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**The relationship between working memory and intelligence in children:**

**Is the scoring procedure important?**

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### **Abstract**

Different procedures have been proposed for scoring working memory (WM) tasks. The Absolute Credit Score (ACS) only considers performance in perfectly recalled trials, while the Partial Credit Score (PCS) considers imperfectly recalled ones too. Research indicates that different relationships between WM and general intelligence (the *g*-factor) may emerge using the ACS or the PCS. We reanalyzed the ACS and PCS obtained in a sample of 176 children in the 4<sup>th</sup> and 5<sup>th</sup> grades, and found that the PCS strengthened the relationship between WM and intelligence, and the relationships between visuospatial short-term memory (STM-VS), active WM and intelligence. When the number of items to be remembered (set size) was considered, however, the PCS only strengthened the relationship between STM-VS, active WM and intelligence in the case of larger set sizes. Practical and theoretical implications of these findings are discussed.

*Keywords:* Working memory; intelligence; *g*-factor; scoring procedure; children.

## 1 Introduction

Working memory and intelligence are closely-related constructs. Working memory (WM) is a limited-capacity system that enables information to be stored temporarily and manipulated (Baddeley, 2000). Intelligence is the ability to reason, plan, solve problems, think abstractly, understand complex ideas, learn quickly, and learn from experience (Gottfredson, 1997).

Intelligence and WM have both been linked to important outcomes. On the one hand, intelligence is related to academic and occupational achievements (Deary, Strand, Smith, & Fernandes, 2007; Schmidt & Hunter, 2004). On the other, a large body of research has shown that WM predicts success in school-related tasks such as reading comprehension (Carretti, Borella, Cornoldi, & De Beni, 2009), mental calculation (Caviola, Mammarella, Cornoldi, & Lucangeli, 2009), mathematical problems (Alloway & Passolunghi, 2011), multi-digit operations (Heathcote, 1994), and achievement in mathematics (Passolunghi, Mammarella, & Altoè, 2008) and geometry (Giofrè, Mammarella, Ronconi, & Cornoldi, 2013). Intelligence and WM are closely related and share a conspicuous portion of the variance (e.g., Engle, Tuholski, Laughlin, & Conway, 1999; Giofrè, Mammarella, & Cornoldi, 2013).

The very close relationship between WM and intelligence raises the question of whether or not the two constructs overlap. Initial evidence seemed to indicate that WM and intelligence were very closely related (Kyllonen & Christal, 1990) and almost isomorphic (e.g., Colom, Abad, Rebollo, & Shih, 2005). These findings were questioned when it came to adults, however. In fact, 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). In children too, there is evidence of WM and intelligence being separable (e.g., Engel De Abreu, Conway, & Gathercole, 2010), and suggesting that only about 50-60% of the variance is shared, while a portion of the variance does not appear to be shared by these two constructs (e.g., Giofrè,

Mammarella, & Cornoldi, 2013). This incomplete overlap between WM and intelligence seems to indicate that the two constructs are distinguishable and not isomorphic (Conway, Kane, & Engle, 2003).

The literature also suggests a partial independence between WM and intelligence. For example, children with learning disabilities typically have WM difficulties despite being normally intelligent (e.g., Swanson & Siegel, 2001; see also Cornoldi, Giofrè, Orsini, & Pezzuti, 2014); and children with ADHD may struggle with WM tasks despite revealing a high level of intelligence (Martinussen, Hayden, Hogg-Johnson, Tannock, 2005; see also Cornoldi, Giofrè, Calgaro, & Stupiggia, 2013). It has been demonstrated, moreover, that WM - not intelligence - is the best predictor of literacy and numeracy (e.g., Alloway & Alloway, 2010), various mathematical skills (Träff, 2013), and academic achievement in geometry (Giofrè, Mammarella, & Cornoldi, 2014). Overall, this evidence converges in indicating that WM and intelligence may provide important, different information on children's cognitive functioning.

It is crucially important to understand the structure of WM when examining the relationship between WM and intelligence. The most classical, so-called tripartite model of WM was first proposed by Baddeley and Hitch (1974). This model involves a central executive responsible for controlling resources and monitoring information-processing across information domains. The storage of information is mediated by two domain-specific slave systems for short-term memory (STM), i.e., the phonological loop (used for the temporary storage of verbal information), and the visuospatial sketchpad (specialized in the recall of visual and spatial representations). Another model distinguishes between a storage component (typically characterized as a STM component) and a processing component, suggesting that WM processing capacity is limited by controlled attention (Engle et al., 1999). Other authors favor a unitary view of WM (Pascual-Leone, 1970), while some researchers have suggested that WM is even more articulated (e.g., Mammarella, Borella, Pastore, & Pazzaglia, 2012;

Mammarella, Pazzaglia, & Cornoldi, 2008). Using different WM measures, two studies have shown that the tripartite model obtains the best fit in children (Alloway, Gathercole, & Pickering, 2006; Giofrè, Mammarella, & Cornoldi, 2013).

Alongside research on the structure of WM, there is also debate on which WM component is the best predictor of intelligence in children. Several studies have been conducted on the relationship between the various sub-components of WM and intelligence, with mixed results. Engel De Abreu et al. (2010) studied young children, for example, and found WM, STM and fluid intelligence related but separate constructs, and WM proved the best predictor of intelligence. In a study on children in kindergarten, on the other hand, Hornung, Brunner, Reuter, and Martin (2011) showed that, once the shared variance between STM and WM had been taken into account, only STM explained a significant portion of the variance in intelligence. Using the WISC-IV, another study on children with typical development showed that the relationship between WM and intelligence was stronger the greater the cognitive control required to complete a task (Cornoldi, Orsini, Cianci, Giofrè, & Pezzuti, 2013) (this does not seem to apply to children with ADHD, however; see Cornoldi, Giofrè, Calgaro, & Stupiggia, 2013). It was recently demonstrated, moreover, that only active WM and visuospatial short-term memory (STM-VS) correlated significantly with intelligence, while verbal short-term memory (STM-V) did not (Giofrè, Mammarella, & Cornoldi, 2013).

It is worth noting, however, that the above-mentioned studies adopted different scoring methods, and the scoring procedure seems to be crucial when testing different models of WM and how it relates with intelligence. Research on adults found that the Partial Credit Score (PCS), which stresses the importance of information obtained with the most difficult (longest) lists of items to recall, may emphasize the role of STM in explaining human intelligence (Unsworth & Engle, 2006, 2007). According to Unsworth and Engle (2006; 2007), the correlation between active WM and intelligence does not change as a function of

the length of lists, but the correlation between simple STM and intelligence does. The PCS contains the same information as the Absolute Credit Score (ACS), which only measures performance in perfectly recalled trials, plus additional information obtained from lists of items that were not perfectly recalled. In adults at least, STM and WM seem to predict higher-order cognitive abilities equally well when the variability emerging from larger sets of items is considered (Unsworth & Engle, 2007).

