Working Memory and Fluid Intelligence in Young Children

Pascale M. J. Engel de Abreu[1],

Andrew R. A. Conway[2] &

Susan E. Gathercole[3]

[1]University of Oxford/ UK, [2]Princeton University/ USA, [3]University of York/ UK

Abstract

The present study investigates how working memory and fluid intelligence are related in young children and how these links develop over time. The major aim is to determine which aspect of the working memory system – short-term storage or cognitive control - drives the relationship with fluid intelligence. A sample of 119 children was followed from kindergarten to second grade and completed multiple assessments of working memory, short-term memory, and fluid intelligence. The data showed that working memory, short-term memory, and fluid intelligence were highly related but separate constructs in young children. The results further showed that when the common variance between working memory and short-term memory was controlled, the residual working memory factor manifested significant links with fluid intelligence whereas the residual short-term memory factor did not. These findings suggest that in young children cognitive control mechanisms rather than the storage component of working memory span tasks are the source of their link with fluid intelligence.

Keywords: working memory; short-term memory; fluid intelligence; cognitive control; developmental.

Working memory and fluid intelligence in young children

1. Introduction

In recent years there has been substantial evidence that fluid intelligence and working memory are closely related (Colom, Flores-Mendoza, & Rebollo, 2003; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Cowan, et al., 2005; Engle, Tuholski, Laughlin, & Conway, 1999; Kane, et al., 2004; Oberauer, Schulze, Wilhelm, & Süß, 2005; Unsworth, Redick, Heitz, Broadway, & Engle, 2009). Although researchers generally agree on the existence of such a relationship, the underlying nature of the association remains an issue of controversy. Furthermore, the vast majority of studies have focused on adults, and it remains to be seen whether the findings extend to children. The main aim of the present study was to explore the development of working memory and fluid intelligence in a population of young children in order to clarify the relationship between these two aspects of fluid cognition.

Definition of the key concepts

Fluid intelligence (Gf) is a complex cognitive ability that allows humans to flexibly adapt their thinking to new problems or situations. The concept has been defined by Cattell (1971) as: “an expression of the level of complexity of relationships which an individual can perceive and act upon when he does not have recourse to answers to such complex issues already sorted in memory” (Cattell, 1971, p. 99). In other words, Gf can be thought of as the ability to reason under novel conditions and stands in contrast to performance based on learned knowledge and skills or crystallized intelligence (Haavisto & Lehto, 2005; Horn & Cattell, 1967). Gf is generally assessed by tasks that are nonverbal and relatively culture-free.

Working memory (WM) has been described as a system for holding and manipulating information over brief periods of time, in the course of ongoing cognitive activities. Most theorists in the field agree that WM comprises mechanisms devoted to the maintenance of information over short period of time, also referred to as short-term memory (STM), and processes responsible for cognitive control that regulate and coordinate those maintenance operations (Baddeley, 2000; Cowan, et al., 2005; Engle, 2010; Engle, Kane, & Tuholski, 1999; Engle, Tuholski, et al., 1999). WM is often assessed by complex span tasks that involve the simultaneous processing and storage of information (Daneman & Carpenter, 1980). An example of such a task is counting span, in which participants are asked to count a particular class of items in successive arrays and to store at the same time the number of target items in each array (Case, Kurland, & Goldberg, 1982). These complex span measures stand in contrast to simple span tasks that require only the storage of information with no explicit concurrent processing task. A typical simple span task is digit span, requiring the immediate recall of lists of digits.

Although STM and WM are theoretically distinct and sometimes separately assessed, no single task is a pure measure of either construct (Conway, et al., 2002; Conway, Jarrold, Kane, Miyake, & Towse, 2008; Engle, Tuholski, et al., 1999). Even a seemingly simple task such as digit span is likely to involve cognitive control mechanisms. In a recent study, Unsworth and Engle (2006) showed that simple span with long lists of items tap the same controlled retrieval mechanism as complex span tasks. The authors argue that items from the end of a long list are retrieved from a capacity-limited STM store (or primary memory), whereas items from the beginning of the list which have been displaced from the limited capacity STM store are retrieved via a controlled search of secondary memory. Also, complex span tasks rely on simple storage as well as cognitive control mechanisms (Bayliss, Jarrold, Gunn, & Baddeley, 2003; La Pointe & Engle, 1990). Thus, simple and complex span tasks are likely to tap both storage and cognitive control, to differing degrees: whereas complex span tasks primarily reflect cognitive control and secondary storage, simple span measures are most sensitive to storage and depend less on cognitive control (Conway, Macnamara, Getz, & Engel de Abreu, in press; Kane, et al., 2004; Unsworth & Engle, 2006).

The balance of these contributions to simple and complex span tasks may change with development. The efficiency of processing improves as children get older (Case, et al., 1982); simple span tasks might therefore rely more heavily on cognitive control processes in younger than in older children or in adults (Engle, Tuholski, et al., 1999). If this is the case, simple and complex span tasks should be more closely associated in children than in adults, due to the common contribution of cognitive control mechanisms. Consistent with this position, Hutton and Towse (2001) found that simple and complex span tasks loaded on the same factor in 8- and 11- year-olds. In contrast, other studies suggest that simple and complex span tasks tap distinct but associated underlying constructs in developmental populations (Alloway, Gathercole, & Pickering, 2006; Alloway, Gathercole, Willis, & Adams, 2004; Gathercole, Pickering, Ambridge, & Wearing, 2004; Kail & Hall, 2001; Swanson, 2008).

Links between working memory and fluid intelligence

Many studies have shown that in adults, Gf and WM are strongly linked (Colom, et al., 2003; Conway, et al., 2002; Cowan, et al., 2005; Engle, Tuholski, et al., 1999; Kane, et al., 2004). The underlying nature of the association is, however, not fully understood. According to Engle and colleagues (Engle, 2010), WM and Gf both rely on attentional control mechanisms. In Gf tasks cognitive control is required to analyze problems, monitor the performance process, and adapt the resolution strategy as performance proceeds. In a similar way, cognitive control might be needed in WM tasks in order to maintain memory representations in an active state in the face of interference. A theoretically different account of the Gf-WM link has been proposed by Colom and colleagues (Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008). They argue that STM storage rather than cognitive control accounts for the relationship between WM and Gf.

Supporting evidence for both positions exists. In a latent variable study, Engle and colleagues (Engle, Tuholski, et al., 1999) have shown that when the common STM and WM variance was removed, the WM residual factor was related to Gf, whereas the STM residual was not. Conway et al. (2002) and Kane et al. (2004) reported similar findings, indicating that the cognitive control demands rather than the storage component of WM span tasks are the source of the link with Gf. In contrast, Colom and colleagues have consistently found that individual differences in Gf are significantly associated with both STM and WM (Colom, et al., 2008; Colom, Flores-Mendoza, Quiroga, & Privado, 2005; Colom, Rebollo, Abad, & Shih, 2006). In some of these studies STM was identified as a stronger predictor of Gf than WM, providing support to their position that short-term storage and not cognitive control mechanisms is responsible for the link between WM and Gf. One explanation of the discrepancies across these and other studies is that the degree to which STM and WM appear to be correlated or distinct depends on the particular tasks employed. The use of different tasks by different research groups therefore confounds direct comparisons of results.

