Cornoldi, C, Orsini, A, Cianci, L, Giofré, D and Pezzuti, L

Intelligence and working memory control: Evidence from the WISC-IV administration to Italian children

The Version of Scholarly Record of this Article is published on LEARNING AND INDIVIDUAL DIFFERENCES (2013), available online at: http://dx.doi.org/10.1016/j.lindif.2013.04.005. **Note that this article may not exactly replicate the final version published on LEARNING AND INDIVIDUAL DIFFERENCES.**

Cornoldi, C., Orsini, A., Cianci, L., Giofrè, D., & Pezzuti, L. (2013). Intelligence and working memory control: Evidence from the WISC-IV administration to Italian children. *Learning and Individual Differences*, *26*, 9–14. doi:10.1016/j.lindif.2013.04.005

Intelligence and Working Memory control: Evidence from the WISC-IV administration to Italian children

Cesare Cornoldi*, Arturo Orsini**, Laura Cianci**, David Giofrè*, and Lina Pezzuti***.

* Department of General psychology, University of Padova, Italy

** Department of Psychology, Sapienza University of Rome, Italy

*** Department of Clinical Psychology, Sapienza University of Rome, Italy

Correspondence concerning this article should be addressed to:

Cesare Cornoldi

Department of General Psychology

University of Padua

via Venezia 8 – 35131 – Padova - Italy

E-mail: cesare.cornoldi@unipd.it

Abstract

Working memory (WM) has been associated with general intelligence (GI). However, evidence is contradictory, as the relationship has in some cases resulted to be very high, and in other cases very low. To explain these differences, it has been argued that WM is an articulated system and only its more attentional components are strictly related with GI. In particular, it has been argued that WM tasks can be located – according to the task characteristics and the subject's age – along a continuum, from the most passive tasks, which do not require cognitive control, to the most active tasks, which do require high cognitive control. The present study tested this hypothesis using data collected during the standardization of the Italian version of the WISC-IV. WISC-IV, includes four measures, i.e. the arithmetic test, the letter-number sequencing test, the backward and the forward digit span tests, which represent decreasing levels of cognitive control. The analysis of correlations between the four tasks and a measure of GI – obtained with the six basic tasks (related to verbal comprehension and perceptual reasoning, but not to working memory) – confirmed the hypothesis and showed that the pattern of correlations only slightly changes across ages.

Keywords: working memory, WM, Intelligence, GAI, IQ, WISC-IV.

Introduction

Working memory (WM) has been associated with general intelligence (GI). Kyllonen and Christal (1990) reported correlations higher than .90 between measures of intelligence and WM (see also Engle, Tuholski, Laughlin, & Conway, 1999; Unsworth, & Engle, 2005). The assumption is that the capacity to maintain and process a large amount of information yields the possibility of better performing a variety of different intellectual tasks, as—for example—suggested by Carpenter, Just, and Shell (1990) in a study of the processes underlying the elaboration of Raven's Matrices.

However, the assumption of a strong relationship between WM and GI has been questioned (Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008). In particular, the fact that intelligence tests typically rely on WM may bias the observation of a relationship between WM and GI. Other perplexities on the relationship have been raised by studies reporting moderate or low correlations between WM and GI (Ackerman, Beier, & Boyle, 2005).

Different results in studies of the relationship between WM and intelligence could be partly due to the fact that diverse aspects of WM can be involved in different tests. In fact, many models of WM suggest that WM is not a unitary system, but that it can be differentiated in different subcomponents. A basic dichotomous differentiation within WM concerns high and low cognitive control components, as involved in the well-known distinction between the central executive and the other most passive components of WM proposed by Baddeley (e.g., Baddeley, 2007), which re-elaborated the distinction between short-term storage (STM) and WM processing (needed to actively maintain the information in the face of distraction) (Kane et al., 2004). A partially similar distinction, which has been related with GI, is the distinction between simple and complex span tasks (Unsworth & Engle, 2005). The former relate to the capacity to simply store information, while the latter also imply cognitive control (Engle & Kane, 2004; Kane et al. 2004).