In previous research, a sequential analysis was used to further investigate the influence of the scoring procedure when using sets of items of different sizes. Sequential analysis enabled the relationship with intelligence for each set size used in WM tasks to be controlled after taking the effect seen with previous set sizes into account (Salthouse & Pink, 2008), the goal of the analysis being to investigate whether each subsequent set size could explain intelligence over and above the effect of the previous one. This procedure is also useful for investigating the influence of the length of lists (as conceptualized by Unsworth and Engle, 2006) or the level of complexity (as conceptualized by Salthouse & Pink, 2008) of items to recall. Using sequential analysis, it was demonstrated that a strong influence of intelligence emerged for smaller sets of items, which would indicate that the relationship between WM and intelligence is independent of the amount of information to retain. To our knowledge, no research has been conducted in children on the effects of the scoring procedure on the relationship between WM and intelligence when lists of different lengths are recalled.

The primary aim of the present study was to see whether, and to what extent, the results obtained using two different scoring procedures could affect the relationship between various WM subcomponents and intelligence in children. One hypothesis is that the PCS stresses the influence of STM on intelligence, but has only a moderate impact on WM. Unlike previous researchers, we drew a distinction between the two verbal and visuospatial subcomponents of STM (i.e., the STM-V and the STM-VS) to investigate whether the scoring procedure has a different impact on the relationship between STM-V, STM-VS and

intelligence. We additionally aimed to quantify any differences due to the different scoring procedures adopted in terms of the explained variance in intelligence.

If the scoring procedure affects the relationship between WM and intelligence, then why is this so? A further aim of this study was to investigate the effect of set size by means of a sequential analysis. It would be interesting to establish whether intelligence correlates increasingly with successively larger set sizes (or increasingly long lists of items to recall) in children, since research on adults (Salthouse & Pink, 2008) has indicated that the relationship between intelligence and active WM is influenced primarily by the effect of smaller set sizes, while for STM the relationship is influenced by larger set sizes.

In short, the purpose of the present study was to investigate: (i) whether the scoring procedure influences the relationship between WM and intelligence; and (ii) if so, to what degree it influences the relationship between WM and intelligence at different set sizes.

## 2 Method

### 2.1 Participants

The data analyzed in the current study were drawn from a large correlation-based study (Giofrè, Mammarella, & Cornoldi, 2013) on 176 typically-developing children (96 males,  $M_{\text{age}}=9.27$ ,  $SD=.719$  months), attending the 4<sup>th</sup> ( $n=72$ ) and 5<sup>th</sup> grades ( $n=104$ ). The children were attending schools in the urban area of two large cities in southern Italy. They were almost all (94%) from Italian families, and the remainder (6%) had lived in Italy for at least three years and had no difficulty understanding the instructions of the tasks. The children were tested from January to March. None of the analyses discussed in this paper were the object of previous reports.

## 2.2 Materials

### 2.2.1 General cognitive ability (*g*)

*Colored progressive matrices* (CPM; Raven, Raven, & Court, 1998). Children were asked to complete a figure by choosing the missing piece from among a set of options. The test consisted of 36 items divided into three sets of 12 (A, AB, and B). The test lasted approximately 20 min. The score was the sum of the correct answers.

*Primary mental abilities - 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 children had to choose which word from a set of four was the odd one out, e.g. *cow, dog, cat, and cap* (the answer is *cap*). The test includes 25 sets of words and children were allowed 11 min to complete it. The score was the sum of the correct answers.

*Primary mental abilities - 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*; and (d) *tiny* (the answer is *tiny*). The test includes 30 items and had to be completed within 12 min. The score was the sum of the correct answers.

### 2.2.2 Short-term and working memory tasks

#### 2.2.2.1 Short-term memory

**2.2.2.1.1 Verbal short-term memory (STM-V).** *Simple span tasks* (the syllable span task, SSPAN; and the digit span task, DSPAN). These tasks examine short-term memory involving the passive storage and recall of information (Cornoldi & Vecchi, 2003). Syllables or 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.

**2.2.2.1.2 Visuospatial short-term memory (STM-VS).** *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 s) 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 on a visible (4×4) grid in the center 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]*).

### **2.2.2.2 Working memory**

#### **2.2.2.2.1 Active working memory (WM)**

*Categorization working memory span* (CWMS; Borella, Carretti, & De Beni, 2008; De Beni, Palladino, Pazzaglia, & Cornoldi, 1998). The material consists of series of word lists containing four words of high-medium frequency. The series include a variable number of lists (from 2 to 5). The children were asked to read each word aloud and press the space bar when there was an animal noun. After completing each series, they had to recall the last word in each list, in the right order of presentation.

*Listening span test* (LST; Daneman & Carpenter, 1980; Palladino, 2005). The children listened to sets of sentences arranged into series of different lengths (containing from 2 to 5 sentences) and they had to say whether each sentence was true or false. After each series had been presented, the children had to recall the last word in each sentence, in the order in which they were presented.

## **2.3 Procedure**

As far as the STM and WM tasks are concerned, all tasks were administered in order of increasing set sizes. Three trials were presented for each set size. Using the PCS, we also considered the trials in which participants provided only a partial response (for instance, if they were able to remember 2 of 3 elements, the score was 2). Using the ACS, we only considered trials

in which participants obtained a perfect performance (so if they could remember 2 of 3 elements the score was 0).

### 3 Results

#### 3.1 Statistical analyses

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

Model fit was tested using various indices according to the criteria suggested by Hu and Bentler (Hu & Bentler, 1999). We used the comparative fit index (*CFI*), the non-normed fit index (*NNFI*), the standardized root mean square residual (*SRMR*), and the root mean square error (*RMSEA*). The measures of multivariate kurtosis were 1.06 and 1.00, for the PCS and the ACS, respectively. These values are 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).

Correlations, with age in months partialled out<sup>1</sup> (for a similar procedure, see Alloway, Gathercole, Willis, & Adams, 2004; Alloway, et al., 2006; Gathercole et al., 2004), reliabilities, and descriptive statistics for the two scoring method are given in Table 1.

