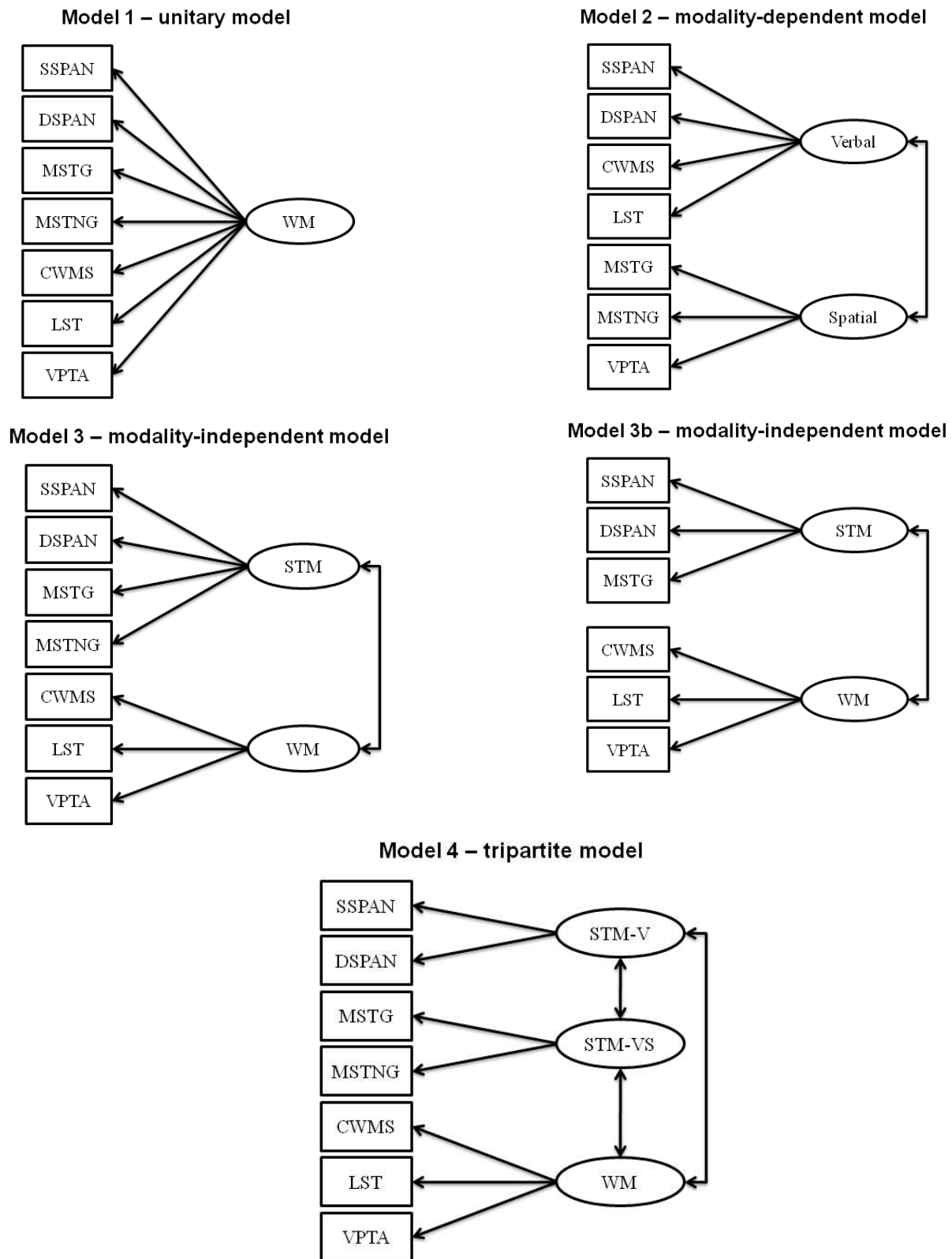
Figure 1. Conceptual diagrams for different WM models. *S*SPAN = syllable span; DSPAN = number span; MSTG = matrix span task, grid; MSTNG = matrix span task, no-grid; CWMS = categorization working memory span; LST = listening span task; VPTA = visual pattern test, active. STM-V = short-term memory, verbal; STM-VS = short-term memory, visuospatial; WM = working memory.
