Running head: WORKING MEMORY AND LANGUAGE



]

# Disentangling the relationship between working memory and language: the roles of short-term storage and cognitive control

Pascale M. J. Engel de Abreu[12]

Susan E. Gathercole[2]

Romain Martin[1]

[1]University of Luxembourg

[2]University of York

**Abstract**

This study investigates the relationship between working memory and language in young children growing up in a multilingual environment. The aim is to explore whether mechanisms of short-term storage and cognitive control hold similar relations to emerging language skills and to investigate if potential links are mediated by related cognitive abilities. A sample of 119 Luxembourgish 6-year-olds completed several assessments of working memory (complex and simple span), native and foreign vocabulary, syntax, reading, rhyme awareness, and fluid intelligence. Results showed that short-term storage and cognitive control manifested differential links with developing language abilities: Whereas verbal short-term storage was specifically linked to vocabulary; cognitive control manifested unique and robust links with syntax and early reading development. The study suggests that in young children the working memory system is composed of separate but interacting components corresponding to short-term storage and cognitive control that can be distinguished by the roles they play in supporting language acquisition.

*Keywords*: working memory; verbal short-term memory; cognitive control; language; multilingual.

Disentangling the relationship between working memory and language: the roles of short-term storage and cognitive control

## 1. Introduction

Increasing evidence suggests that working memory (WM) and language learning are strongly linked (Gathercole, Alloway, Willis, & Adams, 2006; Gupta, 2003; Service, 1992; Swanson, 2003). What remains less clear is why these associations are observed. The main aim of the present study was to identify which components of the WM system relate to which domains of language and to explore whether potential links are mediated by related cognitive abilities.

WM refers to the ability to store and manipulate information in mind for a brief period of time in the course of ongoing cognitive activities (Baddeley, 2000; Daneman & Carpenter, 1983). Most theorists in the field agree that the WM system consists of multiple interacting components. Some of these components are devoted to the maintenance of information over short periods of time (i.e. short-term memory; STM), whereas other components are responsible for cognitive control that regulate and coordinate those maintenance operations (Baddeley, 2000; Cowan, et al., 2005; Engle, 2010). Mechanisms of cognitive control are often assessed by complex span tasks whereas STM is generally evaluated by simple span tasks (for a review see Conway, Kane, Bunting, Hambrick, Wilhelm, & Engle, 2005).

The extent to which the different WM components are involved in language processing and development remains a key theoretical issue. Verbal STM has been associated with new word learning in native (Avons, Wragg, Cupples, & Lovegrove, 1998; Majerus, Poncelet, Greffe, & van der Linden, 2006), foreign (Cheung, 1996; Masoura & Gathercole, 2005) and artificial languages (Gathercole, Hitch, Service, & Martin, 1997; Jarrold, Thorn, & Stephens, 2009; Mosse & Jarrold, 2008). It has been argued that the quality of the temporary representation of a novel word in STM is critical in the formation of a stable phonological representation in long-term memory (Baddeley, Gathercole, & Papagno, 1998; Gathercole, 2006).

Whether STM plays a significant role in aspects of language other than vocabulary is less clear. Findings by Papagno, Cechetto, Reati, and Bello (2007) indicate that verbal STM is necessary for the comprehension of syntactically complex sentences by allowing the sentence to be mentally replayed when comprehension cannot proceed online. Although some evidence of a relationship between syntactic comprehension and verbal STM exists (Dufva, Niemi, & Voeten, 2001; Montgomery, 1995), others have failed to support this position (Hanten & Martin, 2000; Shankweiler, Smith, & Mann, 1984; Willis & Gathercole, 2001). A similar degree of inconsistency in empirical findings exists for reading development. STM has been suggested by some to contribute to the development of early reading skills (Alloway et al., 2005; de Jong & Olson, 2004); other indications are that this is not the case (Dufva et al., 2001; Gathercole et al., 2006).

One reason for the discrepancies across findings is that not all studies control for mechanisms of cognitive control when exploring the links between STM and higher order linguistic abilities. Increasing evidence suggests that simple span tasks reflect both STM and cognitive control (Engel de Abreu, Conway, & Gathercole, 2010; Unsworth & Engle, 2006); the degree to which STM and higher order linguistic abilities seem to be related might thus depend on whether mechanisms of cognitive control have been controlled.