Table 1 about here

#### 3.2 Confirmatory factor analyses

Giofrè, Mammarella, and Cornoldi (2013, 2014) showed that the best-fitting model of WM in children is the tripartite model, which distinguishes between STM-V, STM-VS, and WM. Using this model, WM and STM-VS had the strongest impact on the *g*-factor. We thus

applied the same model to test whether the relationship between WM subcomponents and the *g*-factor changed when different scoring procedures were used.<sup>3</sup>

We tested a CFA model using the two different scoring procedures, the PCS and the ACS (Table 2), and the fit was very good for both models (Table 3). In terms of inter-factor correlations, the relationship with the *g*-factor seems to change depending on the scoring procedure adopted (Table 2). The relationship between STM-VS, WM and intelligence tended to be smaller using the ACS than with the PCS, while the relationship between STM-V and intelligence changed only slightly. Hence our decision to further investigate this finding.

Tables 2 and 3 about here

### 3.3 Scoring procedures and their relationship with the *g*-factor

We ran a series of regression analyses to compare the correlations obtained using the two different scoring procedures. The inter-factor correlations in Table 2 were used for STM-V, STM-VS, WM and the *g*-factor. We also calculated the correlations between the factor scores obtained using the two scoring procedures, which were high (.93, .88, and .92, for the STM-V, STM-VS, and WM, respectively). The inter-factor correlations obtained using the PCS and ACS were used to test statistical differences between two dependent correlations, applying Steiger's *Z* formula (Hoerger, 2013; Steiger, 1980). The results indicate that using the PCS resulted in a significantly higher correlation between intelligence and both active WM ( $\Delta r = .074$ ;  $Z_H = 3.42$ ,  $p < .001$ ) and STM-VS ( $\Delta r = .096$ ;  $Z_H = 3.16$ ,  $p = .002$ ), but the difference was not significant for STM-V ( $\Delta r = -.045$ ;  $Z_H = -1.74$ ,  $p = .081$ ).

To estimate the magnitude of the difference identified using the two scores in terms of the variance explained in the *g*-factor, we performed a multiple regression entering STM-VS and WM as predictors, and intelligence as the response variable. We estimated Cohen's set correlation, using the inter-factor correlations in Table 2 (Cohen, Cohen, West, & Aiken,

2003). The results indicate that the proportion of variance in the *g*-factor explained by STM-VS and WM is higher when the PCS was used ( $R^2=.594$ ; with  $\beta=.34$  and  $.56$  with  $ps < .001$  and semi-partial correlations equating to  $.30$  and  $.50$  for STM-VS and WM, respectively) than when the ACS was used ( $R^2=.468$ ; with  $\beta=.28$  and  $.52$  with  $ps < .001$  and semi-partial correlations equating to  $.25$  and  $.47$  for STM-VS and WM, respectively), with a difference of about 13% in terms of the explained variance in intelligence ( $\Delta R^2=.126$ ).<sup>4</sup>

### 3.4 Proportion of correctly-recalled items using different set sizes

To make the analyses more straightforward, we considered STM-V, STM-VS and WM as single constructs. We thus combined STM-V, STM-VS and WM by averaging the probability of correct responses for each set size in their indicators (see Unsworth & Engle, 2006, for a similar procedure).<sup>5</sup> We found that the two different scoring procedures had an impact on the proportion of correctly-recalled items (Figure 1). The proportion of correct answers was lower with the ACS than with the PCS. When the ACS was used, the proportion tended to be very low for STM-VS and WM in the larger set sizes, and the variability was smaller, and this might influence the correlations. The lower variability and consequent reduction in individual differences appeared to be very important, especially when the relationship with the *g*-factor was investigated.

Notably, with sets of two, three and four items to recall, the proportion of correct responses was much higher for STM-V than for STM-VS or WM. On the other hand, the children's performance in terms of STM-VS and WM was very low with larger set sizes when the ACS was used. It is worth noting that Figure 1 resembles an ellipse: variability is small for very low and very high set sizes (2 and 6), and large for the medium set sizes (4), which is consistent with ceiling and floor effects, as expected with this scoring procedure. We consequently decided to further investigate this finding.

Figure 1 about here

### 3.5 Sequential analyses

Figure 2 shows an analytical model that can be used to analyze unique relations of the *g*-factor in an ordered sequence (see Salthouse & Pink, 2008), in order to test the influence of the *g*-factor on each set size after taking the effect of earlier set sizes into account. The path from the *g*-factor to each set size may be positive, equal or negative. A positive path indicates that a stronger relationship with the *g*-factor is over and above the effect of previous set sizes (see Figure 2).

Figure 2 about here

We fitted three separate models for each WM subcomponent (i.e., STM-V, STM-VS and active WM) using the PCS first, and then the ACS (Figure 3).<sup>2</sup> Using the PCS, we found that, in terms of active WM, the *g*-factor correlated significantly with all the set sizes. The effect of the *g*-factor on STM-VS decreased for smaller set sizes, increased for a set containing 4 items, and was smaller (though not to a statistically significant degree) for sets of 5 or 6 items. Probably due to ceiling effects on sets containing 2, 3 or 4 items, the effect of the *g*-factor on STM-V increased for sets of 5 items, but was negligible and statistically insignificant for sets of 6 items. When the ACS was adopted, the effect of the *g*-factor became negligible and statistically insignificant as regards STM-VS for sets of 5 and 6 items, and as regards active WM for sets of 5 items. This finding confirms that the scoring procedure influences the relationship with the *g*-factor, thus stressing the importance in terms of STM-VS and WM of imperfect recall performance in trials involving larger set sizes.

Figure 3 about here

### 3.6 Age effects on STM, WM and g

We ran a series of analyses to investigate the influence of age on STM, WM, and g. We fitted a model with age regressed on STM-V, STM-VS, WM and g, using the two scoring methods (Figure 4). The results were similar for the two methods and show that age related statistically with STM-VS, WM, and g, but not with STM-V (Table 4).

Figure 4 about here

Table 4 about here

## 4. Discussion

The present study aimed to elucidate how scoring procedures influence the relationship identified between WM and intelligence. Earlier studies on adults found a stronger relationship between STM and intelligence when the PCS was adopted, while the same did not apply to the relationship between WM and intelligence (Unsworth & Engle, 2006, 2007). Consistently with the developmental literature, in the present study we also distinguished between two, verbal and visuospatial STM slave systems with a view to estimating the influence of the scoring procedure on the relationships between intelligence and STM-V and STM-VS. We were also able to estimate to what extent the strength of the relationship between STM-V, STM-VS, WM and intelligence varied when different scoring procedures were used.