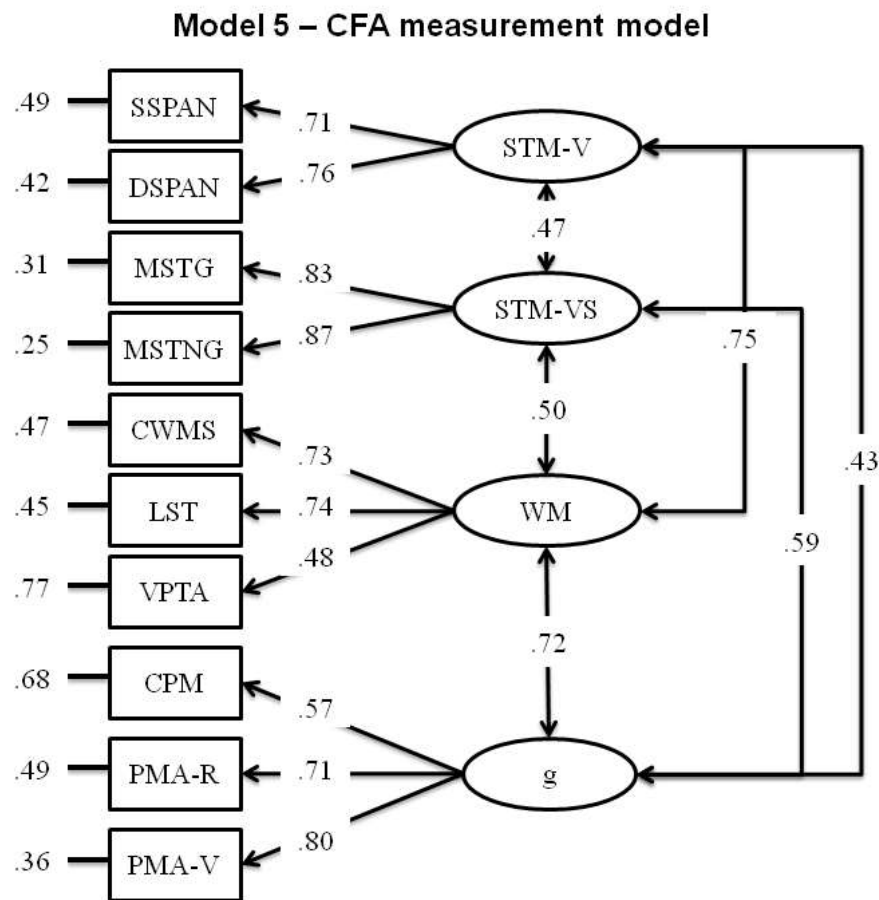
Figure 2. Measurement CFA model for STM-V, STM-VS, WM, and *g* relation. Paths significant at .05 level are indicated by solid lines. CPM=coloured progressive matrices; PMA-R=primary verbal abilities, reasoning; PMA-V=primary mental abilities, verbal; *S*SPAN=syllable span task; DSPAN=number span task; MSTG=matrix span task, grid; MSTNG=matrix span task, no-grid; CWMS=categorization working memory span; LST=listening span task; VPTA=visual pattern test, active; STM-V=short-term memory, verbal; STM-VS=short-term memory, visuospatial; WM=working memory; *g*=intelligence.