The completion of complex language tasks often requires to remember some task elements and to inhibit others. Cognitive control mechanisms might be used to maintain task-relevant information in an active state and to regulate controlling processes. In some developmental studies cognitive control has, indeed, been found to account for unique variance in listening comprehension and reading (Daneman & Blennerhassett, 1984; Leather & Henry, 1994). According to Engle and colleagues (Engle, 2010; Engle, et al., 1999) cognitive control is the key mechanism that WM shares with fluid intelligence and is the crucial factor that is linking WM to many higher order cognitive tasks including language comprehension (Cain, Oakhill, & Bryant, 2004; Seigneuric, Ehrlich, Oakhill, & Yuill, 2000) and reading (Bayliss, Jarrold, Gunn, & Baddeley, 2003; Gathercole et al., 2006).

The purpose of the present study was to explore the relationship between two components of the WM system and language learning in 5- to 6-year-old children growing up in a multilingual environment. The study is an extension of the results of Engel de Abreu and colleagues (2010) on the same dataset in which complex and simple span tasks have been found to relate to separate but associated underlying factors identified as cognitive control and short-term storage respectively. The study had two major objectives: First, to determine which component of the WM system – short-term storage or cognitive control – relate to which domain of language, and second to explore whether potential links between these components and language might be mediated by related cognitive abilities.

# 2. Method

## 2.1. Participants

A total of 119 children with a mean chronological age of 75 months (*SD* = 3.37, range = 69 - 82) participated in the study. The group consisted of 58 girls and 61 boys, recruited from 38 kindergarten classes in Luxembourg. Only Luxembourgish children, with both parents speaking fluently Luxembourgish, took part in the study. The Grand-Duchy of Luxembourg is officially trilingual: The main foreign language that the children were exposed to was German; Children had not yet been introduced into French (parental questionnaire). All the children were tested in their second year of kindergarten before the start of formal instruction in reading had begun.

**2.2. Procedure**

Each child was tested individually in a quiet area of the school in three sessions of 20 to 30 minutes each, on different school days taking one week apart. Tests were administered in a fixed sequence designed to vary the nature of the task demands across successive tests.

**2.3. Tasks**

**Complex span**. In the Luxembourgish *counting recall* task (AWMA, Alloway, 2007: Engel de Abreu et al., 2010) children need to count and memorize the number of circles in a picture containing triangles and circles. At the end of each trial, children are asked to recall the number of circles of each picture in the right order. In the *backwards digit recall* task (AWMA, Alloway, 2007; Engel de Abreu et al., 2010) children hear a list of spoken digits in Luxembourgish and are required to immediately repeat the list in the reverse order.

**Simple span.** In the *digit recall* test (AWMA, Alloway, 2007; Engel de Abreu et al., 2010) the child has to immediately repeat a sequence of Luxembourgish spoken digits in the order that they were presented. In the *Luxembourgish Nonword Repetition Task* (LuNRep, Engel, 2009; Engel de Abreu et al., 2010) children have to immediately repeat unfamiliar phonological word forms that are auditory presented via a laptop computer.

**Fluid intelligence** was evaluated by the Raven Coloured Progressive Matrices test (Raven, Court, & Raven, 1986). In this test, the child is required to complete a geometrical figure by choosing the missing piece among 6 possible drawings.

**Rhyme awareness** was assessed with a Luxembourgish *rhyme detection* test based on the Phonological Assessment Battery (PhAB, Frederickson, Frith, & Reason 1997). In this test, sets of three words are orally and visually presented and the child has to point to the pictures or name the two words that shared the same rhyme pattern.

**Vocabulary.** Luxembourgish and German expressive vocabulary was assessed with the Expressive One Word Picture Vocabulary Test (EOWPVT, Brownell, 2000). In each case the child is required to name a picture consisting of a line drawing of an object, action or concept arranged in order of increasing difficulty. No starting criterion was applied and testing stopped after the failure of 8 consecutive items.

**Syntax.** Children completed a Luxembourgish version of the Test for Reception of Grammar (TROG-2, Bishop, 2003) assessing understanding of grammatical contrasts. In this test, children are required to identify a target picture out of a choice of 4 to match a spoken sentence. Due to structural differences between Luxembourgish and English, two items had to be removed resulting in 78 test items. Children had to fail 5 consecutive blocks and 8 consecutive items before testing stopped.

**Reading**. In the *letter decision test* (Baddeley, Gathercole, & Spooner, 2003) the child views a symbol and has to decide if it is a written letter or not. In the *word detection task*, the child is required to point to a written word out of a choice of 4 that corresponds to a picture.

## 3. Results

### 3.1. Descriptive statistics and correlational analyses

Descriptive statistics for all principal measures are provided in Table 1.