A second aim concerned the relationship between intelligence and different set sizes used in trials. Previous research indicated that larger set sizes in STM tasks correlated more closely with intelligence when the PCS was used instead of the ACS, while the relationship remained fairly constant with both scoring systems in the case of WM (Unsworth & Engle, 2006, 2007). These findings were replicated using a sequential analysis, which also enabled

us to control for the effect at latent level of a given set size over and above the effects of previous set sizes (Salthouse & Pink, 2008). For the present study we adopted a sequential analysis approach to test the relationship between intelligence and STM-V, STM-VS and active WM, for each set size.

Returning to our first aim, we found that the scoring procedure had an important impact on the relationship between intelligence and WM. Comparing two CFA models obtained using either the PCS or the ACS, we found only minimal differences in terms of the fit indexes. But when we analyzed the inter-factor correlation we noticed that the PCS tended to boost the relationship between intelligence and both active WM and STM-VS significantly. We observed that, compared with the ACS, the PCS increased the variance in intelligence explained by active WM and STM-VS by about 13%. It is worth noting that the two scoring procedures rely on the same initial information and the correlations based on PCS and ACS are consequently similar (Conway et al., 2005), though correlating PCS and ACS reveals substantial deviations from the perfect correlation. The PCS should be preferred to the ACS in any case because tasks show a greater internal consistency using this method (Table 1), consistently with findings in adults (Conway et al., 2005).

As for our second aim to elucidate how STM-V, STM-VS and active WM correlated with intelligence for each set size scored using the PCS and ACS, we first calculated the proportion of correctly-recalled items and found that the two scoring methods produce different outcomes: the proportion of correctly-remembered items was higher using the PCS than with the ACS. In particular, using the ACS coincides with a drastic drop in the proportion of correctly-recalled items in terms of STM-V and active WM, and the variability decreases too. In particular, performance in recalling sets of 5 or 6 items (in terms of STM-VS) and 5 items (in terms of WM) neared zero and the variability was reduced. Conversely, in the case of STM-V, the proportion of correctly-recalled items was very high for sets of 2, 3 and 4 items, and this picture was not influenced very markedly by the scoring procedure

adopted. A reduction in the variability should be effective in reducing individual differences, and therefore in reducing the relationship with intelligence. This finding was confirmed using sequential analysis.

We ran a series of sequential analyses on the relationship between intelligence and different set sizes in trials on STM-V, STM-VS and WM, scored using the PCS. Sequential analysis enabled us to correlate intelligence with a given set size after controlling for the effect carried over from the previous set size. The analyses showed that the greatest contribution of intelligence to performance in terms of active WM coincides with a set of two items to recall. We found smaller but significant effects of intelligence for sets of 3, 4 and 5 items. For STM-VS, there was a small but significant relationship between intelligence and sets of 2 and 3 items; a set of 4 items seemed to correlate more with intelligence, while small but significant effects emerged again for sets of 5 or 6 items. As for STM-V, we found that the relationship between intelligence and a set of 2 items was not significant, with a set of 3 the relationship was small but significant, with a set of 4 it was no longer significant, with a set of 5 it was significant and larger than with the smaller sets, and a set of 6 again no longer correlated significantly with intelligence. When the same analysis was run using the ACS, the results changed: the different scoring procedures had an effect on active WM and STM-VS with larger-sized sets of items, in which case the relationship with intelligence becomes smaller and insignificant. The ACS thus seems to influence findings for STM-VS and active WM when larger-sized sets of items have to be recalled.

The importance of our findings stems from the fact that they were obtained in a population of 4<sup>th</sup>- and 5<sup>th</sup>-graders, i.e., children at an age when the relationship between WM and intelligence is strong, but developmental changes are also underway (Demetriou, Spanoudis, Shayer, et al., 2013). Memory and controlled attention both seem to be involved in WM tasks and, as individuals grow older, they can store increasingly complex units of information (Pascual-Leone, 1970). Previous findings showed that children start to remember



more elements when cognitive changes are underway. In fact, changes in fluid intelligence are predicted by changes in WM in three different phases, or cycles, at 4-6, 8-10, and 13-16 years old, and these changes reflect differences in the processing demand of developmental acquisitions (Demetriou, Spanoudis, Shayer, et al., 2013; Demetriou, et al. 2014). Data from supra-span information could thus reflect a major reorganization of the mind, which can eventually enable children to remember more elements.

We believe that the increment in the WM and g relationship with the scoring procedure adopted stems from developmental changes that were occurring (the children in the present study were undergoing an important phase of transition). We might expect similar results in younger children (e.g., 4-6 years old) and older children (e.g., 13-15 years old), i.e., at ages in which transitions are occurring. In all of these age groups, we would expect the scoring procedure adopted to be relevant and ultimately boost the relationship between WM and g. This would happen because supra-span information, which is only taken into account by the PCS, would reflect important changes taking place during development. Conversely, we would not expect to find significant developmental changes in young adults - in active WM at least – and research seems to indicate, in fact, that the scoring procedure only affects STM (Unsworth & Engle, 2006; 2007).

It could be argued, however, that the relationship between intelligence STM-VS and active WM was weaker using the ACS because the lower variability can reduce individual differences, which can in turn reduce the correlations. We believe that the more restricted variability seems to be a “consequence” rather than a cause of the present findings. In developing children, when the mental units that can be handled on a given memory task reach a maximum degree of complexity, the mind tends to reorganize these units on a higher level (Demetriou, Efklides, & Platsidou, 1993). The scoring procedure is therefore crucial when testing children in “transition” between one level and another because children’s WM capacity is rapidly reorganized and its capacity increases, and that is why the PCS may

provide additional information on the important changes taking place. The scoring method thus seems to “capture” naturally-occurring developmental changes in these children. On the other hand, an all-or-nothing approach like the ACS is unable to detect these changes, which can “eventually” result in a “compression” of individual differences, and a consequent weakening of the relationship with other constructs, such as intelligence.