On the basis of the dichotomous differentiations, it has been argued that WM is related with GI especially when the central executive is involved (Engel de Abreu, Conway, & Gathercole, 2010) or cognitive control is required (e.g., Engle, Tuholski, Laughlin, & Conway, 1999; Unsworth & Engle, 2005). However, the possibility that WM and STM can reflect different or identical functions and may be differently related with intelligence is still debated in adults (Alloway, Gathercole, & Pickering, 2006; Colom et al., 2008; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle et al., 1999) and in children (Alloway et al., 2006; Engel de Abreu, Conway, & Gathercole, 2010; Hornung, Brunner, Reuter, & Martin, 2011; Tillman, Nyberg, & Bohlin, 2008).

Different positions could be attributed to a series of factors. For example, Unsworth and Engle (2007) demonstrated the importance of list length: They found that simple and complex span tasks showed similar predictive utility when considering only the longest lists of the STM measures; whereas, complex span tasks were equally predictive of GI across all list lengths. Another possibility is that a dichotomous classification of WM is not able to capture the variety of WM processes and tasks. In fact, a distinction between low (passive) and high cognitive control (active) processes and tasks has been expanded by Cornoldi and Vecchi (2003), who observed that controlled elaboration can be required to a different extent by different working memory tasks (with variations due to age). Therefore, working memory tasks should not be distinguished only in two main categories but should be located according to an active control continuum going from the most passive tasks, exemplified by forward digit span (FDS), to the most active tasks, exemplified by tasks which require highly controlled activity on maintained information.

Better specifying the assumption that the relationship between WM and GI is higher for active rather than passive tasks, Cornoldi (2007, 2010) argued that the relationship should not be considered in a dichotomous perspective (high for active tasks and low for passive tasks), but according to the location of the WM tasks along the continuum, with increasing degrees of relationship in correspondence with increased degrees of required cognitive control, defined as the number/complexity of operations required on maintained information. Evidence on the continuum hypothesis came from observations in individuals with intellectual disabilities (Carretti, Belacchi, & Cornoldi, 2010), Down syndrome (Lanfranchi, Cornoldi, & Vianello, 2004), x-fragile (Lanfranchi, Cornoldi, Drigo, & Vianello, 2008), and with learning-disabled children (Cornoldi, 2010). For example, Lanfranchi et al. (2004) administered to children with Down syndrome and control children, matched for mental ages, two series respectively of verbal and visuospatial WM tasks which varied for the extent of required active control. They assumed that if children with Down syndrome have richer experience but lower GI than controls, then they should have problems in task in which a high cognitive control is required. Results confirmed their predictions. For example, for the verbal tasks, the performance of controls was slightly better for a forward word span task (4.56 vs. 3.94), the difference modestly increased for a backward word span (3.28 vs. 2.61), increased to a large extent for a task requiring more control, i.e., selection of words and inhibition of other words (3.61 vs. 1.33) and was the highest for a task which required not only selection and inhibition but also the classification of the presented words (5.39 vs. 1.44).

In sum, there is debate on the relationship between WM and GI, and different evidences could be due to the variety of required WM processes in the different WM tasks. The appearance of the WISC-IV has offered a good opportunity for testing the hypotheses on the relationship between WM and GI. In fact, the WISC-IV, according to the American (Wechsler, 2003) and the Italian Manual (Orsini, Pezzuti, & Picone, 2011), offers four main general indexes (with a series of associated measures): verbal comprehension (VCI), perceptual reasoning (PRI), working memory (WMI), and processing speed (PSI). The four indexes, although correlated, were also partly independent. The importance of the WMI, and the associated hypothesis concerning a specific WM factor, is also supported by research on the French (Lecerf, Reverte, Coleaux, Favez, & Rossier, 2010) and Spanish (San Miguel Montes, Allen, Puente, & Neblina, 2010) adaptations of the WISC-IV, and indirectly by the German adaptation, which shows that WM factor produces different effects than the other factors when gender differences are considered (Goldbeck, Daseking, Hellwig-Brida, Waldmann, & Petermann, 2010).

The WISC-IV has the advantage not only of offering a WM index, which can be obtained using different measures, but also that the WMI is calculated independently from the other indexes. Thus, a measure of GI can be obtained without using the WMI subtests (Saklofske, Prifitera, Weiss, Rolfhus, & Zhu, 2005), referring to six subtests with high loadings on *g* factor and only related to two different general intelligence indexes (i.e., VCI and PRI).

