

Short-term storage and mental speed account for the relationship between working memory and fluid intelligence

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Here, we explore the role of short-term storage, mental speed, processing efficiency, and controlled attention to account for the relationship between working memory and fluid intelligence. Ninety-six secondary school students were assessed by several tests and tasks to tap these psychological constructs. Specifically, each construct was measured by two tests or tasks from different content domains (verbal-numerical and spatial). The findings show that short-term storage and, to a lesser degree, mental speed, account for the relationship between working memory and fluid intelligence. Further, processing efficiency and controlled attention do not play a significant role.

El almacenamiento a corto plazo y la velocidad mental dan cuenta de la relación entre memoria de trabajo e inteligencia fluida. Se explora el papel del almacenamiento a corto plazo, la velocidad mental, la eficiencia de procesamiento y el control de la atención en la relación de la memoria de trabajo con la inteligencia fluida. Se evaluó a noventa y seis estudiantes de Enseñanza Secundaria mediante varios tests y tareas diseñadas para valorar los constructos psicológicos señalados. Concretamente, cada constructo se valoró con dos tests o tareas de distintos dominios de contenido (numérico-verbal y espacial). Los resultados indican que el almacenamiento a corto plazo, y, en menor medida, la velocidad mental, explican la relación de la memoria de trabajo con la inteligencia fluida. Además, la eficiencia de procesamiento y el control de la atención no juegan un papel significativo en esa relación.

The relationship between working memory and intelligence, at the latent variable level, is well documented. Kyllonen & Christal (1990) estimated a correlation ranging from .80 to .90. Ackerman et al. (2002) found a correlation of .70. Süß, et al. (2002) reported correlations ranging between .38 and .65. Colom et al. (2004) found a mean correlation of .96 across three separate studies. Colom & Shih (2004) reported a correlation of .86. Colom et al. (2005 a) found a correlation of .89. Therefore, it is safe to conclude that there is a high relationship between working memory and intelligence.

Nevertheless, the causes of this correlation remain unknown (Colom et al., 2006 a). It is assumed that working memory measures comprise short-term storage plus some sort of processing requirements. Thus, for instance, the computation span task involves the processing requirement of verifying if several equations sequentially displayed $[(3 * 2) / 2 = 3] \ggg [(8 - 5) + 3 = 5] \ggg [(6 / 3) + 6 = 7]$ are correct or not, as well as the short-term storage requirement of temporarily maintain the equation solutions for later recall (Ackerman et al., 2002). The correlation between these memory span tasks and intelligence measures could derive from their short-term storage or processing requirements.

With respect to the processing component of working memory, some studies argue that the causal factor underlying the relationship with intelligence could be mental speed, as measured by simple reaction time tasks (Kail & Salthouse, 1994; Jensen, 1998). Kyllonen & Christal (1990) reported correlations between working memory and mental speed ranging from .35 to .48. Babcock (1994) found correlations ranging from .29 to .59. Oberauer et al. (2000) reported a correlation of .31. Ackerman et al. (2002) reported a correlation of .48. Thus, it is reasonable to assume that mental speed underlies the working memory-intelligence relationship (Colom et al., in press).

However, Engle & Kane (2004) state that mental speed is not relevant to understand this correlation. The theory first proposed by Engle et al. (1999) postulates that the central executive (or controlled attention) component of the working memory system accounts for the relationship between working memory and intelligence: «we assume that working memory is not really about storage or memory per se, but about the capacity for controlled, sustained attention in the face of interference or distraction» (p. 104). Those researchers assume that variance shared between working memory tasks and short-term memory tasks represents the short-term storage component of the working memory system, whereas the residual variance in working memory tasks (after partialing out the variance shared by both memory span tasks) represents the central executive component of the working memory system –note that some years later Kane et al. (2004) changed this view; see Colom et al. (2005) for a discussion.

The empirical study reported by Engle et al. (1999) considered verbal working memory and verbal short-term memory tasks to

test the theory already described. These researchers predicted that a latent factor derived from working memory tasks would predict individual differences in fluid intelligence, whereas a latent factor derived from short-term memory tasks would not. In fact, they found that the working memory latent factor (with its storage component partialled out) predicted intelligence, whereas the short-term memory latent factor did not.

Nevertheless, Bayliss et al. (2003) note that Engle et al. did not measure processing efficiency so «it is unclear whether the residual working memory component measured in their study reflects a central executive component responsible for the control of information in working memory or simply individual differences in processing efficiency» (p. 73).