The relationship between WM and Gf in children has been less intensively investigated (see Fry & Hale, 2000 for a review), and the few studies that exist generally agree that WM and Gf are strongly related but distinct constructs (Alloway, et al., 2004; Fry & Hale, 2000). However, most of these studies do not address whether WM as a short-term storage system or as a cognitive controlling device is making significant contributions to children's fluid intelligence. In a recent latent variable study on 6- to 9-year-olds, Swanson (2008) found that when controlling for the correlations between WM and STM, the residual WM factor, but not STM, predicted Gf. A similar result was obtained by Bayliss and colleagues (Bayliss, Jarrold, Baddeley, Gunn, & Leigh, 2005). Importantly, in contrast to Swanson (2008), not only WM but also STM accounted for unique variance in Gf (see also Tillman, Nyberg, & Bohlin, 2008). In another developmental study the WM residual factor failed however to manifest significant links with Gf (Bayliss, et al., 2003).

The present study

The purpose of the present study was to explore the underlying nature of the relationship between WM, STM, and Gf in 5- to 9-year-old children. The study had two major aims: First, it explored whether simple and complex span tasks are more closely associated in younger children than in older children or in adults, potentially because of the contribution of cognitive control mechanisms in assessments of STM in younger children (Engle, Tuholski, et al., 1999; Hutton & Towse, 2001). Second, the study investigated whether the pattern of results favors either the proposal that cognitive control is driving the link between complex span tasks and Gf (Engle & Kane, 2004; Kane & Engle, 2002), or that STM accounts for the relationship between complex span tasks and Gf (Colom, et al., 2006). The study is unique in using a latent variable approach to estimate the relationships of WM and STM with Gf in young children followed longitudinally over three years. As complex and simple span tasks have been suggested to reflect both storage and cognitive control to differing degrees, unique relationships of WM and STM with Gf were explored in order to disentangle the specific effects of cognitive control and short-term storage to Gf.

WM and STM were assessed by multiple measures that are widely used in research with children and that are part of many standardized test batteries (e.g., AWMA, Alloway, 2007; CNRep, Gathercole & Baddeley, 1996; WMTB-C, Pickering & Gathercole, 2001). WM was evaluated by two complex span tasks in which recall was verbal and the nature of the processing activity was either verbal (backwards digit recall) or visuo-spatial (counting recall). STM was assessed by two storage-only tasks: digit recall and nonword repetition. Both tasks involve spoken presentation of the stimuli; the to-be-remembered material differed however in terms of content domain and familiarity. Gf was evaluated by the Raven's Colored Progressive Matrices Test (CPM; Raven, Court, & Raven, 1986) a visuo-spatial reasoning and problem solving task in which children need to derive a set of rules or relations between stimuli in order to complete a visual pattern. To complete an item, a number of subresults have to be stored during the period that the item is being solved. The more difficult problems entail a larger number or more difficult rules and more figural elements per entry (see Carpenter, Just, & Shell, 1990 for a review). The Raven's Matrices tests is one of the most commonly adopted means of testing Gf in both adults (Carpenter, et al., 1990; Conway, et al., 2002; Engle, 2010) and in children (Bayliss, et al., 2003; Swanson, 2008), and loads highly on a general factor in psychometric studies of intelligence (Carroll, 1993).

In summary, the presented study investigates the underlying factor structure of the above presented measures in a population of young children in order to explore (a) if WM, STM, and Gf represent dissociable constructs in young children and (b) how these different aspects of fluid cognition are related and develop over time in an attempt to determine more precisely if a link between WM and Raven's Matrices performance exists in young children and whether the possible association is mediated by short term storage or cognitive control.

2. Method

Participants

The initial sample consisted of 122 children from 38 kindergarten classes (11 public schools) in Luxembourg. By careful follow-up and tracking of children who had moved within the country, 119 children were retained from the original sample for the three-year duration of the study. Of the 119 children for whom complete data were available, 61 were boys and 58 were girls. Luxembourgish was the first language for the totality of the participants. All of the children learned German and French as foreign languages in first and second grade respectively. Ethnicity representation for the participants was 100% Caucasian. The socioeconomic status of the sample was primarily middle to upper middle class, established on the basis of caregiver education and occupation. The children were followed from their second year of kindergarten to the end of second grade. When first tested, children had a mean chronological age of 6 years and 3 month (SD = 3.37) with a range of 5 years; 9 month to 6 years; 10 month. Consent was obtained from the main caregiver of every child participating in the study.

Procedure

The measures were administered as part of a larger test battery exploring the effects of working memory on learning in young multilingual children (Engel de Abreu, 2009). Each child was tested individually in a quiet area of the school. Children were assessed in Luxembourgish. Test design followed the same principles underlying the establishment of the English originals. All tests were translated and adapted by the first author who is fluent in both Luxembourgish and English, and were checked for accuracy and clarity by different independent native speakers. The test material was initially piloted on a group of Luxembourgish children aged 5 to 8. All tests were comprehensible, and the material appeared to be adequate for use with Luxembourgish children. Audio recordings were made by a female native speaker in a neutral accent, and digitally edited as necessary using GoldWave (2004). The digital material was presented to all children at a comfortable listening level via a laptop computer with external speakers.

The longitudinal design consisted of three measurement occasions within a three-year time period. The first wave of the data was gathered when children were in their second year of kindergarten before the start of formal instruction in reading and foreign languages had begun. The next two testing sessions took place exactly one and two years later when children were in the first and second grades. As for none of the tests standardized norms on a population of Luxembourgish children were available, raw scores were used as dependent variables for all of the measures. Cronbach's alpha reliability coefficients for the sample were calculated for all scores across all testing waves. The totality of the test material used for the three study waves are presented below. Tasks that form part of published test batteries are described in fewer details.

Tasks

Fluid intelligence. Gf was evaluated by the Raven Colored Progressive Matrices Test (Raven, et al., 1986). In this test, the children are required to complete a geometrical figure by choosing the missing piece among 6 possible drawings. Patterns progressively increase in difficulty. The test consisted of 36 items divided into three sets of 12 (set A, set AB, and set B). Within each set, items are ordered in terms of increasing difficulty. Sets also vary in difficulty, with set B containing the most challenging items. Four scores were calculated: three scores for each set (A, AB, and B) and a total overall score.