In the WISC-IV, the WM assessment is associated with three subtests: the digit span, the letter-numbers sequences (LNS) and the arithmetic subtests (AR). This focus on WM was not present in the previous versions of the WISC, where the LNS subtest was not present and the AR subtest was poorly characterized as a WM task. In the new WISC-IV version of the AR, the interpretation of the nature of the AR subtest still remains controversial (Flanagan & Kaufman, 2004), but the subtest has been excluded from the core tests assessing GI and its association with WM has been emphasized by the authors of the revision: Items have been modified to increase the role of WM in the maintenance of problem information and its solution and the loading of the subtest on a WM factor has become closer than before to the loadings of the other two subtests. For example, the AR subtest has a loading of .46 on the WM factor, versus loadings of .56 and .62 respectively for digit span and LNS in the French adaptation (Wechsler, 2005) and a loading of .54 versus loadings of .77 and .70 in the Italian adaptation (Orsini, Pezzuti, & Picone, 2011). This evidence, obtained during the European standardizations of the scale, further supports the evidence offered by the American Manual (Wechsler, 2003) showing that the AR subtest has an important loading (.51) on the WM factor and modest loadings (between .18 and .03) on the other factors. Therefore, despite the fact that – intuitively – an arithmetic subtest does not directly involve WM, the specific characteristics of the WISC-IV AR subtest legitimate its inclusion within a group of WM subtests and offer the opportunity of having a relatively large number of WM scores to be compared with other intellectual scores.

The WISC-IV offers different measures of WM, which are substantially four. In fact, the digit span subtest can be divided in the forward and the backward versions, as it has been often recommended, due to the different cognitive implications of the two versions. The availability of four different WM measures within the WISC-IV offers the opportunity of contrasting the prediction that the relationship between WM and GI is similar for different WM aspects (e.g., Colom et al., 2008). In particular, on the basis of the dichotomous models of WM (Baddeley, 1986, 2000; Engle & Kane, 2004) and of the continuum model (Cornoldi & Vecchi, 2003), the FDS must be distinguished from the backward digit span (BDS) and the other WM measures, as the latter require more cognitive control in children (Alloway et al., 2006) and should be more related to GI than the FDS. According to the dichotomous models, complex WM measures, relying on attentional executive processes, can be considered altogether; whereas, according to the continuum model, the FDS is the most passive task, but the other three tests can be distinguished for different degrees of required cognitive control.

Working memory research has offered evidence on the differences between a variety of active WM tasks. In particular, it has been observed that the BDS requires a single control operation on maintained information, which is the reversal of its order, whereas other complex tasks (like LNS and AR) involve more than one operation. The distinction between BDS and other WM tasks is supported by some evidence. For example, it has been argued that individuals with central control problems, like children with intellectual disabilities (Lanfranchi et al., 2004) and individuals with x-fragile syndrome (Lanfranchi et al., 2008), compared to typically developing individuals, fail to a lower extent in a backward span task than in WM tasks requiring more complex processes. Moreover, the maintenance, rearrangement and coordination of two different categories of material, required by the LNS and the AR subtests, involve a higher controlled WM function than the BDS (Cornoldi & Vecchi, 2003); although, the degree of this difference could change according to the children's age as the cognitive control required by the BDS can be high for young children (Alloway et al., 2006).

As far as the comparison between LNS and AR is concerned, the continuum model suggests that the latter requires a higher WM cognitive control than the LNS (Cornoldi & Vecchi, 2003), as it involves a series of highly controlled processes such as discourse comprehension, inhibition of irrelevant information, the use of well defined procedures and the discovery of a principle solution (Marzocchi, Lucangeli, De Meo, Fini, & Cornoldi, 2002), that are not involved in the LNS subtest. The relationship between the AR subtest and core aspects of intelligence is also supported by some analyses on the WISC-IV scores (Flanagan & Kaufman, 2004), although, also in this case, the pattern of relationship may vary with age. In fact, the success in arithmetic problem solving is partly related on different factors at different ages: The first items, which are at the basis of the success in young children, seem to require lower cognitive control than the latter items. The problem has become evident with the WISC-IV but was already present for the WISC-III as argued by Kaufmann (1994, p. 70): "*There is a shift in what is required for success on the earlier versus later items*". For example, the first 13 items require the maintenance of a simple text and the calculation of a single operation, which can be only either addition or subtraction; whereas, for the subsequent items, which are at the basis of the success of older children, the number of operations may increase (e.g., from item 18 the child must also make a more complex decision as all the four basic arithmetical operations can be involved). In addition, the complexity of latter items is also increased by the presence of a complex text and more irrelevant information. In fact, it has been argued that for young children the AR subtest assesses short-term memory rather than attentional working memory (Jumel, 2008). On this basis, one could predict that the highest WM control for the WISC-IV AR subtest is required in older levels of age and only for these ages the relationship between AR and the general ability index (GAI) would be higher than in the case of the other WM measures.