Table 1 about here

Zero-order correlation coefficients between all principal measures are shown in Table 2. Within each area of cognitive skill, measures correlated with each other. Correlations between nonword repetition and digit recall were high ($r$ = .59). Counting recall and backwards digit recall were moderately correlated ($r$ = .38). Native and foreign vocabulary correlated highly ($r$ = .63) and correlated significantly also with the TROG (*r's* of .41 and .42). The two reading measures correlated at .39. The highest correlations across constructs were obtained between the simple span tasks with vocabulary and syntax (*r's* ranging from .25 to .45). The complex span tasks correlated moderately with syntax (*r's* of .29 and .38) and fluid intelligence (*r's* of .27 and .34). Rhyme awareness correlated highest with the TROG (*r*

= .30) and manifested moderate associations with word detection (*r* = .20) and native vocabulary knowledge (*r* = .20).

Table 2 about here

**3.3. Confirmatory factor analyses - Measurement models**

A series of confirmatory factor analyses (CFA) models were performed on the covariance structure. Maximum likelihood estimation was applied with the computer program AMOS 7 (Arbuckle, 2006). Model fit was assessed by the following indices (see Kline, 1998 for a review of the different fit indices): the $\chi^2$ statistic (nonsignificant = good fit); Bentler's Comparative Fit Index (CFI; Bentler, 1990; above .90 = good fit), Bollen's Incremental Fit Index (IFI; Bollen, 1989; above .90 = good fit), and the Root Mean Square Error of Approximation (RMSEA; Browne & Cudeck, 1993; below .06 = good fit) .Likelihood ratio tests were performed to evaluate the significance of the covariances between the latent factors (Gonzalez & Griffin, 2001). A $\chi^2$ difference corresponding to a probability level of less than .05 was used as a sufficient reason to reject the null hypothesis. Non-hierarchical factor models were compared via the Akaike Information Criterion index (AIC, Akaike, 1987); in each case the model with the smallest AIC value is preferred (Kline, 1998).

The first part of the analyses explores the associations between the 5 language measures. Fit indices for the tested models are provided in the upper part of Table 3.

Table 3 about here

In model 1, all five variables were specified to load onto a common language factor. Values of selected fit indices in Table 3 clearly show that this single-factor model poorly explained the data with a highly significant $\chi^2$ value; CFI and IFI values below .90; and an RMSEA above .06. Next, a two-factor model was fitted to the data with letter decision and word detection loading onto a separate reading construct. The RMSEA value of this model was slightly high and the standardized residuals for the TROG were high, indicating that the two-factor model did not provide a good account of the correlations of this particular measure. A final third model was therefore explored in which the TROG variable was specified to load onto a separate construct. The error term of the TROG was constrained to an estimate based on the established reliability of this measure (Table, 1). The fit indices of this three-factor model were excellent with a non-significant $\chi^2$ value, CFI and IFI values of 1, and an RMSEA of 0. The AIC index (26.86) indicates that the model provided a significantly better account of the data then the single factor model 1 (AIC = 48.48) and the two-factor model 2 (AIC = 29.01). The model solution with the standardized estimates is summarized in Figure 1.

Figure 1

In the next set of models the complex and simple span tasks were added into the analyses in order to explore their relationship with vocabulary, syntax, and reading. Previous analyses on the same dataset have shown that nonword repetition and digit span related to a common factor and that the two complex span task – counting recall and backwards digit recall – loaded on a related but separate construct (Engel de Abreu et al., 2010). To avoid model complexity separate CFA models were performed for each language construct. In total 3 models were tested (Table 3: Model 4, 5, and 6) containing 3 latent factors each (simple span, complex span and either vocabulary, syntax or reading). In all the analyses the factor loadings and error variances were fixed to the values obtained from the measurement models (Engle et al., 1999).

Fit statistics in the middle part of Table 3 indicate that all of the tested models provided a good account of the data. The correlations of the complex and simple span factors with the different language constructs are presented in the upper part of Table 4. The results show that verbal simple span was strongly linked to vocabulary and syntax and manifested weaker, yet significantly, associations with reading. Complex span correlated highest with syntax and reading and manifested weaker links with vocabulary.

Table 4 about here

**3.4. Structural regression models**

In order to get an estimation of the unique contribution of short-term storage and cognitive control to language learning, structural regression (SR) models were used. The basic model used for all the SR analyses is depicted in Figure 2.

Figure 2

As in the previous analyses, factor loadings and error variances of the observed variables were fixed to the values obtained in the measurement models[2]. Model fits did not differ from the preceding CFA models 4, 5, and 6 (Table 3). Standardized regression coefficients of the SR analyses are represented in the middle part of Table 4. When cognitive control was partialled out, the link between short-term storage and vocabulary was maintained with STM accounting for a significant 27% of the variance in vocabulary. Cognitive control in contrast, did not manifest significant associations with vocabulary once verbal short-term storage was taken into account. Both memory components appeared to make specific contributions to syntax, accounting for 12% of its variance each. Finally, the data showed that cognitive control accounted for a significant 13% of the variance in reading when short-term storage was controlled. Verbal STM did not manifest any specific links with pre-reading skills.