Working memory. Luxembourgish adapted versions of two complex memory span tasks from the computer-based Automated Working Memory Assessment[1] (AWMA, Alloway, 2007) were administered – counting recall and backwards digit recall. Both measures were span tasks in which the amount of items to be remembered increased progressively over successive blocks containing 6 trials each. The criterion for moving on to the next block was correct recall of 4 out of the 6 trials. Test administration stopped if the child failed 3 trials in one block (for futher details of the psychometric properties of the measures see, Alloway, Gathercole, Kirwood, & Elliot, 2008). In the *Counting Recall* task (AWMA, Alloway, 2007) the child is instructed to count and memorize the number of circles in a picture containing triangles and circles. At the end of each trial the child is required to recall the number of circles of each picture in the correct order. The test consisted of 7 blocks with trials of 1 picture in the first block, increasing to trials of 7 pictures in the last block. The number of correct recalled trials was scored for each child, with a possible maximum score of 42. For *Backwards Digit Recall* (AWMA, Alloway, 2007) the child is required to immediately recall a sequence of spoken digits in the reverse order. The test consisted of 6 blocks, starting with

2 digits in block one, increasing to sequences of 7 digits in the last block. Each correct trial was scored with a possible maximum of 36.

Verbal short-term memory. STM was assessed with the Luxembourgish translated *Digit Recall Task* from the AWMA[1] (Alloway, 2007) in which sequences of spoken digits have to be immediately repeated in the order that they were presented. The test consisted of 9 blocks of 6 trials each, starting with one digit and increasing to sequences of 9 digits. The criterion for moving on to the next block was correct recall of 4 trials. After the failure of 3 trials in one block testing stopped. A correct recalled list received a score of 1, and the possible maximum score on the test was 54. A Luxembourgish *Nonword Repetition task* (LuNRep, Engel de Abreu, 2009) based on the Children's Test of Nonword Repetition (CNRep, Gathercole & Baddeley, 1996) was administered as a second measure of STM. In this task the child hears a nonsense word - an unfamiliar phonological word form - and has to immediately repeat it. In total 50 nonwords are presented, ranging in lengths from 1 to 5 syllables, with 10 nonwords in each category. The phoneme sequence in each nonword conforms to the phonotactic rules of Luxembourgish, and the items were constructed to correspond to the dominant syllable stress pattern in Luxembourgish for words of that length. The nonwords were auditory presented via a laptop computer, and each child's responses were digitally recorded for later analysis. Recall accuracy as well as phonetic transcription for each individual item was recorded on a response sheet by the experimenter. The digitally recorded responses were later transcribed into phonetic script with the original scoring sheet, recorded at the time of testing, being used to aid phonetic transcription. Responses were scored as incorrect if the child produced a sound that differed from the target nonword by one or more phonemes. For cases in which it was apparent from the child's spontaneous speech that a specific phoneme was consistently misarticulated as another phoneme (e.g., [ʃ] for [s]), credit was given for the consistent substitution. The number of correctly repeated nonwords was calculated with a total maximum score of 50.

3. Results

Preliminary data analysis

All variables were examined separately for each of the three study waves. Skew and kurtosis for all the variables met criteria for univariate normality (see Kline, 2005). Univariate outliers on each of the 15 variables were defined as values more than 3 *SD* above or below the group mean (Kline, 2005). Four cases, out of the 1785 in the data set met this criterion and were replaced with scores corresponding to plus or minus 3 *SD* as appropriate. The data manifested reasonable multivariate normality with standardized kurtosis values below 3. For none of the analyses multivariate outliers were identified (Mahalanobis distance D^2; $p < .005$).

Internal reliability estimates for the scores on the different measures were calculated using Cronbach's alpha. Reliability coefficients of the scores on all the measures for the different study waves are presented in Table 1. The two WM tasks and the digit recall measure consisted of 6 trials at different list length. For each of the three tasks 6 subscores were computed by combining the first, second, third, fourth, fifth, and sixth trials at each different list length into a single score. Cronbach's alpha was then established from these subscores (Unsworth, Heitz, Schrock, & Engle, 2005). For the nonword repetition measure 10 subscores were devised, each of which contained 5 nonwords of each of the 5 syllable lengths. Cronbach's alpha was computed from these 10 subscores. Scores on the WM and STM measures manifested good reliability with alphas ranging from .79 to .91. Scores on the Raven Colored Progressive Matrices manifested lower yet tolerable reliability (*r*'s ranging from .67 to .72). For nonword repetition, inter-rater reliability was established by having 25% of the kindergarten, 21% of the first grade, and 23% of the second grade recorded data scored by a second qualified rater. The index of inter-rater reliability based on Cohen's Kappa (Cohen, 1960), taking into account the agreement occurring by chance, was .78 for the kindergarten scores, .82 for first grade, and .72 for second grade which can be considered substantial strengths of agreements for all three measurement occasions (Landis & Koch, 1977).

Table 1 about here

Descriptive statistics

Descriptive statistics for the kindergarten, first grade, and second grade measures are presented in Table 2. A series of repeated measure analyses of variance were performed with study wave specified as the within-subject factor. Repeated contrasts were conducted in which performance in wave two was compared to performance in wave one and wave three.

Table 2 about here

As reported in Table 2, all univariate *F*-tests were significant and effect sizes were large, indicating that test performance increased significantly over the years. Pairwise comparisons revealed that, with the exception of nonword repetition for which performance in first and second grade did not differ, scores on all of the measures increased significantly from kindergarten to first grade and from first to second grade.

Table 3 about here

Correlations between all pairs of variables are presented in Table 3. Across the years correlations between nonword repetition and digit recall, associated with verbal STM were high (*r's* ranging from .59 to .61). Counting recall and backwards digit recall, indexing WM, were moderately correlated in kindergarten and third grade (*r's* of .38 and .36) and manifested a weaker association in first grade that was, however, significant (r = .19). Notably, across constructs, the WM measures correlated significantly with the Raven's Colored Matrices (*r*'s ranging from .19 to .34) whereas STM did not appear to be strongly linked to Raven's Matrices across the years (*r*'s ranging from .12 to .21). With one exception in kindergarten (Raven – nonword repetition, $r = .12$ and Raven - backwards digit recall, $r = .34$; $p = .02$) these differences in the strengths of association between Raven Colored Matrices with the observed STM and WM measures did, however, not reach statistical significance.

Confirmatory factor analyses

A series of confirmatory factor analyses (CFA) were performed on the covariance structure to test competing theoretical models of the associations between the measures and to compare the goodness of fit of each model. Maximum likelihood estimation was applied with the computer program AMOS 7 (Arbuckle, 2006) to estimate the model's parameters and fit indices. The goodness of fit for the estimated models was assessed by a combination of different fit statistics: the χ^2 statistic; Bentler's Comparative Fit Index (CFI; Bentler, 1990), Bollen's Incremental Fit Index (IFI; Bollen, 1989), and the Root Mean Square Error of Approximation (RMSEA; Browne & Cudeck, 1993). RMSEA, CFI, and IFI were selected because they are relatively independent of sample size (see Kline, 2005 for a review of the different fit indices). Likelihood ratio tests were performed to evaluate the significance of regression coefficients. This procedure was used because it is more reliable than test statistics based on standard errors (Gonzalez & Griffin, 2001).