The prediction concerning an increased relationship between WM and GI in correspondence with increases in the control required by the WM task is partly supported by the evidence offered in the American Manual (Wechsler, 2003) as the digit span, the LNS and the AR subtests correlated respectively .51, .60 and .72 with a measure of intelligence excluding the considered subtest. However, these data were not calculated to test specific hypotheses concerning the organization of WM and did not consider the specificities of the two versions of the digit span. Furthermore, age changes were not considered. In fact, it could be argued that no general conclusions concerning the relationship between WM and GI can be derived, given that this relationship may change at different ages (e.g., Fry & Hale, 2000).

In sum, WM seems related to GI but to a different extent for different WISC-IV measures of WM, but evidence is still necessary to clarify this pattern of relationships. To examine these issues, the present study used the data collected during the Italian standardization of the WISC-IV and considered the relationships between different WM measures and GI. In particular, it predicted to find a high relationship between WM measures and GI, but with degrees of relationship varying according to the degree of active cognitive control required by the WM task. Furthermore, by controlling the age effects the study examined whether or not the pattern of relationships varies across ages.

Method

Participants

Subjects considered for this study were the 2200 children who took part to the Italian standardization of the WISC-IV. For the standardization, 200 children (100 males and 100 females) for each age between 6 and 16, representative of the Italian population by parent education level, were individually administered the WISC-IV.

Materials and Procedure

Participants were tested in their school in individual sessions lasting between 45 and 70 min in a quiet room away from the classroom. The WISC-IV subtests were administered following the order defined by the original Manual (see Wechsler, 2003) that has been also used for the Italian standardization (Orsini et al., 2011).

Results

First, we considered the results of the overall group. In order to make data comparable across ages, all scores were transformed in standard scores (*M*= 10, *SD*= 3). We computed the four main indexes (standard scores: *M*= 100, *SD*= 15) according to the instructions of the original Manual (Wechsler, 2003). Furthermore, the GAI was computed – as suggested by Raiford, Weiss, Rolfhus, and Coalson (2005) – by summing up the scores in six subtests (similarities, vocabulary, comprehension, block design, picture concepts, and matrix reasoning) and the working memory index (WMI) was computed by summing up the scores in two subtests (digit span, letter-number sequencing). The Pearson's correlation between the WM and the GAI indexes (r= .52) was substantial, further supporting the existence of a relationship between WM and GI.

The general relationship between WM and GI is better described by the correlations between general measures of intelligence and the WM scores, with the scores in the two versions of the digit span separately considered. In the present study this aspect was examined in two ways. We first analyzed the strength of the relationship between a WM factor derived from the four WM measures and a *g*-factor derived from the tasks measuring verbal comprehension and perceptual reasoning. Figure 1 presents the results of a confirmatory factor analysis, which showed an acceptable fit and showed a high relationship between WM and GI (r = .89).

Insert Figure 1 about here

However, the main focus of the present study concerned the differentiated pattern of relationship between the four WM measures and the overall measures of GI. Table 1 presents the

Pearson's correlations between the children's standard scores in the four WM tests and the intelligence general measures obtained for the overall sample. It must be noticed that the pattern of correlations is present not only for the GI measure but also for other intelligence measures. The significance of the correlations, due to the large numerosity (N=2200), was inflated by the power of the significance test. For these reason, according to the Cohen's (1988) guidelines, we considered the strength of the correlations as small (between .1 and .3), medium (between .3 and .5), and large (above. 5). As shown in Table 1, the relationship between GAI and WM aligns with our predictions, increasing from medium/small (FDS), medium (BDS and LNS), to large (AR).

To verify whether or not the correlation between a WM measure and GAI was still significant when the contribution of one or more of the other WM measures was partialed out, we calculated the partial correlations between GAI and the four WM scores, eliminating the contribution of the three other measures of WM (Table 2). The pattern was particularly clear as the GAI index differently correlated with the four WM measures. Correlations remained significant, but –also due to the partialing out– were reduced in value, increasing from very small (FDS), small (BDS and LNS), to medium in (AR) (see Table2). Notably, the specific verbal characteristics of the FDS increase its relationship with the verbal comprehension index.