Süß, et al. (2002) suggest that the processing requirements of working memory tasks are not more demanding than those of mental speed tasks. The sharp difference between working memory and typical mental speed tasks relies in that there is an additional cognitive requirement in the former tasks: short-term storage. Assuming that the working memory processing component parallels that of mental speed tasks, these processing and short-term storage components of the working memory system could account for the relationship between working memory and intelligence.

The study reported by Fry & Hale (1996) is consistent with this latter assumption. They found that individual differences in mental speed mattered in the working memory tasks considered in their study. Nevertheless, they also found that the relation between working memory and intelligence was still significant when the relation between working memory and mental speed was partialled out. This finding suggests that working memory comprises something more than mental speed and one reasonable candidate is its short-term storage component.

In conclusion, the general picture is still unclear. There are no published reports measuring *concurrently* the presumably relevant constructs. Therefore, the present study was expressly designed to evaluate the independent contribution of the short-term storage and processing components (mental speed, processing efficiency, and controlled attention) of the working memory system to the relationship between working memory and fluid intelligence. This is done in two steps: (a) which of the short-term storage and processing components predict working memory, and (b) which of the surviving components predict fluid intelligence.

Method

Participants

96 secondary school students took part in the study (48 boys and 48 girls). They were randomly selected from the same scholastic grade (mean age= 13.35; SD= .58; range: from 13 to 15 year olds). Note that most of the published studies analyze samples selected for above average intelligence (university undergraduates) (Miyake & Shah, 1999) whereas here we consider unselected high-school students.

Measures

Numerical-verbal and spatial tasks were used for the measurement of each construct washing out unwanted variance specific for each measure (Ackerman et al., 2005). All computerized tasks were programmed in Visual Basic.

Short-term memory was measured by tasks requiring the temporary maintenance of simple items for latter recall, whereas working memory was measured by tasks requiring processing + storage. Mental speed was measured by simple verification tasks in which participants were requested to verify, as quickly and accurately as possible, if a given test stimulus was presented within a small sized memory set. The control of attention is usually defined as the ability to maintain mental representations in a highly active state in the presence of interference. Processing efficiency is usually measured by tasks involving identical processing requirements to working memory tasks, but without storage requirements (see Bayliss et al., 2003, p. 75).

Therefore, short-term storage was measured by the forward digit span and Corsi Block tasks (Miyake et al., 2001). Working memory was measured by the computation span and dot matrix tasks (Ackerman et al., 2002; Miyake et al., 2001). Mental speed was measured by quantitative and spatial speed tasks (Colom et al., in press). Controlled attention was measured with a numerical version of the flanker task and a version of the Simon task (Colom et al., 2007) following Heitz & Engle (2007). Processing efficiency required the design of new tasks, quantitative and spatial processing efficiency, whose features are detailed below. Finally, fluid intelligence was measured by the reasoning subtest (R) from the Primary Mental Abilities (PMA) Battery (Thurstone, 1938) and the abstract reasoning (AR) subtests from the Differential Aptitude Test (DAT) Battery (Bennett et al., 1990).

More specific information can be found in the Appendix.

Processing efficiency measures

These tasks were thought and designed to control for short-term memory loadings (Bayliss et al., 2003). Further, they were modelled after standard working memory measures. Two important features of these tasks are: (1) contrary to other studies (e.g. Bayliss et al., 2003) complexity level is manipulated to model standard working memory tasks, and (2) *processing* is referred to information temporarily stored in short-term memory, not peripheral information (e.g. perceptual speed).

The quantitative processing efficiency task is based on computation span, and includes three levels of difficulty, with 10 trials each. Every trial comprises three consecutive screens: A, B, and final (figure 1).

Participants are requested to verify, as quickly as possible, whether the equation shown in screen A is correct or not. Further, the result of this equation must be temporarily retained, regardless of its accuracy. Screen B also requires the verification of an equation and the temporary retention of the result. The final screen comprises an equation that must be verified, implicating the results of screens A and B. Importantly, the memory load for this final screen is always the same, but processing complexity is gradually

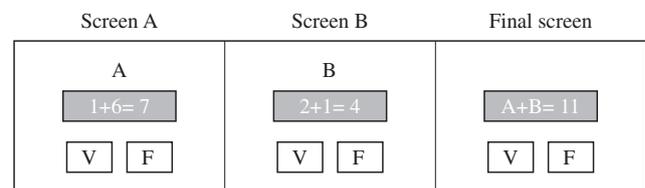


Figure 1. Example of one trial from the quantitative processing efficiency task. Correct answer: V (True)

increased from level 1 (addition) to level 2 (subtraction) to level 3 (addition or subtraction randomly requested).