We also found that the scoring procedure had a different influence on results in terms of STM-V and STM-VS. We further confirmed that verbal and visuospatial STM are distinguishable modalities, in children at least (Gathercole, Pickering, Ambridge, & Wearing, 2004; Giofrè, Mammarella, & Cornoldi, 2013). Between the 4<sup>th</sup> and 5<sup>th</sup> grades, however, there are some developmental changes in STM-VS, WM and *g*, while STM-V does not seem to develop. This finding is in line with the developmental literature showing that STM-VS and WM develop from the age of 4 to 10 years, while STM-V reaches a “plateau” at about 9 years old (Alloway, et al., 2006). In particular, we found that performance in terms of STM-V reveals a ceiling effect for sets of 2, 3 or 4 items. Performance in recalling a given number of items was influenced to some degree by item content. For instance, children tend to remember numbers better than visuospatial material (Demetriou et al., 1993), though the developmental trajectory seems to be similar (Gathercole et al., 2004). This could mean that children use strategies to separate verbal items into smaller sets. The use of strategy may reduce the relationship between STM-V and intelligence. In fact, when we look at STM-VS we found no ceiling effect for the smaller set sizes: this is probably because the visuospatial material is novel and children find it more difficult to use strategies even for the smaller-sized sets. A greater familiarity with verbal material can help to explain why STM-VS seems to be a better predictor of intelligence than STM-V, since intelligence (and fluid intelligence in particular) is needed to deal with new situations/materials (Horn & Cattell, 1966).

Our findings have some important theoretical implications. First, many studies investigating the relationship between intelligence and WM used the ACS (e.g., Demetriou,

Spanoudis, Shayer, et al., 2013; Engel De Abreu et al., 2010; Hornung et al., 2011), and other scoring methods traditionally used with children do not consider the effect of supra-span set sizes (e.g., Cowan et al., 2005; Cowan, Fristoe, Elliott, Brunner, & Saults, 2006). Such studies are likely to have underestimated the real relationship between WM and higher-order cognition. Theories on the development of WM and its relationship with higher-order cognition (e.g., the developmental-differential theory of the mind; Demetriou, Spanoudis, & Shayer, 2013; Demetriou, Spanoudis, Shayer, et al., 2013) would benefit from using the PCS instead of the ACS when the relationship between intelligence and WM is investigated.

Our findings may also have practical implications. For example, many batteries used in clinical settings rely on the ACS, but we have demonstrated here that individual differences are smaller when this scoring procedure is used. It would be better to use the PCS in clinical settings too because, by stressing individual differences, it would be more informative and ensure a greater discriminatory power of test batteries.

Though it contains some insightful findings, the present study also has some limitations that will need to be addressed in future studies. Further research is needed to clarify the effect of scoring method on different age groups. For instance, the scoring procedure has a different influence in adults, and concerns only STM, not WM. We estimated that the influence of the scoring procedure would be considerable in children in 4<sup>th</sup> and 5<sup>th</sup> grades, but this influence might produce different results in other age groups; further studies should therefore consider 4- to 6-year-old children and 13- to 15-year-old adolescents, for instance. Future studies should also include more set sizes. We only considered sets containing from 2 to 6 items, based on the typical performance of 4<sup>th</sup>- and 5<sup>th</sup>-graders reported in the literature (Gathercole, et al., 2004; Alloway, et al., 2006). Unfortunately, since the ACS was generally used in the developmental literature, it may be that using the PCS would reveal a unique relationship between intelligence and larger-sized sets (over and above the effects of the set sizes considered in the present study), particularly in the case of STM-V.

In conclusion, although this issue seems to be very important, there is a paucity of research on the influence of scoring procedures. The present study contributes important theoretical and practical information on the influence of the scoring procedure used on the relationship identified between WM and intelligence in children.

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Footnotes.

<sup>2</sup> To take the children's different ages into account, we ran a series of regressions using each indicator as a response variable and age in months as a predictor; from each regression we obtained residuals, which were then correlated to obtain a correlation matrix. This method is statistically equivalent to a partial correlation analysis.

<sup>3</sup> We chose not to include the Visual Pattern Test (active version; VPTA) in the WM composite for two reasons: 1) in order to include a consistent number of indicators in each factor (i.e., two indicators per factor); and 2) because the VPTA factor loading on the WM factor was lower than the CWMS and LST factor loadings (see Giofrè, Mammarella, & Cornoldi, 2013). It is worth noting that the results changed very little when the VPTA was included in the analyses (data not shown).

<sup>4</sup> We first performed a regression including STM (-V and -VS) and WM as predictors of intelligence, showing that the variance explained in the g-factor was higher when the PCS was used ( $R^2=.651$ ; with  $\beta = -.37, .40, .81$   $ps < .001$  for STM-V, STM-VS, and WM respectively) than when the ACS was used ( $R^2=.469$ ; with  $\beta = -.05$   $p = .593$ ;  $\beta = .28$  and  $.55$   $ps < .001$  for STM-VS, and WM respectively). Notably, STM-V and WM correlated very closely and when they were included together in the PCS regression, as predictors of g, STM-V tended to have a negative beta. We therefore decided to omit the STM-V, which could not contribute uniquely to explaining intelligence.

<sup>5</sup> For each set size, we first averaged the performances in the three trials for each indicator and then, for each factor, we averaged the medium performance in the two indicators [e.g.,  $((3+2+1)/9 + (3+3+2)/9)/2 = .778$ ]. In SSPAN we used only two trials instead of three for the set of 2 items because the children's performance was extremely poor. This was due to a single syllable being used, which proved extremely difficult for the children to recognize.

Table 1

*Partial correlations (controlling for age), means (M), standard deviations (SD), and reliabilities for the measures of g and WM.*

	1	2	3	4	5	6	7	8	9	M	SD	$\alpha$
<i>g</i>												
1 CPM	—	.433	.432	.246	.170	.235	.201	.334	.177	28.26	4.93	.82
2 PMA-R	.433	—	.568	.278	.180	.304	.249	.301	.305	16.30	4.08	.78
3 PMA-V	.432	.568	—	.289	.257	.310	.259	.446	.332	20.73	7.34	.93
<u>STM-V</u>												
4 SSPAN	.251	.258	.272	—	.503	.199	.235	.374	.374	30.60	9.74	.60
5 DSPAN	.127	.187	.240	.541	—	.218	.153	.405	.427	38.05	10.70	.66
<u>STM-VS</u>												
6 MSTG	.290	.381	.393	.249	.261	—	.559	.257	.264	24.86	11.35	.74
7 MSTNG	.313	.363	.387	.349	.315	.720	—	.253	.127	12.78	7.09	.56
<u>WM</u>												
8 CWMS	.309	.340	.485	.397	.386	.292	.297	—	.540	12.65	7.60	.65
9 LST	.226	.359	.402	.390	.462	.299	.266	.544	—	13.21	8.67	.76
<i>M</i>	28.26	16.30	20.73	41.80	46.28	39.50	29.53	26.57	27.43			
<i>SD</i>	4.93	4.08	7.34	8.58	8.15	10.14	10.03	6.65	6.78			
<i><math>\alpha</math></i>	.82	.78	.93	.70	.69	.83	.83	.78	.83			

*Note.* Partial correlations, after partialing out age, and descriptive statistics; the Partial Credit Score is below and the Absolute Credit Score is above the diagonal; all coefficients  $\geq .148$  are significant at .05 level; CPM=colored progressive matrices; PMA-R=primary verbal abilities, reasoning; PMA-V=primary mental abilities, verbal; SSPAN=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;  $\alpha$  = Cronbach's alpha.