Insert Tables 1 and 2 about here

We then considered the correlations for the different age groups (collected for groups of three years in all cases except the group 6-7 where two years were considered together, see the American Manual [Wechsler, 2003] for a similar grouping). Table 3 highlights the patterns of relationship for the different ages substantially replicating the general pattern found when all the children were considered together. For example, the correlation between LNS task and GAI was very similar across different ages, ranging from .461 to .483. Moreover, all the correlations were in the predicted direction and, in many cases, the differences between correlations were significant. However, some minor differences between ages emerged and not all the differences between correlation were significant. These variations between ages could be due to the nature of the task and/or to the items that are most critical in defining the score at a particular age. For example, for the youngest group, the fact that BDS was related with GAI to a similar extent as the other two high control tasks could be partly due to the specific difficulty of young children to meet the relatively simple request of reversing the item order. Moreover, the first items of the AR subtest do not require complex reasoning operations on maintained information. This fact, could explain why for both the youngest groups the correlation between GAI and the AR subtest was not significantly greater than the correlation between GAI and the LNS subtest. On the contrary, for the oldest group, we note a high correlation between GAI and the two spans, which has been already explained on the basis of the high list length of the items that are particularly critical at that age.

Insert Table 3 about here

Discussion

The results of our analyses confirmed the main predictions of the study. First, a substantial relationship between general measures of intelligence and WM was found, further supporting the hypothesis that the two aspects are partly overlapping, as already observed in general and also with reference to the WISC-IV indexes (Wechsler, 2003, 2008). Moreover, this finding does add further support to a well consolidated line of research which shows that the relationship between WM and GI is not particularly high, when the raw correlations are considered, whereas it results very high when the underlying factors are considered (e.g., Kane, Hambrick, & Conway, 2005). For example, the Ackerman and colleagues (2005) meta-analysis reported only moderate correlations, whereas our confirmatory analysis showed a correlation of .89 between GI and WM factors. Moreover, differently from other studies, in the present research the correlation was found using a measure of GI (i.e., the GAI) in which the direct measures of the WM component were explicitly ruled out from the GI measure. This does not mean that WM and GI are independent, because – as the correlation suggests – also the subtests used for obtaining the GAI measure presumably involve to a large extent WM (and it cannot be excluded also the opposite, especially in the case of the Arithmetic subtest). However, literature suggests a partial independence between the two constructs. For example, children with learning disabilities typically present WM difficulties, despite having high intelligence (e.g., Swanson & Siegel, 2001).

Second, differently from other observations and assumptions (e.g., Colom et al., 2008) the relationship between WM and GI may vary as, in the present case, it changed according to the different tests used by the WISC-IV for assessing WM. On this respect, it is a pity that the focus in WISC-IV is on a general measure of WM and, in particular, the two digit spans are considered together (as in the previous versions of WISC batteries). In fact, coherently with the dichotomous and the continuum views of WM, the relationship between GI and WM was different in the cases of the forward and backward versions of the digit span.

Third, different from the predictions of dichotomous models (e.g., Engle & Kane, 2004) and in agreement with the hypothesis of more complex variability within WM (Cornoldi & Vecchi, 2003), WM tasks were differently related with GI. In fact, the relationship was not only the lowest for the FDS, but also it was followed by the BDS, and then by the LNS and the AR subtests, in correspondences with the increases in the required cognitive control.

Fourth, the relationships between WM and GAI were similar, although, not exactly the same in the different age ranges. In fact, for the youngest group, the three most controlled tasks had a similar pattern of relationship with GAI, which was higher than the relationship observed for the FDS. The high relationship between BDS and GAI in the youngest group could be due to the fact that, due both to their WM limitations and scarce familiarity with the manipulation of numbers, the relatively simple operation of reverting the order of numbers requires a high cognitive control in young children (Alloway et al., 2006). At the same time, the fact that, in young children, the AR subtest did not correlate with GAI significantly more than the LNS subtest could be due to the specific characteristics of the items of the AR subtest critical for young children, which require relatively simple operations (Kaufman, 1994). Finally, the medium/high correlations for the oldest group between the FDS and BDS, on the one side, and GAI, on the other side, could be due to list length effects (Unsworth & Engle, 2007). Moreover, for this group, the performance in the BDS is considered successful only when a very high number of items is reversed in its order and this requires the use of highly controlled processes and strategies. Obviously, these explanations are tentative and other explanations could be advanced. For example, the limited range of scores in the digit span tasks, particularly critical for young children, and the developmental changes also in the six subtests used for obtaining the GAI measure should be better considered. Further research should clarify these points.