A first set of models tested whether WM and STM were operating as distinct processes in young children. For this purpose one and two-factor CFA models were fitted to the data. Separate analyses were performed for each study wave. The starting point was a two-factor model in which digit recall and nonword repetition loaded on one factor and counting recall and backwards digit recall loaded on another factor.

Figure 1 about here

As data on digit recall and backwards digit recall were obtained by using a similar instrument, with both tasks involving the manipulation of numbers, the error variances of these measures were constrained to be equal. The model solution is summarized in Figure 1 and the fit statistics are shown in Table 4 (Model 1). This two-factor model was contrasted with a more parsimonious single factor model in which all the measures loaded on a common factor (Table 4, Model 2).

Table 4 about here

Across the three testing waves the two-factor solution provided a good fit to the data with non-significant χ^2 values, CFI and IFI indexes above .96, and low RMSEA values. The two-factor model accounted significantly better for the data than the single factor model for the kindergarten and the second grade data [kindergarten: $\Delta\chi^2(1) = 7.94$; second grade: $\Delta\chi^2(1) = 14.53$; $p < .05$ in both cases]. For first grade the chi-square difference test just failed to reach significance [$\Delta\chi^2(1) = 3.37$, $p = .06$]; in light of the other fit indices a two factor model was preferred over a single factor solution supporting the hypothesis that the two target STM tasks and the two WM measures reflect different latent variables across the childhood years.

Figure 2 about here

The next set of models explored how WM, STM and Gf were related across the years. In the three-factor model, represented in Figure 2, the Raven's subscores[2] were specified to load onto a separate factor, distinct from STM and WM. As can be seen from Table 4 (Model 3), model fits were excellent in each study wave, with non-significant χ^2 values (p's ranging from .42 to .73); CFI and IFI indices of 1; and RMSEA values ranging from .00 to .02.

Table 5 about here

The standardized factor loadings of each variable onto its respective latent factor are provided in the top part of Table 5; inter-factor correlations are represented in the lower part of Table 5. With the exception of the Raven A subscore that did not manifest a significant link with Gf in second grade (p = .12), all the other tasks loaded significantly onto their intended constructs. For the correlations between the latent factors the data showed that across the years Gf manifested strong links with WM (r's ranging from .50 to .62). For the Gf-STM correlations the results showed nonsignificant links in kindergarten (.18, p = .12) but medium associations in first (.26, p = .04) and in second grade (.30, p = .01). Constraining the Gf-WM and Gf-STM correlation to be equal within each study wave significantly worsened model fit for kindergarten [$\Delta\chi^2(1) = 8.14$, $p < .01$] but not for first [$\Delta\chi^2(1) = .06$, $p = .81$] or for second grade [$\Delta\chi^2(1) = 1.49$, $p = .22$].

The preceding analyses suggest that the general three-factor structure of separate but related WM, STM, and Gf constructs holds through the early childhood years. This hypothesis was assessed more directly by fitting the same baseline model (represented in Figure 2) simultaneously across the three study waves. A model in which measurement weights and structural covariances were constant across the years provided a good fit to the data [$\chi2$ (26) = 71.71, p = .11].

Hierarchical regression models

In the preceding CFA models the links between WM and STM with Gf were estimated without controlling for the WM-STM inter-correlations. A major aim of the study was to explore the specific effects of STM and WM on Gf: Hierarchical, or fixed-order, regression analyses were therefore conducted in this second part of the analyses. In contrast to standard structural regression models in which all the latent predictors are specified as simultaneous causes of the outcome factor, hierarchical regression models, just like regular hierarchical regression analyses with observed variables, allow one to enter the latent predictors into the regression equation in a pre-specified order. The variance of the observed variables is thus partitioned into a part due to the general factor and a part accounted for by the specific factor. Regression of Gf on these factors reveals the independent contributions of the general and the specific factors. Conceptually the common factor purportedly represents either STM or WM (depending on the model specification), and the specific factor reflects the residual after the general factor has been partialled out (see de Jong, 1999; Gustafsson & Balke, 1993 for further details). Hierarchical regression models therefore provide the opportunity to explore both specific and general contributions of STM and WM to Gf. Furthermore, this method avoids the problem of multicollinearity that can arise if correlated predictors are entered simultaneously into the analyses. Although hierarchical regression analyses are of common practice with observed variables, its use with latent factors is recent and consequently less regular.

The method adopted in the present study is based on an approach by de Jong (1999), in which a Cholesky factoring is applied to the latent predictors (see also, Loehlin, 1996). All the models were specified as second-order factor models. The second-order factors were uncorrelated and their number was identical to the first-order predictor factors. The dependent latent factor (i.e. Gf) was regressed onto the second-order factors. The order in which the latent predictors were entered into the analyses (i.e. the order in which the dependent factor was regressed onto the latent predictors) was determined by the specific pattern of loadings of the first-order onto the second-order factors.

Figure 3 about here

As an illustrative example, the structural part of a model is represented in Figure 3. The pattern of loadings of the original predictors on the newly created predictors (i.e. second-order factors) specifies a hierarchical regression analysis in which STM is entered first and WM is entered second. The path coefficient linking the second-order WM factor to Gf can thus be interpreted as the square root of the proportion of variance that WM explains in Gf after STM has been taken into account. Because Cholesky factoring corresponds to a rearrangement of the factor inter-correlation matrix of the latent predictors, the fits of the hierarchical regression models did not differ from the fits of the three-factor CFA models reported in Table 4.

Table 6 about here

For each study wave two sets of hierarchical regression analyses were performed to examine the specific effects of WM and STM to Gf. The standardized estimates are represented in Table 6. In the first set of analyses, represented in the upper part of Table 6, STM was entered in the first step of the analyses whereas in the second set of models WM was entered first (bottom part of Table 6). The total R^2 for each study wave is provided in italics. Results were very clear: After the effects of STM were controlled, the WM residual described additional variance in Gf in all three study waves, accounting for 31% of additional variance in Gf in kindergarten, 32 % in first grade, and 17% in second grade. STM in contrast did not make any specific contributions to Gf after controlling for the variance shared with WM.

4. Discussion

The main objective of the present paper was to examine the links between WM, STM, and fluid intelligence in a population of young children followed from kindergarten through second grade. A particular focus of the study was to explore whether significant links between WM and fluid intelligence would emerge and more specifically, which aspect of the WM system - short-term storage or cognitive control - might mediate the relationship.