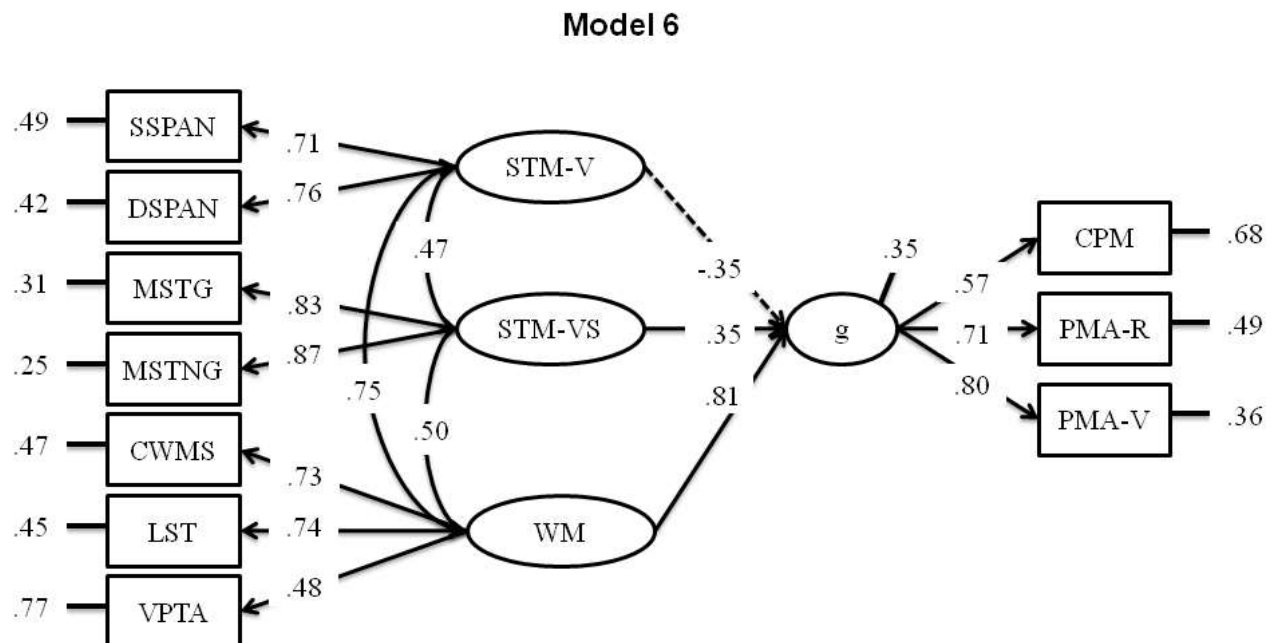
Model 6

Figure 3. SEM model for WM and *g* factor relationship (model 6). Paths significant at .05 level are indicated by solid lines. The residual variance components (error variances) indicate the amount of unexplained variance ($R^2 = 1$ - error variance). CPM=coloured progressive matrices; PMA-R=primary verbal abilities, reasoning; PMA-V=primary mental abilities, verbal; *S*SPAN=syllable span task; DSPAN=number span task; MSTG=matrix span task, grid; MSTNG=matrix span task, no-grid; CWMS=categorization working memory span; LST=listening span task; VPTA=visual pattern test, active; STM-V=short-term memory, verbal; STM-VS=short-term memory, visuospatial; WM=working memory; *g*=intelligence.