In conclusion, the present results further support the observations that WM is related to GI. Furthermore, results offer a possible explanation as to why results on the relationship between WM and GI differ across various studies, suggesting that it may be affected by the degree of active control involved in the WM test. This pattern seems to be general across ages, as the minor differences between age groups seem to be related with the peculiar characteristics of the subtest items that are critical for a particular age group. As populations, test adaptations can vary, we do not expect that our results offer a final response to the state of the problem and a definite description of the implications of different WISC-IV measures of WM; although, we do hope that the present approach and our data offer a contribution in this direction, which could take advantage from the fact that WISC-IV has many different national standardizations. In fact, the present study took place during the Italian standardization of the WISC-IV, but – as a similar standardizations have been already made in many different countries – the generality of our results and conclusions could be easily tested. Therefore, as WISC-IV is largely used and accepted in research and application settings (e.g., it is the most used psychological test in Europe; Evers et al., 2012), we think that conclusions derived from this test can have an important impact on the scientific community.

References

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

Alloway, T. P., Gathercole, S. E., & Pickering, S. J. (2006). Verbal and visuospatial short-term memory in children: Are they separable? *Child Development, 77*, 1698−1716. doi: 10.1111/j.1467-8624.2006.00968.x

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

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

Baddeley, A. (2007). *Working memory, thought, and action*. New York, NY: Oxford University Press.

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,* 404–431. doi: 10.1037//0033-295X.97.3.404

Carretti, B., Belacchi, C., & Cornoldi, C. (2010). Difficulties in working memory updating in individuals with intellectual disability. *Journal of Intellectual Disability Research: JIDR, 54,* 337-45. doi:10.1111/j.1365-2788.2010.01267.x

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences. (2nd edition).* Hillsdale, NJ: Erlbaum.

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

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*, 163-183. doi:10.1016/S0160-2896(01)00096-4

Cornoldi, C. (2007). *L'intelligenza. [Intelligence].* Bologna, Italy: Il Mulino.

Cornoldi, C. (2010). Metacognition, intelligence, and academic performance. In H. S. Waters & W. Schneider (Eds.), *Metacognition, Strategy Use, and Instruction* (pp. 257-277). New York: the Guilford Press.

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

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

Engle, R. W., & Kane, M. J. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. *The Psychology of Learning and Motivation, 44,* 145−199. doi:10.1016/S0079-7421(03)44005-X

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*, 309–331. doi:10.1037/0096-3445.128.3.309

Evers, A., Muñiz, J., Bartram, D., Boben, D., Egeland, J., Fernández-Hermida, J. R., Frans, Ö., et al. (2012). Testing Practices in the 21st Century. *European Psychologist, 17,* 300–319. doi:10.1027/1016-9040/a000102

Fry, A. F., & Hale, S. (2000). Relationships among processing speed, working memory, and fluid intelligence in children. *Biological Psychology, 54*, 1–34. doi:10.1016/S0301-0511(00)00051-X

Flanagan, D. P., & Kaufman, S. (2004). *Essentials of Assessment with WISC-IV*. New York, NY: Wiley.

Goldbeck, L., Daseking, M., Hellwig-Brida, S., Waldmann, H. C., & Petermann, F. (2010). Sex Differences on the German Wechsler Intelligence Test for Children (WISC-IV). *Journal of Individual Differences*, *31*, 22–28. doi:10.1027/1614-0001/a000003

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

Jumel, B. (2008). *Guide clinique des tests chez l'enfant*. Paris, France: Dunod.

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

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

Kaufmann, A.S. (1994). *Intelligence testing with the WISC-III*. New York, NY: Wiley.