The data indicate that STM and WM performance reflect distinguishable but related processes, in line with the theoretical framework on adults proposed by Baddeley (2000) and Engle et al. (Engle, Kane, et al., 1999; Engle, Tuholski, et al., 1999) and consistent with previous studies on children (Alloway, et al., 2006; Alloway, et al., 2004; Gathercole, et al., 2004; Kail & Hall, 2001; Swanson, 2008). The findings provide little support for the hypothesis that WM and STM are less distinct in younger children than in older children or adults due to less automated rehearsal and chunking processes and consequently increased implications of cognitive control in assessments of STM in younger children (Engle, Tuholski, et al., 1999; Hutton & Towse, 2001). Contrary to this hypothesis, the same two-factor structure that Engle et al. (Engle, Tuholski, et al., 1999) identified in adults was found in children as young as 6 years of age. In fact, in the present study the links between the WM and STM factors were lower than in latent variable studies on adults in which correlations between these two constructs ranged from .68 to .82 (e.g., Colom, Abad, Rebollo, & Shih, 2005; Colom, Flores-Mendoza, et al., 2005; Conway, et al., 2002; Engle, Tuholski, et al., 1999; Kane, et al., 2004) suggesting greater independence among these measures in children than in adults (see Kail & Hal, 2001 and Swanson, 2008 for similar findings).

Although complex span measures shared substantial variance with tests of simple storage, they also reflected some unique variance that was highly predictive of performance on the Raven’s Colored Progressive Matrices (see Bayliss, et al., 2005; Swanson, 2008 for similar findings). According to the theoretical framework proposed by Engle and colleagues (Engle, Tuholski, et al., 1999), the residual WM variance should conceptually represent cognitive control. Importantly, STM did not share any specific links with Gf after variance associated with complex span tasks was taken into account. These findings run counter to proposals that the relationship between Gf and WM is mediated by an individual’s STM capacity (Colom, et al., 2008; Colom, Flores-Mendoza, et al., 2005; Colom, et al., 2006), favoring instead the view that cognitive control mechanisms underlie performance on complex span tasks of WM and assessments of fluid intelligence (Conway, et al., 2002; Engle, Tuholski, et al., 1999; Kane & Engle, 2002).

Unsworth and Engle (2006, 2007) recently suggested that due to the attention-demanding processing component of complex span tasks, the to-be-remembered items are quickly displaced from an initial short-term store (primary memory) into secondary memory.

Attention is needed to engage in a cue-dependent search of secondary memory and combat potential problems, such as proactive interference, in order to successfully retrieve and recall the displaced items. Matrix reasoning tasks like the Raven Progressive Matrices are likely to rely on the same mechanism: to successfully complete an item, a number of intermediate results have to be stored during the period that the item is being solved. These intermediate results might be briefly held in primary memory but as a consequence of having to manipulate other aspects of the problem might then be rapidly displaced into secondary memory. Children with low scores on WM and Gf tasks might have difficulty engaging an attention-based search of secondary memory and consequently may be more likely to consider unnecessary information and alternative interpretations of material, which could depress their performance. The ability to use attention to actively retrieve representations from secondary memory in the presence of proactive interference might therefore underlie the correlation of complex span tasks and Gf.

When considered in isolation (i.e. without controlling for the variance shared with complex span tasks) significant links between simple span tasks and performance on the Raven's Matrices emerged. If only cognitive control is driving the link with Gf, how are these correlations to be explained? Although complex and simple span task relate to separate underlying factors they will inevitably overlap to some extent and be distinguished only by the balance of their underpinning mechanisms. It has been argued that in certain situations performance in simple span tasks reflect both short-term storage and cognitive control. Unsworth and Engle (2006, 2007) have repeatedly shown that long-list simple span tasks correlate as strongly with measures of Gf as complex span tasks. According to their position, span tasks correlate with higher order cognition if they require retrieval from secondary memory: Complex spans task are linked to Gf because these measures rely heavily on retrieval from secondary memory whereas simple span tasks manifest lower and less specific associations with Gf because they only require retrieval from secondary memory under conditions of STM overload.

The contribution of STM to fluid intelligence increased steadily over the childhood years, suggesting that whereas very young children rely heavily on short-term storage, older children might be able to engage in a controlled search of secondary memory when performing simple span tasks. This developmental change is likely to occur when children are around 7, and might account for the developmental increase in span performance observed across the early childhood years. Interestingly, the age at which children start to engage in subvocal rehearsal (Flavell, Beach, & Chinsky, 1966; Gathercole, Adams, & Hitch, 1994) coincides with the increase in the STM-Gf relationship observed in the present study. Subvocal rehearsal is thought to reactivate traces in STM (Baddeley, 1986), it is therefore likely that the shift from relying exclusively on primary memory to making use of both primary and secondary memory when completing STM tasks is driven by the emergence of subvocal rehearsal. Further studies are clearly needed in order to address this hypothesis more directly. One possibility is to follow Unsworth and Engle's procedure (2006) and increase variability in longer list lengths in young children and explore if under these circumstances a significant STM-Gf link emerges.

In summary, the present study demonstrates that in young children individual differences in WM and STM are distinct, but associated. Whereas complex span tasks uniquely predict fluid intelligence, simple span tasks do not. These findings suggest that complex WM span tasks tap into a fundamental aspect of cognition that is shared with measures of fluid intelligence and that might represent the ability to effectively control attention in order to maintain task goal relevant information activated in the face of interference.

References

Alloway, T. P. (2007). *Automated Working Memory Assessment*. London: Pearson Assessment.

Alloway, T. P., Gathercole, S. E., Kirwood, H., & Elliot, J. (2008). Evaluating the validity of the Automated Working Memory Assessment. *Educational Psychology, 28*(7), 725-734.

Alloway, T. P., Gathercole, S. E., & Pickering, S. J. (2006). Verbal and visuo-spatial short-term and working memory in children: Are they separable? *Child Development, 77*(6), 1698-1716.

Alloway, T. P., Gathercole, S. E., Willis, C., & Adams, A. M. (2004). A structural analysis of working memory and related cognitive skills in young children. *Journal of Experimental Child Psychology, 87*, 85-106.

Arbuckle, J. L. (2006). *AMOS 7*. Chicago: SmallWaters.

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

Baddeley, A. D. (2000). The episodic buffer: a new component of working memory? *Trends in Cognitive Sciences, 4*(11), 417-423.

Bayliss, D. M., Jarrold, C., Baddeley, A. D., Gunn, D. M., & Leigh, E. (2005). Mapping the developmental constraints on working memory span performance. *Developmental Psychology, 41*(4), 579-597.

Bayliss, D. M., Jarrold, C., Gunn, D. M., & Baddeley, A. D. (2003). The complexities of complex span: Explaining individual differences in working memory in children and adults. *Journal of Experimental Psychology-General, 132*(1), 71-92.

Bentler, P. M. (1990). Comparative fit indexes in structural models. *Psychological Bulletin, 107*(2), 238–246.