A final set of models examined the specific links of short-term storage and cognitive control with language when controlling for related cognitive abilities. The preceding SR models were run again including rhyme detection and the Raven in addition to short-term storage, cognitive control, and the language constructs (Table 3: Model 7, 8, and 9). The error term of the two additional measures were constrained to estimates based on their reliability (Table 1).

Fit indices in the lower part of Table 3 indicate that the three tested models provided a good account of the data. The standardized regression coefficients in the lower part of Table 4 show that short-term storage remained significantly linked to vocabulary and syntax even after fluid intelligence and rhyme awareness were taken into account. The analyses further showed that the significant links between cognitive control with syntax and reading dropped to a non-significant level once the Raven and rhyme detection was considered.

To explore whether the links between verbal short-term storage and syntax were mediated by lexical knowledge, a last set of models entered a latent vocabulary factor as additional covariate into the analyses [6-factor model: $\chi^2 = 28.46$, $df = 24$, $p = .24$; CFI = .98; IFI = .98; RMSEA = .04]. These analyses showed that verbal short-term storage did no longer manifest a significant link with syntax ($r = .25$) once vocabulary was controlled. Notably, the analyses further showed that when fluid intelligence was excluded from the model, the links between cognitive control with syntax and reading remained significant (*r*'s of .32 and .33 respectively) despite vocabulary and rhyme detection as covariate [5-factor models: Syntax, $\chi^2 = 26.02$, $df = 21$, $p = .21$; CFI = .98; IFI = .98; RMSEA = .04; Reading, $\chi^2 = 26.66$, $df = 30$, $p = .48$; CFI = .98; IFI = .98; RMSEA = .04].

## 4. Discussion

The study showed that when their common variance was considered, simple and complex span tasks were differentially associated with children’s emerging language abilities in line with the position that the WM system consists of separate interacting components (Alloway, Gathercole, Willis, & Adams, 2004; Baddeley, 2000, Engle et al., 1999). Conceptually, the simple span residual should represent short-term storage whereas the complex span residual is suggested to mainly reflect mechanisms of cognitive control

(Conway, Cowan, Bunting, Therriaut, & Minkoff, 2002; Engel de Abreu et al., 2010; Engle et al., 1999).

Vocabulary knowledge was strongly related to verbal short-term storage. These results are consistent with previous evidence suggesting that verbal STM is the driving force behind both native and foreign vocabulary acquisition, by supporting the formation of stable phonological representations of new words in long-term memory (Cheung, 1996; Gathercole et al., 1997; Jarrold et al., 2009; Masoura & Gathercole, 2005; Service, 1992). The finding that the association was independent of cognitive control, fluid intelligence, and rhyme awareness suggests that the link between verbal STM and vocabulary is highly specific, in line with the view that it is the short-term storage component of the WM system that underpins vocabulary development (Baddeley et al., 1998; Gathercole, 2006). Notably, neither cognitive control nor rhyme awareness had specific effects on vocabulary, providing further support for the unique contribution of verbal STM to vocabulary acquisition.

The study further showed that verbal short-term storage made significantly contributions to syntactic comprehension. These associations were, however, largely mediated by vocabulary knowledge that is critical for the understanding of syntactically complex sentences.

Finally, the study identified specific links between cognitive control with syntax and reading that were independent of short-term storage, rhyme awareness, and vocabulary. Importantly, the data showed that the associations could be fully accounted for by the component that the complex span residual shared with fluid intelligence. These findings provide support to the hypothesis that it is the capacity for controlled processing – the postulated underlying common trait of fluid intelligence and complex span task (Conway et al., 2002; Engle et al. 1999) – that is driving the relationship between complex span tasks and higher order language processing.

**References**

Akaike, H. (1987). Factor analysis and AIC. *Psychometrica, 52*, 317-332.

Alloway, T. P. (2007). *Automated working memory assessment*. London: Pearson Assessment. Translated and reproduced by permission of Pearson Assessment.

Alloway, T. P., Gathercole, S. E., Adams, A. M., Willis, C., Eaglen, R., & Lamont, E. (2005). Working memory and phonological awareness as predictors of progress towards early learning goals at school entry. *British Journal of Developmental Psychology, 23*, 417-426.

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., 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.

Avons, S. E., Wragg, C. A., Cupples, L., & Lovegrove, W. J. (1998). Measures of phonological short-term memory and their relationship to vocabulary development. *Applied Psycholinguistics, 19*(4), 583–601.