Kyllonen, C., & Christal, R. E. (1990). Reasoning ability is (little more than) working memory capacity? *Intelligence, 14,* 389–433. doi:10.1016/S0160-2896(05)80012-1

Lanfranchi, S., Cornoldi, C., Drigo, S., & Vianello, R. (2008). Working Memory In Individuals With Fragile X Syndrome. *Child Neuropsychology, 15,* 105-119. doi:10.1080/09297040802112564

Lanfranchi, S. , Cornoldi, C., & Vianello, R. (2004). Verbal and Visuospatial Working Memory deficits in children with Down syndrome. *American Journal on Mental Retardation, 6,* 456–466. doi:10.1352/0895-8017(2004)109<456:VAVWMD>2.0.CO;2

Lecerf, T., Reverte, I., Coleaux, L., Favez, N., & Rossier, J. (2010). Indice d'aptitude général pour le WISC-IV: normes francophones. *Pratiques Psychologiques, 16,* 109–121. doi:10.1016/j.prps.2009.04.001

Marzocchi, G. M., Lucangeli, D., De Meo, T., Fini, F., & Cornoldi, C. (2002). The disturbing effect of irrelevant information on arithmetic problem solving in inattentive children. *Developmental neuropsychology, 21,* 73–92. doi:10.1207/S15326942DN2101_4

Orsini, A., Pezzuti, L., & Picone, L. (2011). *WISC-IV. Contributo alla taratura Italiana. [WISC-IV Italian Edition]*. Firenze, Italy: Giunti, OS,.

Raiford, S. E., Weiss, P. D. L. G., Rolfhus, P. D. E., & Coalson, P. D. D. (2005). *General Ability Index*. Harcourt Assessment, Technical Report.

Saklofske, D.H., Prifitera, A., Weiss, L.G., Rolfhus, E., & Zhu, J. (2005*).* Clinical interpretation of the WISC-IV FSIQ and GAI. In A. Prifitera, D.H. Saklofske, & L.G. Weiss (Eds.), *WISC-IV. Clinical use and interpretation*. San Diego, CA: Elsevier.

San Miguel Montes, L. E., Allen, D. N., Puente, A. E., & Neblina, C. (2010). Validity of the WISC-IV Spanish for a clinically referred sample of Hispanic children. *Psychological assessment, 22,* 465–469. doi:10.1037/a0018895

Swanson, H. L., & Siegel, L. S. (2001) . Learning disabilities as a working memory deficit. *Issues in Education, 7*, 1-48.

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

Unsworth, N., & Engle, R. W. (2005). Working memory capacity and fluid abilities: Examining the correlation between Operation Span and Raven. *Intelligence, 33,* 67–81. doi:10.1016/j.intell.2004.08.003

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

Wechsler, D. (2003). *Wechsler Intelligence Scale for Children–Fourth Edition.* San Antonio, TX: Psychological Corporation.

Wechsler, D. (2005). WISC-IV. *Manuel d'interprétation (French edition edited by C. Wierzbicki)*. Paris: Edition du Centre de Psychologie Appliquée (ECPA).

Wechsler, D. (2008). *Wechsler Adult Intelligence Scale-Fourth Edition: Technical and interpretive manual*. San Antonio, TX: Pearson