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

Browne, M. W., & Cudeck, R. (1993). Alternative ways of assessing model fit. In K. A. Bollen & J. S. Long (Eds.), *Testing structural models*. Newbury Park, CA: Sage.

Carpenter, P. A., Just, M. A., & Shell, P. (1990). What one intelligence test measures - A theoretical account of the processing in the Raven Progressive Matrices Test. *Psychological Review, 97*(3), 404-431.

Carroll, J. B. (1993). *Human cognitive abilities: A survey of factor analytic studies*. New York: Cambridge University Press.

Case, R., Kurland, D. M., & Goldberg, J. (1982). Operational efficiency and the growth of short-term memory span. *Journal of Experimental Child Psychology, 33*(3), 386–404.

Cattell, R. B. (1971). *Abilities: Their structure, growth, and action*. New York: Houghton Mifflin.

Cohen, J. (1960). A coefficient of agreement for nominal scales. *Educational and Psychological Measurement, 20*, 37–46.

Colom, R., Abad, F. J., Quiroga, M. A., Shih, P. C., & Flores-Mendoza, C. (2008). Working memory and intelligence are highly related constructs, but why? *Intelligence, 36*(6), 584-606.

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.

Colom, R., Flores-Mendoza, C., Quiroga, M. A., & Privado, J. (2005). Working memory and general intelligence: The role of short-term storage. *Personality and Individual Differences, 39*(5), 1005-1014.

Colom, R., Flores-Mendoza, C., & Rebollo, I. (2003). Working memory and intelligence. *Personality and Individual Differences, 34*(1), 33-39.

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.

Conway, A. R. A., Cowan, N., Bunting, M. F., Therriault, D. J., & Minkoff, S. R. B. (2002). A latent variable analysis of working memory capacity, short-term memory capacity, processing speed, and general fluid intelligence. *Intelligence, 30*(2), 163-183.

Conway, A. R. A., Jarrold, C., Kane, M. J., Miyake, A., & Towse, J. N. (2008). Variation in working memory: an introduction. In A. R. A. Conway, C. Jarrold, M. J. Kane, A. Miyake & J. N. Towse (Eds.), *Variation in working memory*. New York: Oxford University Press.

Conway, A. R. A., Macnamara, B., Getz, S., & Engel de Abreu, P. M. J. (in press). Working memory and fluid intelligence: A multi-mechanism view. In R. Sternberg & S. B. Kaufman (Eds.), *Cambridge Handbook of Intelligence*. New York: Cambridge University Press.

Cowan, N., Elliott, E. M., Saults, J. S., Morey, C. C., Mattox, S., Hismjatullina, A., et al. (2005). On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychology, 51*(1), 42-100.

Daneman, M., & Carpenter, P. A. (1980). Individual-differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior, 19*(4), 450-466.

de Jong, P. F. (1999). Hierarchical regression analysis in structural equation modeling. *Structural Equation Modeling, 6*(2), 198-211.

Engel de Abreu, P. M. J. (2009). *Working memory and learning.* University of York, York.

Engle, R. W. (2010). Role of working memory capacity in cognitive control. *Current Anthropology, 51*, S1.

Engle, R. W., & Kane, M. J. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. In B. H. Ross & D. Irwin (Eds.), *Psychology of learning and motivation: Advances in research and theory* (Vol. 44, pp. 145-199). San Diego: Academic Press Inc.

Engle, R. W., Kane, M. J., & Tuholski, S. W. (1999). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence, and functions of the prefrontal cortex. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 102–134). New York: Cambridge University Press.

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.

Flavell, J. H., Beach, D. R., & Chinsky, J. M. (1966). Spontaneous verbal rehearsal in a memory task as a function of age. *Child Development, 37*(2), 283-299.

Fry, A. F., & Hale, S. (2000). Relationships among processing speed, working memory, and fluid intelligence in children. *Biological Psychology, 54*(1-3), 1-34.

Gathercole, S. E., Adams, A. M., & Hitch, G. J. (1994). Do young children rehearse - An individual differences analysis. *Memory and Cognition, 22*(2), 201-207.

Gathercole, S. E., & Baddeley, A. D. (1996). *The children's test of nonword repetition*. London: Psychological Corporation.

Gathercole, S. E., Pickering, S. J., Ambridge, B., & Wearing, H. (2004). The structure of working memory from 4 to 15 years of age. *Developmental Psychology, 40*(2), 177-190.

GoldWave Inc. (2004). *GoldWave digital audio editor software* (fifth ed.). St. John's, NL: GoldWave Inc.

Gonzalez, R., & Griffin, D. (2001). Testing parameters in structural equation modeling: Every "one" matters. *Psychological Methods, 6*(3), 258-269.

Gustafsson, J. E., & Balke, G. (1993). General and specific abilities as predictors of school achievement. *Multivariate Behavioral Research, 28*(4), 407-434.

Haavisto, M. L., & Lehto, J. E. (2005). Fluid/spatial and crystallized intelligence in relation to domain-specific working memory: A latent-variable approach. *Learning and Individual Differences, 15*(1), 1-21.

Horn, J. L., & Cattell, R. B. (1967). Age differences in fluid and crystallized intelligence. *Acta Psychologica, 26*(2), 107-129.

Hutton, U. M. Z., & Towse, J. N. (2001). Short-term memory and working memory as indices of children's cognitive skills. *Memory, 9*(4-6), 383-394.

Kail, R., & Hall, L. K. (2001). Distinguishing short-term memory from working memory. *Memory & Cognition, 29*(1), 1-9.

Kane, M. J., & Engle, R. W. (2002). The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: An individual-differences perspective. *Psychonomic Bulletin & Review, 9*(4), 637-671.

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 visuo-spatial memory span and reasoning. *Journal of Experimental Psychology: General, 133*(2), 189–217.

Kline, R. B. (2005). *Principles and practice of structural equational modeling* (second ed.). New York: The Guilford Press.

La Pointe, L. B., & Engle, R. W. (1990). Simple and complex word spans as measures of working memory capacity. *Journal of Experimental Psychology-Learning Memory and Cognition, 16*(6), 1118-1133.

Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics, 33*(1), 159-174.

Loehlin, J. C. (1996). The Cholesky approach: A cautionary note. *Behavior Genetics, 26*(1), 65-69.

Oberauer, K., Schulze, R., Wilhelm, O., & Süß, H. M. (2005). Working memory and intelligence - Their correlation and their relation: Comment on Ackerman, Beier, and Boyle (2005). *Psychological Bulletin, 131*(1), 61-65.

Pickering, S. J., & Gathercole, S. E. (2001). *Working memory test battery for children*. London: Psychological Corporation Europe.

Raven, J. C., Court, J. H., & Raven, J. (1986). *Coloured progressive matrices*. London: H. K. Lewis.