Table 2. *Factor loadings and inter-factor correlations for the measurement model (PCS and ACS)*

Factor loading matrix					
		<i>g</i>	STM-V	STM-VS	WM
1	CPM	.56-.57			
2	PMA-R	.72-.72			
3	PMA-V	.80-.79			
4	SSPAN		.72-.69		
5	DSPAN		.76-.73		
6	MSTG			.82-.82	
7	MSTNG			.88-.68	
8	CWMS				.74-.77
9	LST				.73-.70
Inter-factor correlation matrix					
	<i>g</i>	1	.474	.495	.636
	STM-V	.429	1	.370	.752
	STM-VS	.591	.477	1	.418
	WM	.710	.753	.456	1

*Note.* All the paths and correlations are significant  $p < .05$ ; Partial Credit Score (PCS) on the left (factor loadings) and below (inter-factor correlations) the diagonal; Absolute Credit Score (ACS) on the right (factor loadings) and above (inter-factor correlations) the diagonal; CPM=colored progressive matrices; PMA-R=primary verbal abilities, reasoning; PMA-V=primary mental abilities, verbal; SSPAN=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.

Table 3

*Fit indices for different CFA analyses for relationship between WM and g*

Model	$\chi_M^2$ (df)	<i>p</i>	<i>RMSEA</i>	<i>SRMR</i>	<i>CFI</i>	<i>NNFI</i>
(1) PCS	18.14(21)	.640	<.01	.03	1.00	1.01
(2) ACS	21.20(21)	.447	<.01	.03	1.00	1.00

*Note.*  $\chi_M^2$  = 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.

Table 4

*Standardized effects and significance levels for the models in Figure 4*

	PCS	ACS
<u>Parameter estimates</u>		
Age (factor) → Age	1 <sup>F</sup>	1 <sup>F</sup>
g → CPM	.54*	.55*
g → PMA-R	.74*	.74*
g → PMA-V	.84*	.84*
STM-V → SSPAN	.72*	.71*
STM-V → DSPAN	.75*	.71*
STM-VS → MSTG	.80*	.79*
STM-VS → MSTNG	.91*	.72*
WM → CWMS	.75*	.77*
WM → LST	.75*	.72*
Error in Age	0 <sup>F</sup>	0 <sup>F</sup>
Error in CPM	.70*	.70*
Error in PMA-R	.45*	.46*
Error in PMA-V	.29*	.29*
Error in SSPAN	.48*	.49*
Error in DSPAN	.44*	.50*
Error in MSTG	.37*	.38*
Error in MSTNG	.18*	.48*
Error in CWMS	.44*	.40*
Error in LST	.44*	.49*
<u>Structural model</u>		
Age → STM-V	.11 <sup>n.s.</sup>	.15 <sup>n.s.</sup>
Age → STM-VS	.22*	.22*
Age → WM	.26*	.23*
Age → g	.41*	.41*
STM-V ↔ STM-VS	.49*	.40*
STM-V ↔ WM	.75*	.76*
STM-V ↔ g	.43*	.49*
STM-VS ↔ WM	.48*	.45*
STM-VS ↔ g	.60*	.53*
WM ↔ g	.73*	.66*
Residual for STM-V	.99*	.98*
Residual for STM-VS	.95*	.95*
Residual for WM	.93*	.95*
Residual for g	.83*	.83*

*Note.* PCS= partial credit score; ACS= absolute credit score; CPM=colored progressive matrices; PMA-R=primary verbal abilities, reasoning; PMA-V=primary mental abilities, verbal; SSPAN=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.

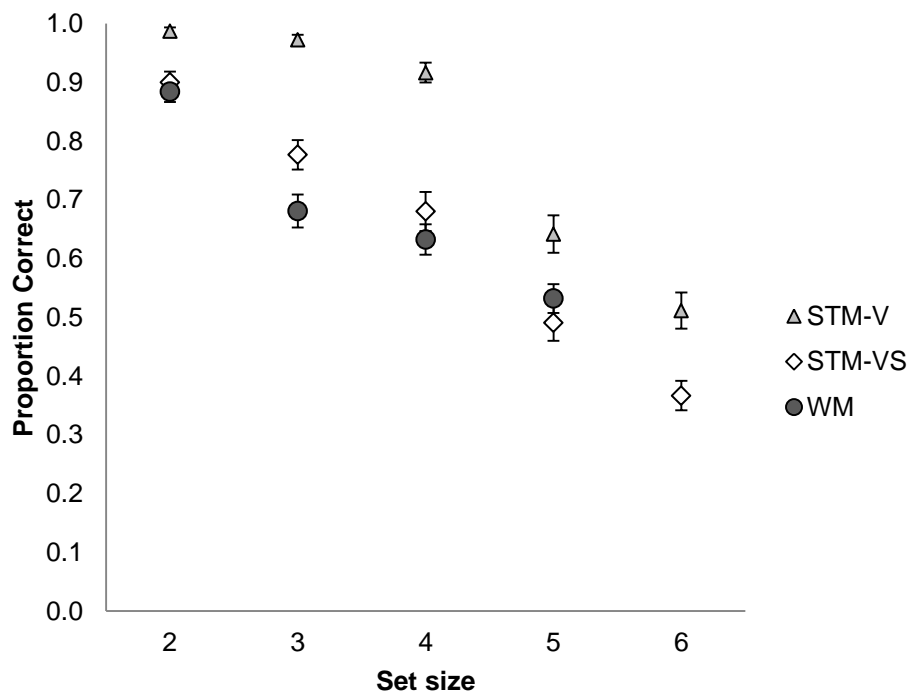
<sup>F</sup> = fixed

<sup>n.s.</sup> = statistically no different from 0

\*  $p < .05$ .