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

Baddeley, A. D., Gathercole, S. E., & Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review, 105*(1), 158-173.

Baddeley, A. D., Gathercole, S. E., & Spooner, A. L. R. (2003). *The reading decision test*. Brighton: Psychology Press.

Bayliss, D. M., Jarrold, C., Gunn, M. D., & 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.

Bishop, D. (2003). *Test for reception of grammar-Version 2*. London: Psychological Corporation.

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

Bowey, J. A. (2001). Nonword repetition and young children's receptive vocabulary: A longitudinal study. *Applied Psycholinguistics, 22*(3), 441-469.

Bowey, J. A. (2006). Clarifying the phonological processing account of nonword repetition. *Applied Psycholinguistics, 27*(4), 548-552.

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

Brownell, R. (2000). *Expressive one word picture vocabulary test*. London: Psychological Corporation.

Bryant, P. E., Maclean, M., Bradley, L. L., & Crossland, J. (1990). Rhyme and alliteration, phoneme detection, and learning to read. *Developmental Psychology, 26*(3), 429-438.

Cain, K., Oakhill, J., & Bryant, P. (2004). Children’s reading comprehension ability: Concurrent prediction by working memory, verbal ability, and component skills. *Journal of Educational Psychology, 96*(1), 31–42.

Cheung, H. (1996). Nonword span as a unique predictor of second-language vocabulary learning. *Developmental Psychology, 32*(5), 867-873.

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., 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., Getz, S. J., Macnamara, B., & Engel de Abreu, P. M. J. (2010). Working memory and fluid intelligence: A multi-mechanism view. In. R. J. Sternberg & S. B. Kaufman (Eds). *Cambridge Handbook of Intelligence*. Cambridge, UK: 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., & Blennerhassett, A. (1984). How to assess the listening comprehension skills of prereaders. *Journal of Educational Psychology, 76*(6), 1372-1381.

Daneman, M., & Carpenter, P. A. (1983). Individual-differences in integrating information between and within sentences. *Journal of Experimental Psychology-Learning Memory and Cognition, 9*(4), 561-584.

de Jong, P. F., & Olson, R. K. (2004). Early predictors of letter knowledge. *Journal of Experimental Child Psychology, 88*(3), 254-273.

Dufva, M., Niemi, P., & Voeten, M. J. M. (2001). The role of phonological memory, word recognition, and comprehension skills in reading development: from preschool to grade 2. *Reading and Writing, 14*(1-2), 91-117.

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

Engel de Abreu, P. M. J., Conway, A. R. A. & Gathercole, S. E. (2010). Working memory and fluid intelligence in young children. *Intelligence*, *38*(6), 552-561.

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

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.

Frederickson, N., Frith, U., & Reason, R. (1997). *Phonological assessment battery*. London: NFER-Nelson.

Gathercole, S. E. (2006). Complexities and constraints in nonword repetition and word learning. *Applied Psycholinguistics, 27*(4), 599-613.

Gathercole, S. E., Alloway, T. P., Willis, C., & Adams, A. M. (2006). Working memory in children with reading disabilities. *Journal of Experimental Child Psychology, 93*(3), 265-281.

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

Gathercole, S. E., Hitch, G. J., Service, E., & Martin, A. J. (1997). Phonological short-term memory and new word learning in children. *Developmental Psychology, 33*(6), 966-979

GoldWave Inc. (2004). *GoldWave digital audio editor software* (5 ed.): GoldWave Inc, St. Johns.

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

Gupta, P. (2003). Examining the relationship between word learning, nonword repetition, and immediate serial recall in adults. *Quarterly Journal of Experimental Psychology Section a-Human Experimental Psychology, 56*(7), 1213-1236.

Hanten, G., & Martin, R. C. (2000). Contributions of phonological and semantic short-term memory to sentence processing: Evidence from two cases of closed head injury in children. *Journal of Memory and Language, 43*(2), 335-361.

Hoyle, R. H. (1995). *Structural Equation Modeling*. Thousand Oaks: Sage.

Hu, L., & Bentler, P. M. (1995). Evaluating model fit. In R. H. Hoyle (Ed.), *Structural equation modeling: Concepts, issues, and applications* (pp. 76 – 99). Thousand Oaks: Sage.

Jarrold, C., Baddeley, A. D., Hewes, A. K., Leeke, T. C., & Phillips, C. E. (2004). What links verbal short-term memory performance and vocabulary level? Evidence of changing relationships among individuals with learning disability. *Journal of Memory and Language, 50*(2), 134-148.