Like the previous one, the spatial processing efficiency task controls memory loadings, but manipulates processing complexity. There are three levels of difficulty, with 10 trials each. Every trial shows three consecutive screens: A, B, and final (see figure 2).

First, participants are requested to memorize the figure depicted in screen A, and then the figure shown in screen B. The final screen shows a figure that may or may not result from a combination of the figures depicted on screens A and B. Therefore, memory loadings are always the same across levels,

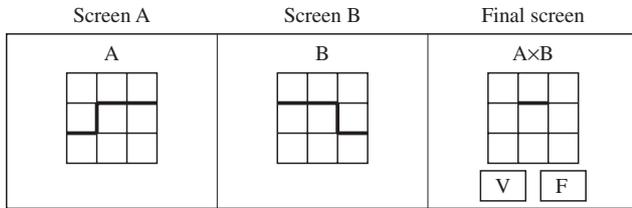


Figure 2 A. Example of one trial from the spatial processing efficiency task (level 1). Correct answer: V (True)

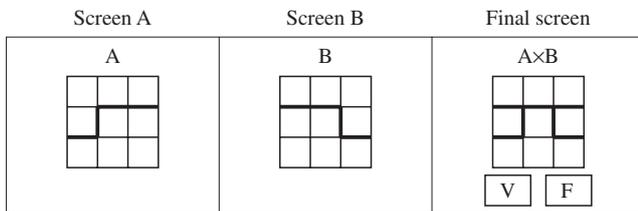


Figure 2 B. Example of one trial from the spatial processing efficiency task (level 2). Correct answer: V (True)

and figures are low demanding in order to avoid overloading participants' short-term storage capacity. However, the complexity of the operation required to verify the figure shown in the final screen increases gradually: level 1 (A × B's operations, Figure 2 A) implicates, first, the superimposition of figures depicted on screens A & B, and second removing not shared lines; level 2 (A + B's operations, Figure 2 B) requires the superimposition of figures shown in screens A & B. Finally, Level 3 is a random combination of levels 1 & 2.

The predicted effect for the complexity levels was confirmed. First, for the quantitative processing efficiency task, average RTs were: Level 1= 1625.36; Level 2= 1999.71; Level 3= 2132.34. Second, for the spatial processing efficiency task, average RTs were: Level 1= 1363.84; Level 2= 1499.03; Level 3= 1912.85.

Procedure

The measures were applied in groups of 15-20 participants in four sessions of 40–60 minutes each. Session 1 comprised the assessment of short-term storage and working memory; session 2 included mental speed and controlled attention; session 3 measured quantitative and spatial processing efficiency; and session 4 assessed fluid intelligence.

Results

Table 1 shows the descriptive statistics, the zero-order correlation matrix, and the reliability indices.

First, a confirmatory factor analysis is computed testing if the planned factor structure fits the obtained data (Arbuckle, 2003). The factors and measures are: short-term memory (forward digit span and corsi block), working memory (computation span and dot matrix), mental speed (quantitative and spatial speed), controlled attention (quantitative and spatial controlled attention),

	1	2	3	4	5	6	7	8	9	10	11	12
1. FDSPAN		.311**	.009	.012	.426**	.277**	.169	.253*	.229*	.314**	.227*	.128
2. Corsi Block			.141	.267**	.390**	.261*	.296**	.489**	.503**	.478**	.310**	.211*
3. QPTASK				.550**	.202*	.180	.486**	.311**	.270**	.314**	.576**	.412**
4. SPTASK					.177	.192	.388**	.231*	.310**	.228*	.388**	.282**
5. Computation Span						.298**	.273**	.100	.323**	.366**	.317**	.114
6. Dot Matrix							.318**	.239*	.467**	.227*	.164	.181
7. Flanker task (numerical)								.371**	.245*	.201*	.513**	.179
8. Simon task (spatial)									.430**	.257*	.376**	.349**
9. DAT-AR										.518**	.271**	.369**
10. PMA-R											.332**	.275**
11. Q PRO												.474**
12. S PRO												
Mean	8.92	64.71	2338.93	1334.17	3.64	23.33	916.79	652.37	20.46	16.46	1911.53	1587.32
SD	2.74	18.26	1135.68	497.07	2.99	6.77	304.91	177.68	6.46	5.41	600.08	461.29
Reliability (α)	.86	.88	.93	.70	.84	.87	.94	.87	.79	.84	.83	.79