Swanson, H. L. (2008). Working memory and intelligence in children: What develops? *Journal of Educational Psychology, 100*(3), 581-602.

Tillman, C. M., Nyberg, L., & Bohlin, G. (2008). Working memory components and intelligence in children. *Intelligence, 36*(5), 394-402.

Unsworth, N., & Engle, R. W. (2006). Simple and complex memory spans and their relation to fluid abilities: Evidence from list-length effects. *Journal of Memory and Language, 54*(1), 68-80.

Unsworth, N., & Engle, R. W. (2007). On the division of short-term and working memory: An examination of simple and complex spans and their relation to higher order abilities. *Psychological Bulletin, 133*, 1038-1066.

Unsworth, N., Heitz, R. R., Schrock, J. C., & Engle, R. W. (2005). An automated version of the operation span task. *Behavior Research Methods, 37*(3), 498-505.

Unsworth, N., Redick, T. S., Heitz, R. P., Broadway, J. M., & Engle, R. W. (2009). Complex working memory span tasks and higher-order cognition: A latent-variable analysis of the relationship between processing and storage. *Memory, 17*(6), 635-654.

Footnotes

[*] This project was funded by the Economic and Social Research Council (ESRC) of Great Britain and the Fond National de la Recherche (FNR) of Luxembourg. The authors wish to thank the schools, parents, and children who consented to participate in this study and Christiane Bourg for assistance on task scoring. Correspondence concerning this article should be addressed to Pascale M. J. Engel de Abreu, EMACS Research Unit, University of Luxembourg, L-7201 Walferdange, G.D. de Luxembourg. E-mail: Pascale.Engel@uni.lu

[1] Translated and reproduced by Permission.

[2] For fluid intelligence only one observed measure was obtained. To optimize the models solution and avoid biasing effects of error, fluid intelligence was indexed by the three subscores: Raven A; Raven AB; and Raven B. All the analyses were conducted again with the Raven overall score as outcome variable and with the error term constrained to an estimate based on the measures established reliability. The results did not change considerably.

[3] The analyses were run again using standard structural regression models. The results did not change considerably.

Table 1

Reliability Coefficients for the Different Study Waves

Measures	Kindergarten			First grade			Second grade		
	Reliability	Skewness	Kurtosis	Reliability	Skewness	Kurtosis	Reliability	Skewness	Kurtosis
Fluid intelligence									
Raven	.72	.09	.23	.71	.08	-.39	.67	-.19	-.34
Working memory									
Counting Recall	.85	.87	.63	.81	.28	-.24	.89	-.14	-.21
Backwards digit recall	.85	-.53	.85	.84	.20	-1.11	.80	.16	.90
Short-term memory									
Digit Recall	.84	.26	-.24	.91	.50	.20	.89	.20	-.11
Nonword repetition	.79	-.66	.12	.81	-.83	.23	.83	-.85	.32
	.78[a]			.82[a]			.72[a]		

Note. Raven: Raven Colored Progressive Matrices Test; [a]interrater reliability

Table 2

Descriptive Statistics for the Kindergarten, First, and Second Grade Study Waves

Measures	Max.	Kindergarten			First grade			Second grade			*F*	η^2	Contrasts
		Mean	*SD*	Range	Mean	*SD*	Range	Mean	*SD*	Range			
Age (in month)	--	75.13	3.37	69-82	87.03	3.44	80-94	99.03	3.44	92-106			
Fluid intelligence													
Raven	36	18.97	4.31	8-31	23.65	4.03	15-34	25.98	3.44	17-33	227.01^{**}	.66	K<Gr1<Gr2
Working memory													
Counting Recall	42	9.69	3.07	5-19	14.45	3.12	7-22	18.17	3.61	8-26	350.91^{**}	.75	K<Gr1<Gr2
Backwards DR	36	5.90	2.42	0-12	8.84	2.42	5-15	11.41	2.52	6-19	227.04^{**}	.66	K<Gr1<Gr2
Short-term memory													
Digit Recall	54	20.50	3.17	14-30	23.03	3.51	15-32	24.55	3.23	18-32	149.54^{**}	.56	K<Gr1<Gr2
Nonword repetition	50	35.19	6.14	18-46	38.33	5.10	23-47	38.76	5.20	24-49	60.61^{**}	.34	K<Gr1=Gr2

Note. Max: Maximum possible score; Raven: Raven Colored Progressive Matrices Test; Backwards DR: Backwards Digit Recall; ** $p < .01$

Table 3

Correlations Between the Scores Using Pearson's Correlation Coefficient (N = 119)

Measures	Kindergarten						First Grade						Second Grade					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
1. Age (in month)	--						--						--					
Fluid intelligence																		
2. Raven	.18	--					.17	--					.11	--				
Short-term memory																		
3. Nonword rep.	.16	.16	--				.01	.16	--				.05	.18	--			
4. Digit Recall	.05	.12	**.59**	--			-.09	.18	**.60**	--			.01	**.21**	**.61**	--		
Short-term memory																		
5. Counting recall	.08	**.27**	.13	**.27**	--		.08	**.25**	-.05	.08	--		.13	**.20**	.13	.16	--	
6. Bachwards DR	.13	**.34**	**.40**	**.41**	**.38**	--	.09	**.19**	**.19**	.14	**.19**	--	.05	**.25**	**.24**	**.32**	**.36**	--

Note. Raven: Raven Colored Progressive Matrices Test; Nonword rep.: Nonword repetition; Backwards DR: Backwards Digit Recall; significant values marked in boldface, $p < .05$

Table 4

Fit Indices of the Confirmatory Factor Analyses Models for the Different Study Waves

Model	χ^2	*df*	*p*	*CFI*	*IFI*	*RMSEA*
Model 1: Two-factor model: WM and STM						
Kindergarten	4.49	2	.11	.97	.97	.10
First grade	4.11	2	.13	.96	.97	.09
Second grade	.00	2	.99	1.00	1.02	.00
Model 2: Single factor model						
Kindergarten	12.43	3	.00	.90	.90	.16
First grade	7.48	3	.06	.92	.93	.11
Second grade	14.53	3	.00	.85	.86	.18
Model 3: Three factor model: WM, STM, and fluid intelligence						
Kindergarten	11.47	12	.49	1.00	1.00	.00
First grade	12.35	12	.42	1.00	1.00	.02
Second grade	8.69	12	.73	1.00	1.02	.00

Note. WM: Working memory; STM: Short-term memory

Table 5

Standardized Factor Loadings and Inter-factor Correlations from Confirmatory Factor Analyses (Model 3)