Jarrold, C., Thorn, A. S. C., & Stephens, E. (2009). The relationships among verbal short-term memory, phonological awareness, and new word learning: Evidence from typical development and Down syndrome. *Journal of Experimental Child Psychology, 102*(2), 196-218.

Kline, R. B. (1998). *Principles and practice of structural equational modeling*. New York: The Guilford Press.

Landerl, K., & Wimmer, H. (2008). Development of word reading fluency and spelling in a consistent orthography: An 8-year follow-up. *Journal of Educational Psychology, 100*(1), 150–161.

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

Leather, C. V., & Henry, L. A. (1994). Working-memory span and phonological awareness tasks as predictors of early reading-ability. *Journal of Experimental Child Psychology, 58*(1), 88-111.

Majerus, S., Poncelet, M., Greffe, C., & van der Linden, M. (2006). Relations between vocabulary development and verbal short-term memory: The relative importance of short-term memory for serial order and item information. *Journal of Experimental Child Psychology, 93*(2), 95-119.

Martin, R., & Burton, R. (2003). *Untergrad Lesetest*: University of Luxembourg.

Masoura, E. V., & Gathercole, S. E. (2005). Contrasting contributions of phonological short-term memory and long-term knowledge to vocabulary learning in a foreign language. *Memory, 13*(3-4), 422-429.

McDonald, R. P., & Ho, M. H. R. (2002). Principles and practice in reporting structural equation analyses. *Psychological Methods, 7*(1), 64-82.

Metsala, J. L. (1999). Young children's phonological awareness and nonword repetition as a function of vocabulary development. *Journal of Educational Psychology, 91*(1), 3-19.

Montgomery, J. W. (1995). Sentence comprehension in children with specific language impairment - The role of phonological working-memory. *Journal of Speech and Hearing Research, 38*(1), 187-199.

Mosse, E. K., & Jarrold, C. (2008). Hebb learning, verbal short-term memory, and the acquisition of phonological forms in children. *Quarterly Journal of Experimental Psychology, 61*(4), 505-514.

Myers, J. L., & Well, A. D. (2002). *Research design and statistical analysis* (2nd ed.). New York: Harper Collins.

Papagno, C., Cecchetto, C., Reati, F., & Bello, L. (2007). Processing of syntactically complex sentences relies on verbal short-term memory: Evidence from a short-term memory patient. *Cognitive Neuropsychology, 24*(4), 292 - 311.

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). *Raven's coloured matrices*. London: H.K. Lewis.

SCRIPT. (2005). *Les chiffres clés de l'éducation nationale: Statistiques et indicateurs 2003-2004*. Luxembourg: MENFP.

Seigneuric, A., Ehrlich, M. F., Oakhill, J. V., & Yuill, N. M. (2000). Working memory resources and children's reading comprehension. *Reading and Writing, 13*(1-2), 81-103.

Service, E. (1992). Phonology, working memory, and foreign-language learning. *Quarterly Journal of Experimental Psychology Section a-Human Experimental Psychology, 45*(1), 21-50.

Shankweiler, D., Smith, S. T., & Mann, V. A. (1984). Repetition and comprehension of spoken sentences by reading disabled children. *Brain and Language, 23*(2), 241-257.

Snowling, M., Chiat, S., & Hulme, C. (1991). Words, nonwords, and phonological processes - Some comments on Gathercole, Willis, Emslie, and Baddeley. *Applied Psycholinguistics, 12*(3), 369-373.

Swanson, H. L. (2003). Age-related differences in learning disabled and skilled readers' working memory. *Journal of Experimental Child Psychology, 85*(1), 1-31.

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.

Willis, C. S., & Gathercole, S. E. (2001). Phonological short-term memory contributions to sentence processing in young children. *Memory, 9*(4-6), 349–363.

**Footnotes**

[1] Translated and reproduced by permission. 

[2] All the models were fitted again without fixing any of the values derived from the measurement models and the results were almost identical. On average correlation coefficients changed by .04 for the CFA models and by .05 for the SR models.