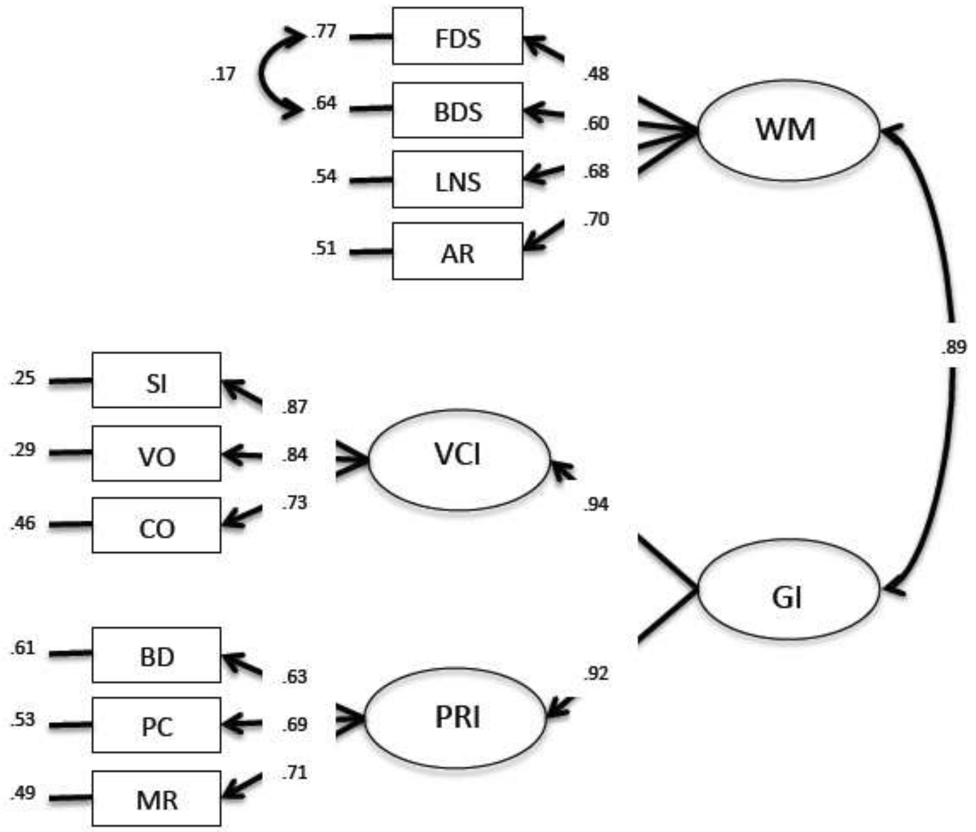

Figure 1. Results of a confirmative factorial analysis for WM and general intelligence. $\chi^2(32)=374.07$, $p<.001$; *CFI* =.97; *RMSEA*=.07, 95% CI [.063, .076]; *TLI*=.96. FDS=Forward digit span, BDS=Backward digit span, LNS=Letter-numbers sequencing, AR= Arithmetic, SI=Similarities, VO=Vocabulary, CO=Comprehension, BD=Block design, PC=Picture concepts, MR=Matrix reasoning, VCI=Verbal comprehension index, PRI=Perceptual reasoning index, GI=General intelligence.

Table 1

Correlations between the weighted scores in the four Working memory subtests and the standard scores in WISC-IV general measures in the whole group of children

	FDS	BDS	LNS	AR	GAI	VCI	PRI	PSI
FDS	1							
BDS	.422	1						
LNS	.322	.402	1					
AR	.284	.357	.387	1				
GAI	.300	.403	.470	.532	1			
VCI	.292	.331	.408	.467	.894	1		
PRI	.236	.384	.425	.473	.871	.559	1	
PSI	.137	.212	.255	.295	.343	.266	.345	1

Note. *N*=2200; FDS=Digit span forward, BDS=Digit span backward, LNS=Letters numbers sequences, AR=Arithmetic, GAI=General ability index, VCI=Verbal comprehension index, PRI=Perceptual reasoning index, PSI=Processing speed index.

Table 2

Partial correlations between GAI and the weighted scores in each of four WM subtests, partialing out the contribution of the three non interested subtests in the whole group of children

	FDS	BDS	LNS	AR
GAI	.059	.159	.269	.385
VCI	.097	.089	.218	.326
PRI	-.006	.181	.235	.327
PSI	-.003	.072	.129	.197

Note. *N*= 2200; FDS=Forward digit span, BDS=Backward digit span, LNS=Letters numbers sequences, AR=Arithmetic, GAI=General ability index, VCI=Verbal comprehension index, PRI=Perceptual reasoning index, PSI= Processing Speed Index.

Table 3.

Correlations between the standardized scores in the four WM subtests and the general intelligence measure (GAI)

		A	B	C	D	Difference between correlations				
	Age Group	FDS	BDS	LNS	AR					
GAI	[1] 6-7	.339	.453	.467	.486	A<B*	A<C*	A<D***		
	[2] 8-10	.236	.365	.461	.488	A<B***	A<C****	A<D****	B<C*	B<D***
	[3] 11-13	.277	.330	.471	.543	A<C****	A<D****	B<C****	B<D****	C<D*
	[4] 14-16	.358	.480	.483	.593	A<B****	A<C****	A<D****	B<D***	C<D***
Difference between correlations		[1] > [2]*	[1] > [3]*		[1] < [4]**					
		[2] < [4]*	[2] < [4]**		[2] < [4]**					
			[3] < [4]***							

Note. A, B, C, d are associated with the correlations which are significantly different according to the different group ages; **p*< .05; ** *p*< .01, *** *p*< .001; **** *p*< .0001; FDS=Forward digit span, BDS=Backward digit span, LNS=Letters numbers sequences, AR=Arithmetic, GAI=General ability index.