FDSPAN= Forward Digit Span; QPTASK= quantitative mental speed; SPTASK= spatial mental speed; DAT-AR= abstract reasoning; PMA-R= inductive reasoning; Q-PRO= quantitative processing efficiency; S PRO= spatial processing efficiency; SD= standard deviation. Speed, attention and efficiency scores are reflected

* p<.05; ** p<.01

processing efficiency (quantitative and spatial efficiency), and fluid intelligence (DAT-AR and PMA-R). The fit of this measurement model was reasonable: $\chi^2_{(36)} = 51.4$, $\chi^2/df = 1.4$, CFI = .95, TLI = .91, GFI = .92, RMSEA = .067.

Second, given that the postulated factor structure is confirmed, raw scores are standardized in order to compute six aggregates representing the constructs of interest (Ackerman et al., 2002, 2005). Raw correlations among the resulting aggregates are shown in table 2.

Third, aggregated scores are factored by means of principal axis factoring (PAF) followed by a Promax rotation (table 2). Two factors are obtained. The first factor is defined by fluid intelligence, short-term memory, and working memory, whereas the second factor is defined by mental speed, processing efficiency, and controlled attention. The correlation between both factors is .52.

Fourth, a multiple regression analysis is computed selecting working memory as the dependent measure, and short-term storage, mental speed, processing efficiency, and controlled attention as predictors. Note that, in terms of a lineal equation, working memory variance can be broken down between the contribution of each relevant predictor and what is not explained by the model. This latter component defines a working memory residual [WM-r]. This residual is thought to represent specific variance of the working memory system partialing out their short-term storage and processing components (i.e. mental speed, processing efficiency, and controlled attention) (see Colom et al., 2005 b for further details).

Table 3 shows that only short-term storage and mental speed contribute to the prediction of working memory. Short-term storage explains 27%, whereas mental speed increase the value to 31%, of the working memory variance ($R = .519$, $p < .05$) [in interest of parsimony, we tested a more restrictive model ($p < .01$) and the results indicated that mental speed can be excluded]. The obtained standardized regression coefficients (β) in the model are .491 for short-term storage and .195 for mental speed.

Fifth, we test if short-term storage, mental speed, and WM-r predict fluid intelligence —processing efficiency and controlled attention are excluded, given that these scores did not contribute to the prediction of working memory. Table 4 shows the results.

	Correlation matrix						Factor matrix	
	WM	STM	MS	PE	CA	Gf	F-I	F-II
1. WM		.519**	.265**	.280**	.368**	.493**	.653	.383
2. STM			.142	.315**	.416**	.540**	.830	.321
3. MS				.549**	.508**	.366**	.312	.840
4. PE					.488**	.417**	.449	.687
5. CA						.365**	.521	.638
6. Gf							.684	.496

WM= working memory; STM= short-term memory; MS= mental speed; PE= processing efficiency; CA= controlled attention; Gf= fluid intelligence. Speed, attention and efficiency scores are reflected
** $p < .01$

Step / predictors	R	R ²	ΔR^2
1. STM	.519	.269	.269
2. STM, MS	.554	.307	.037

STM= short-term memory; MS= mental speed
P of entry $\leq .05$

Step / predictors	R	R ²	ΔR^2
1. STM	.540	.292	.292
2. STM, MS	.614	.377	.085
3. STM, MS, WM(r)	.642	.412	.035

WM-r= working memory residual; STM= short-term memory; MS = mental speed
P of entry $\leq .05$

Short-term storage, mental speed, and the working memory residual [WM-r] are significant predictors of fluid intelligence (p of entry $\leq .05$). Regarding R^2 , the final model explains 41% of the fluid intelligence variance. However, short-term storage accounts for 30% of the variance. The ΔR^2 values show the secondary role for mental speed (8.5%) and the negligible contribution for WM-r (3.5%). The standardized regression coefficients (β) are: .50 for short-term storage, .29 for mental speed, and .19 for the working memory residual.