Table 1

*Descriptive Statistics for All Test Scores (N = 119)*

| Measures | | Max. | Mean | *SD* | Range | $r_{xx}$ |
|---|---|---|---|---|---|---|
| Age (in month) | | -- | 75.13 | 3.37 | 69-82 | -- |
| Complex span | Counting recall | 42 | 9.69 | 3.07 | 5-19 | .85[a] |
| | Backwards digit recall | 36 | 5.90 | 2.42 | 0-12 | .85[a] |
| Simple span | Digit recall | 54 | 20.50 | 3.17 | 14-30 | .84[a] |
| | Nonword repetition | 50 | 35.19 | 6.14 | 18-46 | .79[a] |
| | | | | | | .78[b] |
| Fluid intelligence | Raven | 36 | 18.95 | 4.31 | 8-31 | .71[c] |
| Rhyme awareness | Rhyme detection | 20 | 14.06 | 3.21 | 5-20 | .73[c] |
| Vocabulary | EOWPVT native | -- | 59.15 | 11.43 | 34-80 | .91[c] |
| | EOWPVT foreign | -- | 32.98 | 18.71 | 0-80 | .96[c] |
| Syntax | TROG | 78 | 51.97 | 9.51 | 23-72 | .86[c] |
| Reading | Word detection | 7 | 2.79 | 1.93 | 0-7 | .60[c] |
| | Letter decision | 40 | 28.40 | 3.31 | 20-35 | .53[c] |

*Note*: Max: Maximum possible score; Raven: Raven Coloured Progressive Matrices Test; EOWPVT: Expressive One Word Picture Vocabulary Test; TROG: Test for Reception Of Grammar; [a] reliabilities are coefficient alpha; [b] interrater reliability based on Cohen's Kappa [c] reliabilities are K-R 20

Table 2

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

| Measures | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Age | -- | | | | | | | | | | | |
| Complex span | | | | | | | | | | | | |
| 2. Counting recall | .08 | -- | | | | | | | | | | |
| 3. Backwards digit recall | .13 | **.38** | -- | | | | | | | | | |
| Simple span | | | | | | | | | | | | |
| 4. Digit recall | .05 | **.27** | **.41** | -- | | | | | | | | |
| 5. Nonword repetition | .16 | .13 | **.40** | **.59** | -- | | | | | | | |
| Fluid intelligence | | | | | | | | | | | | |
| 6. Raven | .18 | **.27** | **.34** | .12 | .15 | -- | | | | | | |
| Rhyme awareness | | | | | | | | | | | | |
| 7. Rhyme detection | .08 | -.04 | **.21** | **.19** | **.22** | .10 | -- | | | | | |
| Vocabulary | | | | | | | | | | | | |
| 8. EOWPVT native | .12 | .02 | **.20** | **.25** | **.45** | .17 | **.20** | -- | | | | |
| 9. EOWPVT foreign | .04 | .09 | **.22** | **.32** | **.42** | .07 | .15 | **.63** | -- | | | |
| Syntax | | | | | | | | | | | | |
| 10. TROG | .11 | **.29** | **.38** | **.41** | **.45** | **.42** | **.30** | **.41** | **.42** | -- | | |
| Reading | | | | | | | | | | | | |
| 11. Word detection | .05 | **.19** | **.19** | **.22** | **.18** | .16 | **.20** | .10 | .04 | **.23** | -- | |
| 12. Letter decision | **.22** | **.18** | .15 | .05 | .05 | **.24** | .04 | -.05 | -.08 | .13 | **.39** | -- |

*Note:* Raven: Raven Coloured Progressive Matrices Test; EOWPVT: Expressive One Word Picture Vocabulary Test; TROG: Test for Reception of Grammar; significant values marked in boldface, $p < .05$.

Table 3

*Fit Indices (N = 119)*

| Model | χ2 | *df* | *p* | *CFI* | *IFI* | *RMSEA* |
|---|---|---|---|---|---|---|
| Language Models | | | | | | |
| Model 1: Single factor model | | | | | | |
| | 28.48 | 5 | .00 | .78 | .79 | .20 |
| Model 2: Two-factor model - language & reading | | | | | | |
| | 9.01 | 4 | .11 | .96 | .96 | .08 |
| Model 3: Three-factor model - vocabulary, syntax, & reading | | | | | | |
| | 2.86 | 3 | .41 | 1.00 | 1.00 | .00 |
| CFA Models Including Complex Span and Simple Span | | | | | | |
| Model 4: Vocabulary | | | | | | |
| | 17.91 | 15 | .27 | .98 | .98 | .04 |
| Model 5: Syntax | | | | | | |
| | 9.33 | 9 | .41 | 1.00 | 1.00 | .02 |
| Model 6: Reading | | | | | | |
| | 8.21 | 15 | .91 | 1.00 | 1.06 | .00 |
| SR Models Including Complex Span, Simple Span, Phonological Awareness, and Fluid Intelligence | | | | | | |
| Model 7: Vocabulary | | | | | | |
| | 25.53 | 21 | .22 | .98 | .98 | .04 |
| Model 8: Syntax | | | | | | |
| | 14.65 | 13 | .33 | .99 | .99 | .03 |
| Model 9: Reading | | | | | | |
| | 16.80 | 21 | .72 | 1.00 | 1.03 | .00 |