	Latent factors								
	Kindergarten			First grade			Second grade		
Variable	STM	WM	Gf	STM	WM	Gf	STM	WM	Gf
Nonword rep.	$.70^{**}$			$.76^{**}$			$.73^{**}$		
Digit Recall	$.86^{**}$			$.78^{**}$			$.84^{**}$		
Counting Recall		$.50^{**}$			$.45^{**}$			$.50^{**}$	
Backwards DR		$.75^{**}$			$.43^{**}$			$.72^{**}$	
Raven A			$.62^{**}$			$.52^{**}$			.18
Raven AB			$.81^{**}$			$.71^{**}$			$.75^{**}$
Raven B			$.67^{**}$			$.68^{**}$			$.68^{**}$
	Inter-factor correlations								
STM	--			--			--		
WM	$.65^{**}$	--		$.27^{*}$	--		$.48^{**}$	--	
Gf	.18	$.55^{**}$	--	$.26^{*}$	$.62^{**}$	--	$.30^{*}$	$.50^{**}$	--

Note: STM: short-term memory; WM: working memory; Gf: fluid intelligence; $^{*}p < .05$; $^{**}p < .01$

Table 6

Standardized Regression Coefficients from Hierarchical Regression Analysis with WM and STM predicting Fluid Intelligence

Step	Latent predictor	Kindergarten	First Grade	Second Grade
1	STM	.18	.26*	.30*
2	WM	.56**	.57**	.41*
1	WM	.55**	.62**	.50**
2	STM	-.23	.10	.07
Total R^2		*.35*	*.39*	*.26*

Note. STM: short-term memory; WM: working memory; * $p < .05$; ** $p < .01$

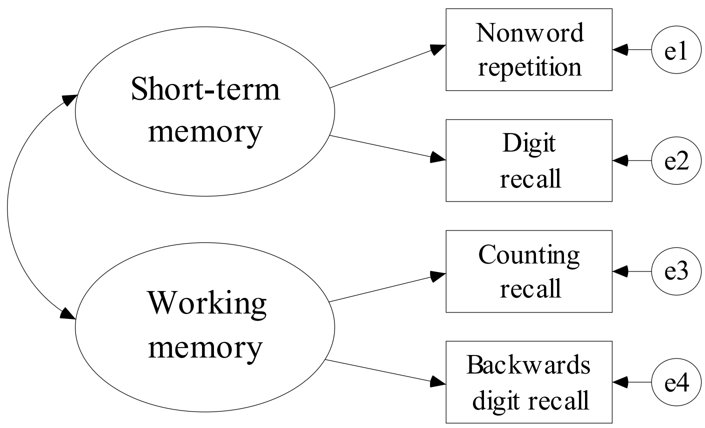

Figure 1. Two-factor Confirmatory Factor Analyses model.

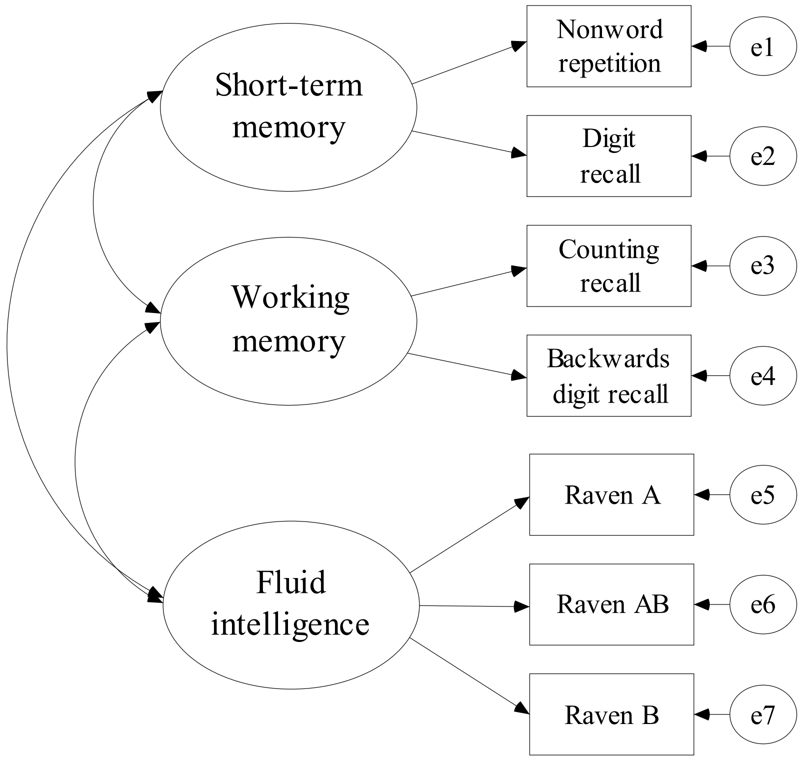

Figure 2. Three-factor Confirmatory Factor Analyses model.

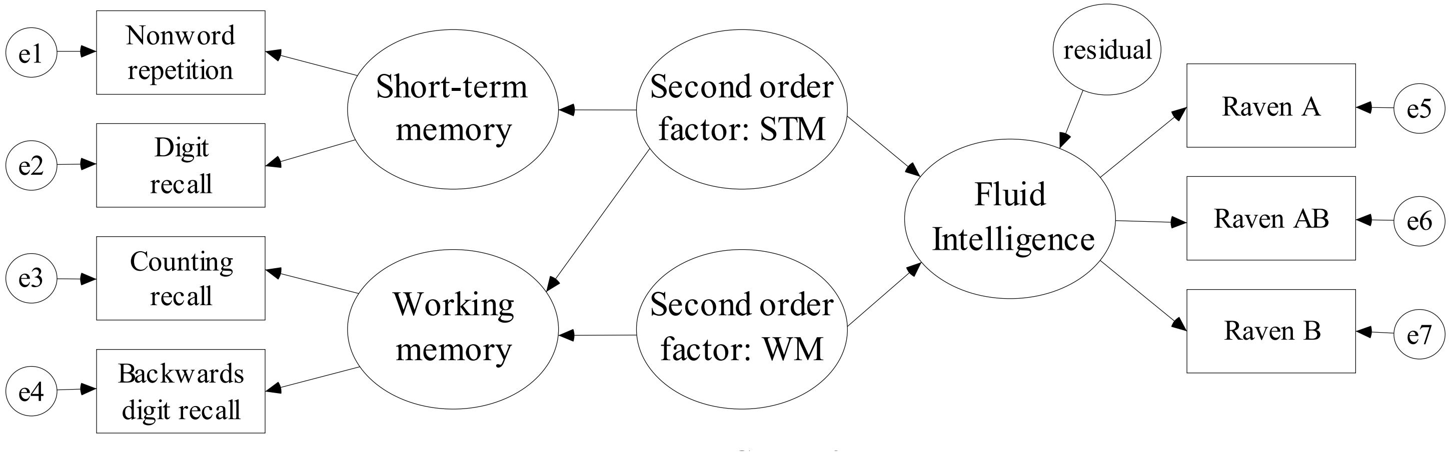

Figure 3. Hierarchical regression model with short-term memory (step 1) and working memory (step 2) as predictors.