A - Partial credit score



B - Absolute credit score

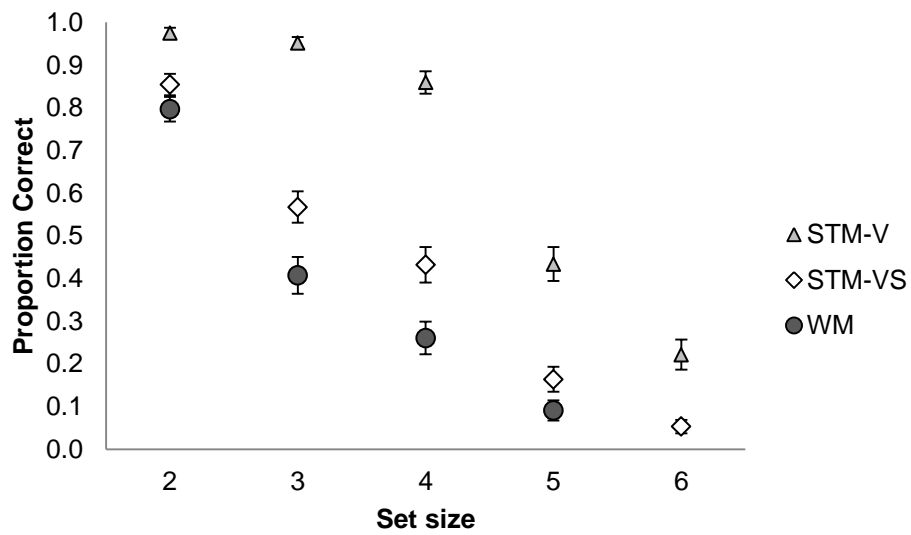
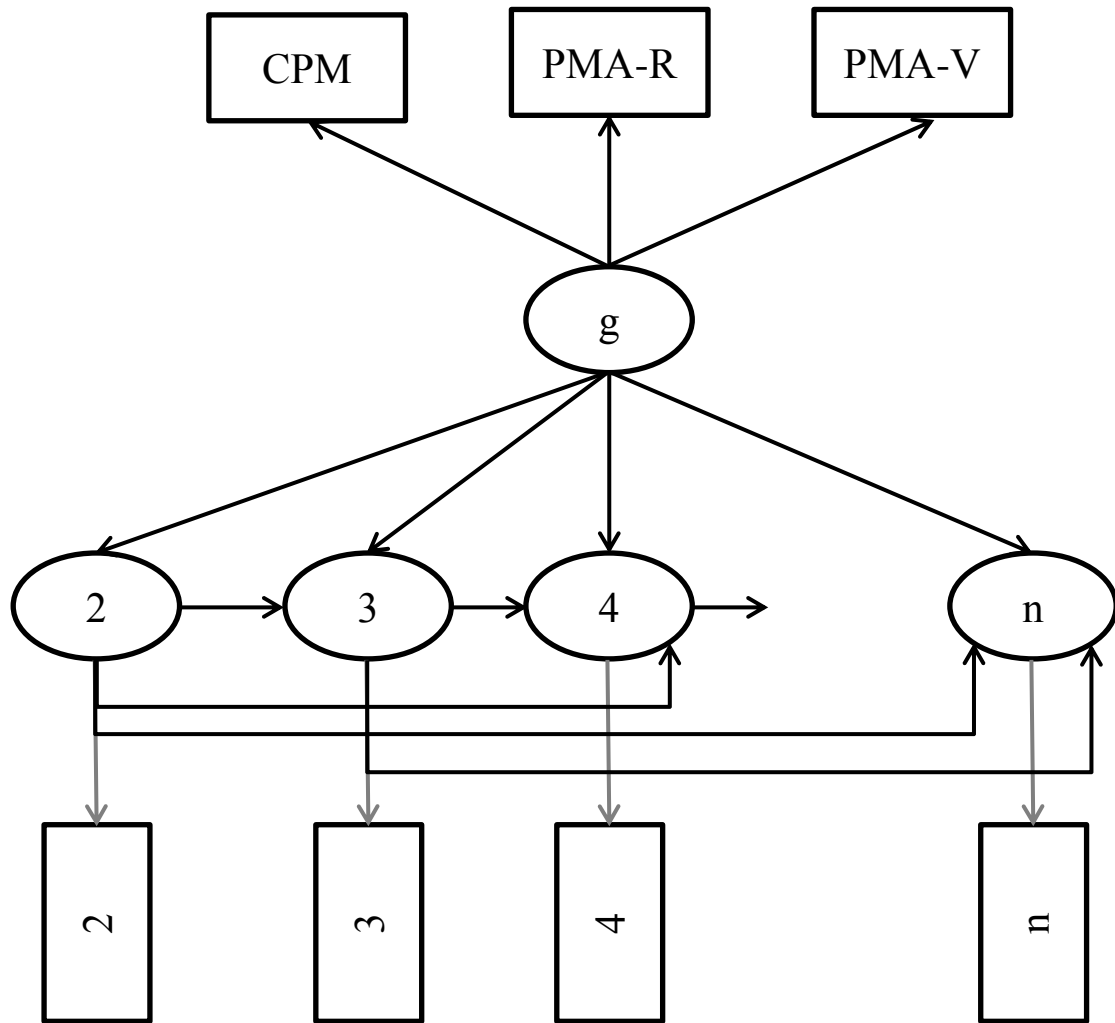
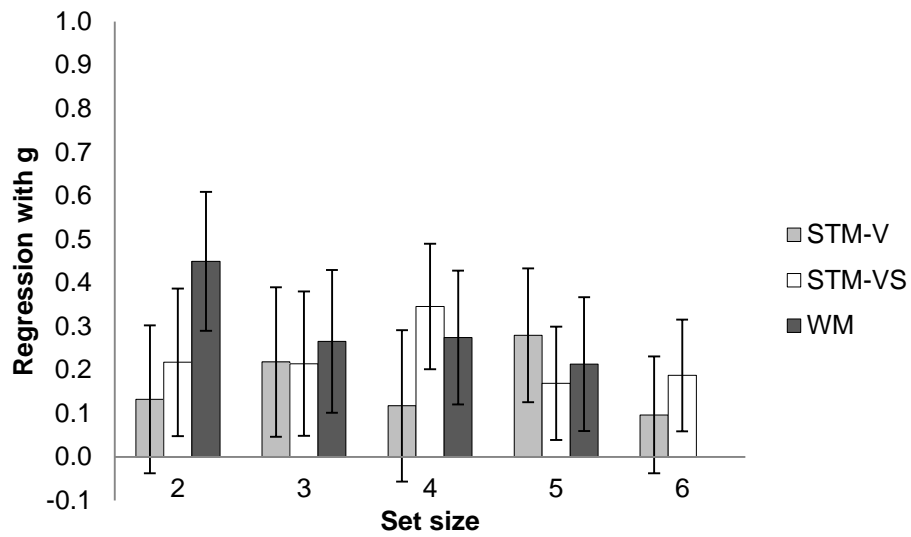


Figure 1. Means of the proportions of correctly-recalled items in STM-V, STM-VS and WM. Error bars represent 95% CIs of the mean.