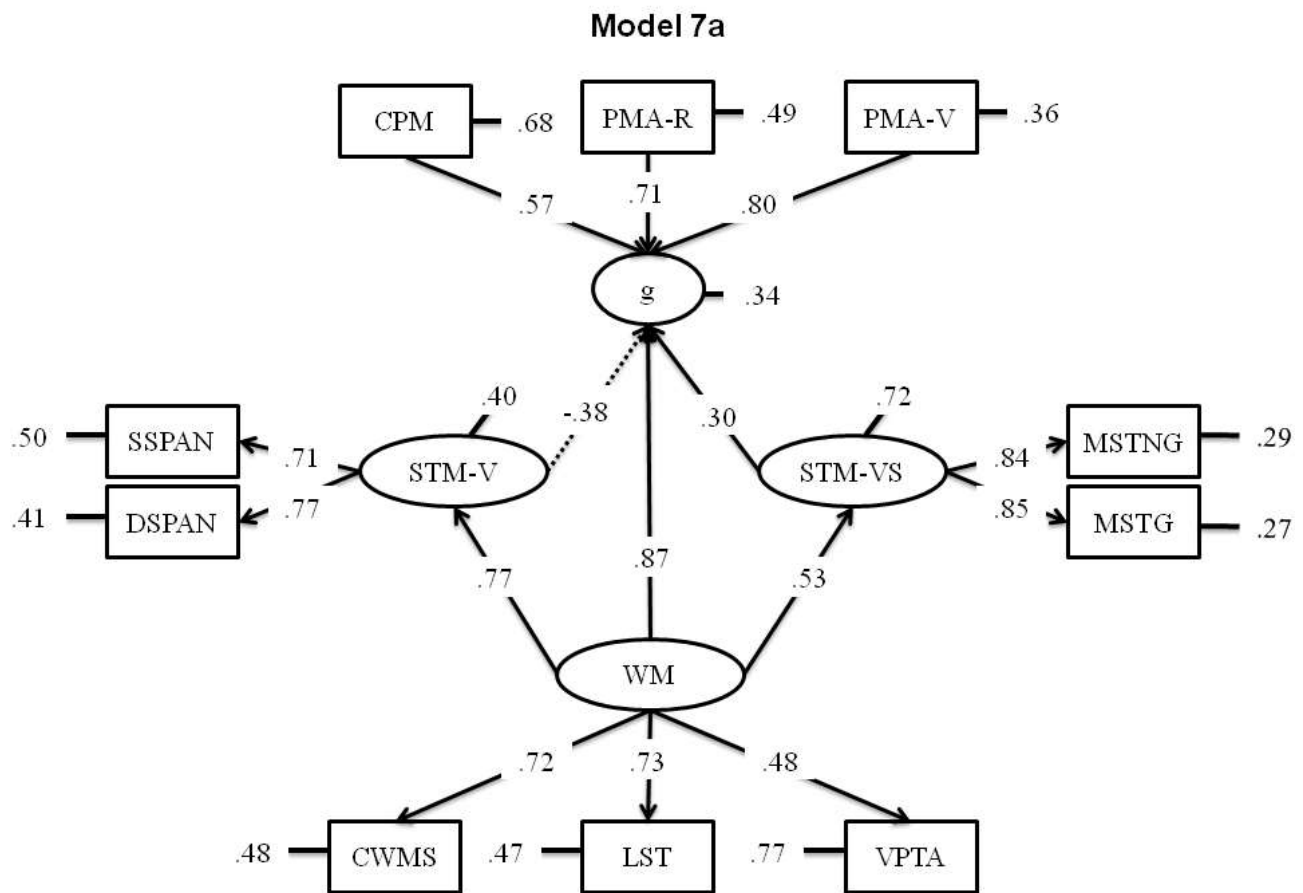
Figure 4. SEM with STM-V and STM-VS mediating the relationship between WM and *g*. Paths significant at .05 level are indicated by solid lines. The residual variance components (error variances) indicate the amount of unexplained variance (R^2= 1 - error variance). CPM=coloured progressive matrices; PMA-R=primary verbal abilities, reasoning; PMA-V=primary mental abilities, verbal; *S*SPAN=syllable span task; DSPAN=number span task; MSTG=matrix span task, grid; MSTNG=matrix span task, no-grid; CWMS=categorization working memory span; LST=listening span task; VPTA=visual pattern test, active; STM-V=short-term memory, verbal; STM-VS=short-term memory, visuospatial; WM=working memory; *g*=intelligence.