Table 4

*Standardized Regression Coefficients of the CFA and SR Models (N = 119)*

| Factors | Vocabulary | Syntax | Reading |
|---|---|---|---|
| Confirmatory factor analysis models | | | |
| Simple span | **.51** | **.55** | **.29** |
| Complex span | **.31** | **.55** | **.40** |
| Structural regression models | | | |
| Short-term storage | **.52** | **.34** | .06 |
| Cognitive control | -.02 | **.34** | **.36** |
| *Total* $R^2$ | *.26* | *.37* | *.16* |
| Structural regression models controlling for related cognitive abilities | | | |
| Short-term storage | **.53** | **.42** | .08 |
| Cognitive control | -.12 | -.01 | .19 |
| Rhyme detection | .12 | .20 | .16 |
| Raven | .12 | **.44** | .20 |
| *Total* $R^2$ | *.28* | *.54* | *.21* |

*Note:* Raven: Raven Coloured Progressive Matrices; significant values marked in boldface, $p < .05$.

**Figure Captions**

*Figure 1.* Three-factor CFA model for the language measures. Solid lines indicate coefficients significant at the .05 level. Numbers next to the circles are proportions of variance in the observed variables explained by the latent construct; EOWPVT: Expressive One Word Picture Vocabulary Test; TROG: Test for Reception Of Grammar.

*Figure 2.* Three-factor structural regression model.

Figure 1

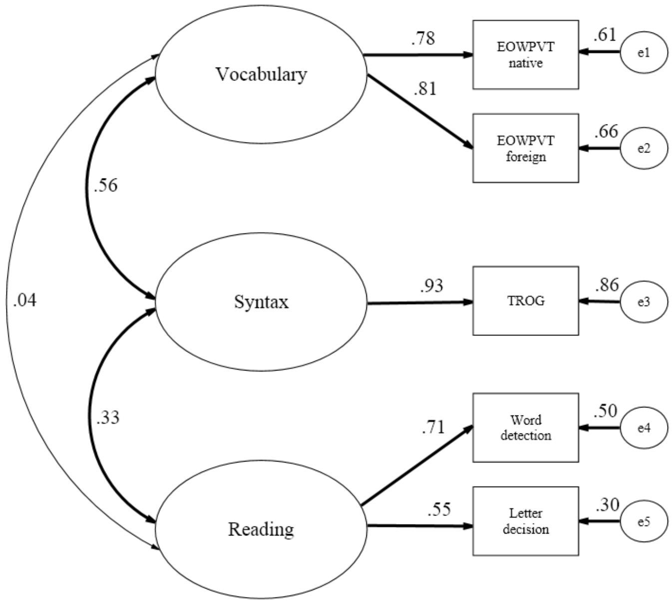
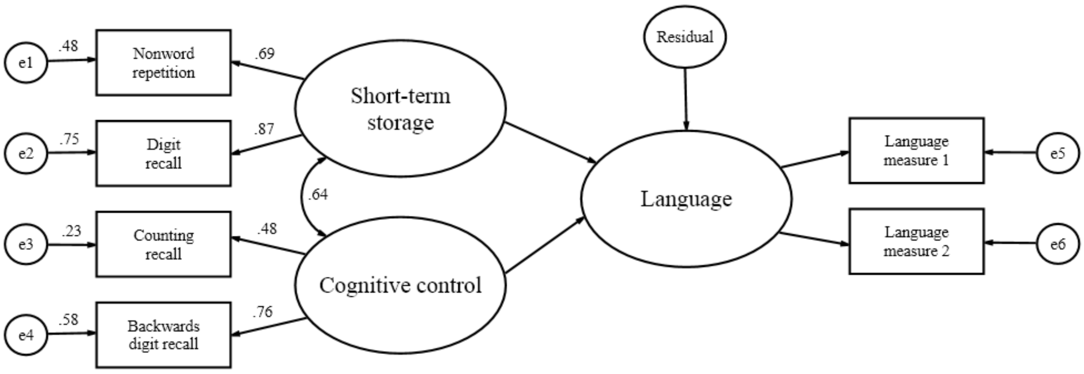

Vocabulary
Syntax
Reading
EOWPVT native
EOWPVT foreign
TROG
Word detection
Letter decision
.78
.81
.93
.71
.55
.61
.66
.86
.50
.30
e1
e2
e3
e4
e5
.56
.33
.04

Figure 2



e1
.48
Nonword repetition
.69
e2
.75
Digit recall
.87
e3
.23
Counting recall
.48
e4
.58
Backwards digit recall
.76
Short-term storage
.64
Cognitive control
Residual
Language
Language measure 1
Language measure 2
e5
e6