*Figure 2.* Illustration of the sequential analysis model used to investigate the influence of the  $g$ -factor on successive elements in an ordered sequence after taking the influence on earlier elements in the sequence into account. Parameters in gray are fixed.

A - Partial credit score



B - Absolute credit score

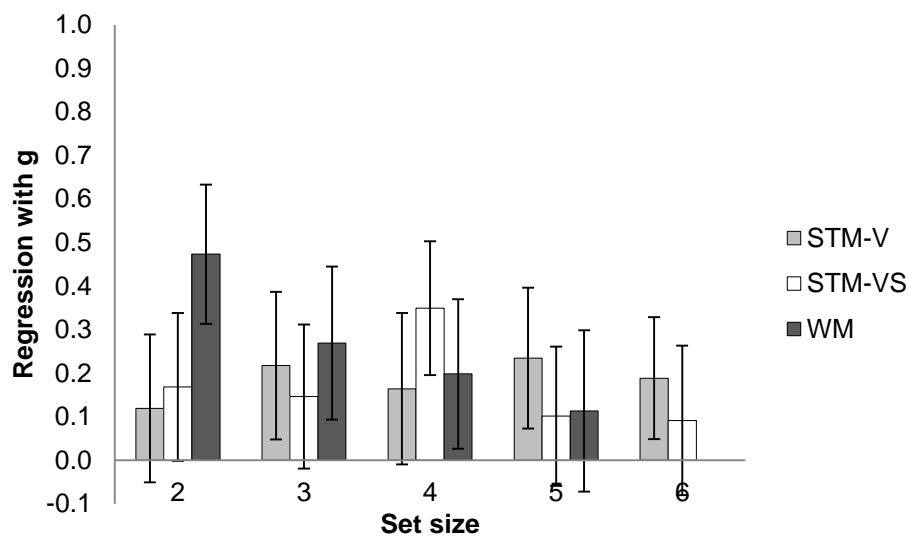


Figure 3. Standardized regression coefficients derived from the model in Figure 2, with the elements in the sequence corresponding to increases in set size. Error bars represent 95% CIs. The effect is statistically significant if the 95% CI does not include zero.

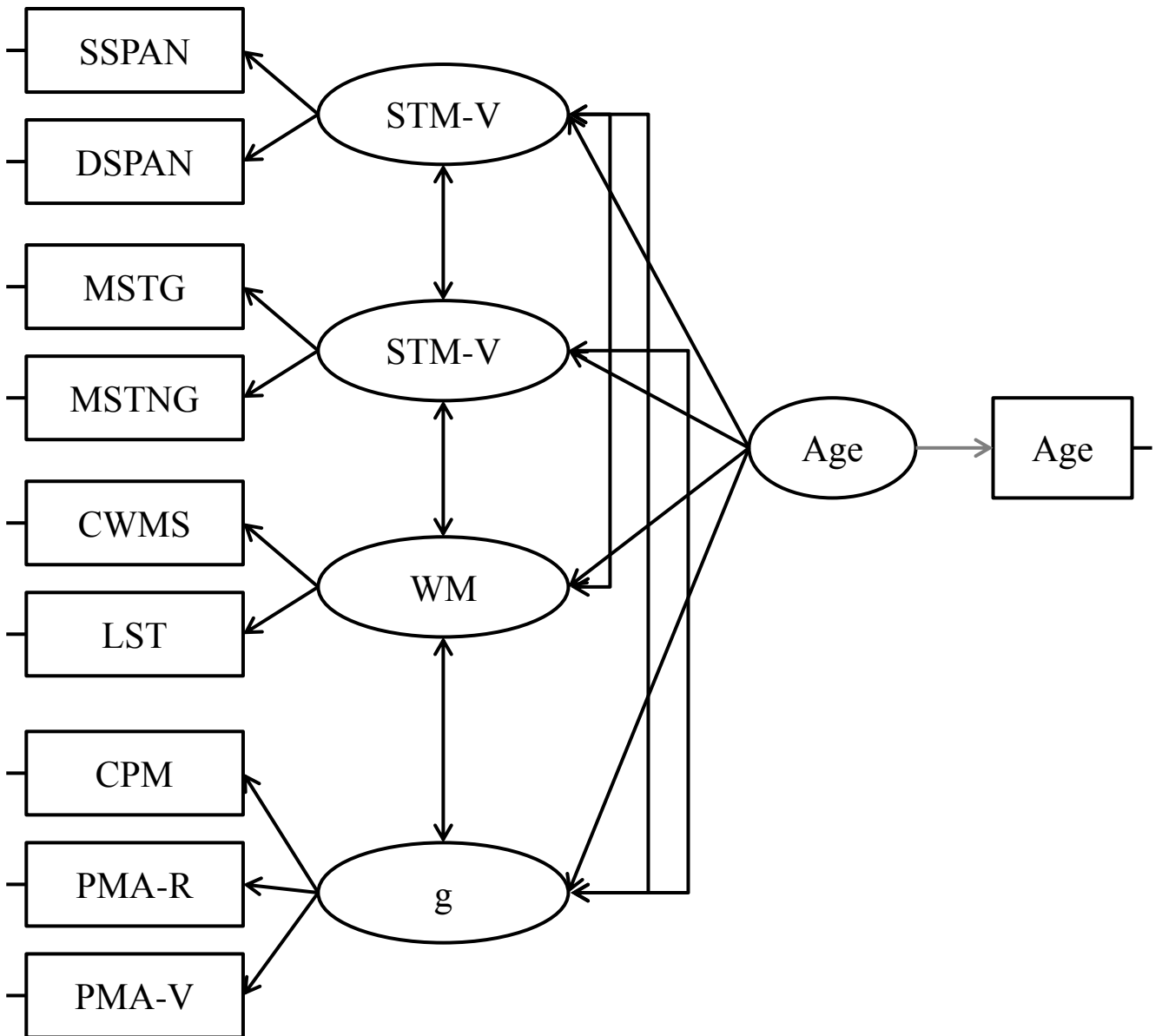


Figure 4. Illustration of the model used to investigate the influence of age on STM (-V and -VS), WM and g. Parameters in gray are fixed.