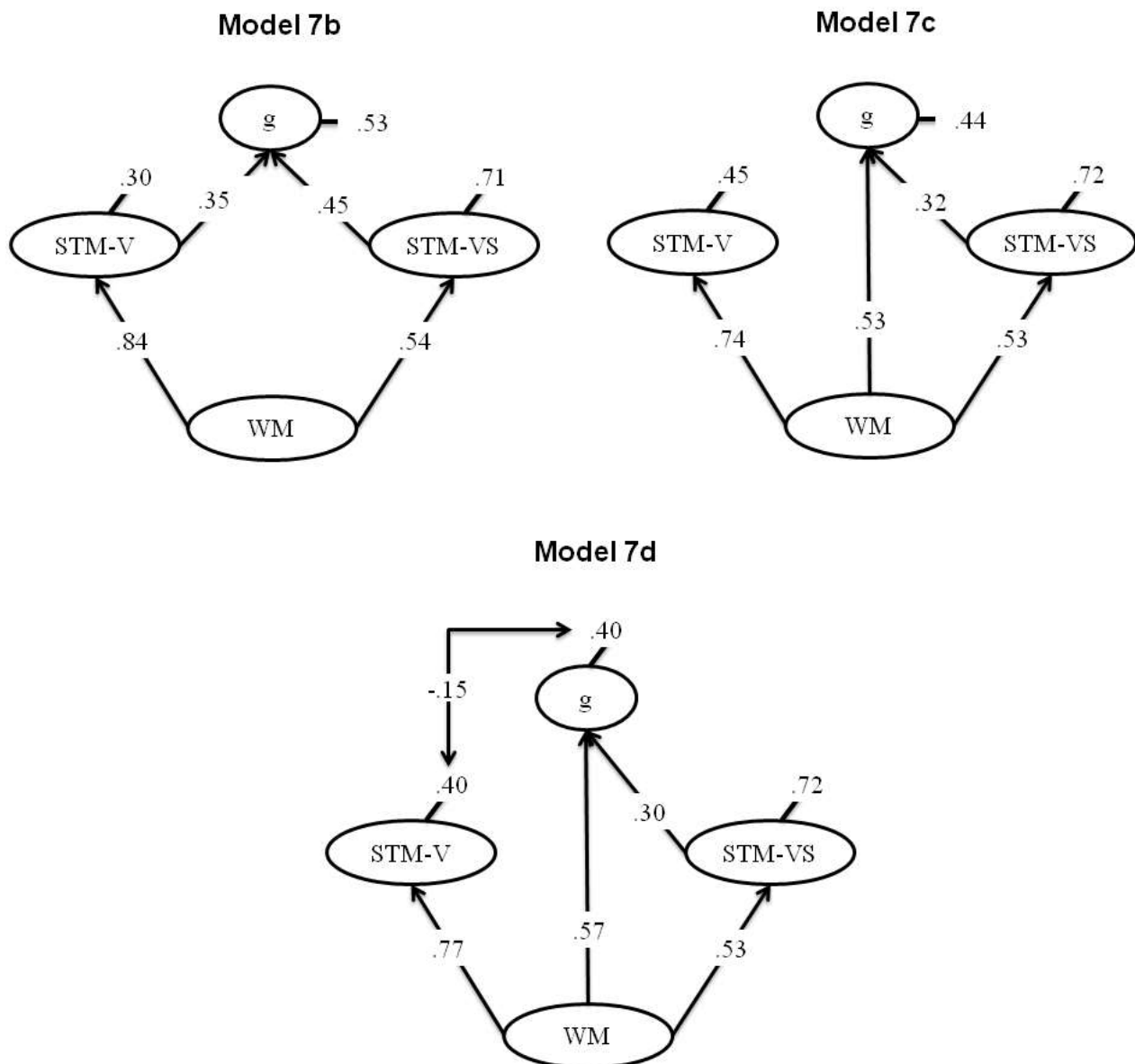
Figure 5. Models 7b and 7c are nested and 7d is equivalent to model 7a. Paths significant at .05 level are indicated by solid lines. The residual variance components (error variances) indicate the amount of unexplained variance (R^2= 1 - error variance). CPM=coloured progressive matrices; PMA-R=primary verbal abilities, reasoning; PMA-V=primary mental abilities, verbal; SSPAN=syllable span task; DSPAN=number span task; MSTG=matrix span task, grid; MSTNG=matrix span task, no-grid; CWMS=categorization working memory span; LST=listening span task; VPTA=visual pattern test, active; STM-V=short-term memory, verbal; STM-VS=short-term memory, visuospatial; WM=working memory; *g*=intelligence.