The above results are obtained for a liberal p value of .05. When a more conservative model is tested ($p < .01$) the working memory residual is excluded from the equation ($t = 2.348$, $p = .021$).

Discussion

Here we found several findings of interest. First, the factor analysis of the aggregates representing all the constructs of interest shows a solution comprising two correlated factors. One of these factors is loaded by fluid intelligence, short-term storage, and working memory. This is especially noteworthy because it supports the view that fluid intelligence and memory span tap common mental resources to a high degree (Colom et al., 2007). Further, it is reasonable to assume that short-term storage is the main underlying component, because (1) temporary storage is common to both short-term and working memory, and (2) short-term storage is the best predictor for both working memory and fluid intelligence (see below).

Second, processing efficiency does not predict working memory. This finding is not consistent with Bayliss et al.'s (2003) studies. These researchers found that processing efficiency is relevant to understand the working memory-intelligence relationship. However, we failed to replicate such result.

Third, controlled attention does not predict working memory either. Note that this is not an inferred finding, but the result of a

direct testing. Here we followed the guidelines proposed by Bayliss et al. (2003) (see above). Controlled attention was directly measured by means of a quantitative version of the flanker task (Heitz & Engle, in press) and a spatial version of the Simon task. In conclusion, contrary to Engle and colleagues (Engle et al., 1999; Conway et al., 2002; Kane et al., 2004):

Working memory \neq short-term storage + controlled attention

It is also of note that short-term storage accounts for the relationship between working memory and fluid intelligence, contrary to the prediction of Engle and colleagues—recently, Unsworth & Engle (2007) have written: «this conclusion [that the variance common to simple and complex span is responsible for their predictive power] is contrary to previous research (including our own) suggesting that complex span [working memory] predicts higher-order abilities [fluid intelligence] better than simple span».

Finally, the general model that best fits the observed data indicates that:

Working memory = short-term storage + mental speed

Indeed, working memory comprises short-term storage and mental speed. Processing efficiency and controlled attention are not relevant processing components of the working memory system and, therefore, they cannot account for the relationship between working memory and fluid intelligence.

In addition, it should be underscored that temporary storage accounts for much more working memory variance than mental speed. Actually, short-term storage is almost three times more relevant than mental speed to predict individual differences in working memory. Consequently, it can be expected that the relation between working memory and fluid intelligence would be (almost) exhausted by simple short-term storage.

In summary, the general picture is largely consistent with Colom et al. (2005 b). They did find that shared variance between short-term storage and working memory is the best predictor of the working memory-intelligence correlation. It is also in agreement with the re-analysis of five key datasets reported by Colom et al. (2006 b) in which short-term storage accounted for the relationship between complex span (working memory) tasks and several diverse cognitive abilities.

Appendix

In all the computerized tasks, participants completed a set of three practice trials as many times as desired to ensure they have understood the instructions.

Forward Digit Span: Single digits (from 1 to 9) were presented on the computer screen at the rate of one digit per second. Unlimited time was allowed to type in *direct order* the digits presented. Set size ranged from three to nine items (7 levels \times 3 trials each= 21 trials total). Digits were randomly grouped to form trials. The score was the number of accurately reproduced trials.

Corsi Block: Nine boxes are shown on the computer screen. Three different configurations of boxes that changed on each trial were used. One box at a time turned orange for 650 ms each and the order in which they were sequentially highlighted must be remembered. There was unlimited time to respond. The sequences increased from 3 to 9 highlighted boxes (7 levels \times 3 trials each=

21 trials total). The score was the number of boxes reproduced appropriately according to the sequence in which they were highlighted.

Computation Span: The task includes verification and a recall test. Several math equations are displayed on successive screens and the participant is asked to decide if they are correct or not. For instance: $(10/2) - 3 = 1$ >> $(6 \times 2) - 5 = 7$ >> $(3 + 5) + 1 = 9$. Further, she must retain the results in their correct serial order, irrespective of its accuracy, for later recall. The task contains five levels of difficulty: from three to seven consecutive equations. Each level consists of three trials (5 levels \times 3 trials = 15 trials total). The score is obtained from the number of correct answers in the verification and recall tasks.

Dot Matrix: The participant is asked to verify whether a spatial equation is correct or not (verification task), and then, she must memorize a dot placed at a 5×5 grid. The spatial equation must be solved by adding or subtracting simple lines. Once the equation is verified, the dot on the grid appears for 1.5 s. After a series of equation-dot pairs, participants recall the dot locations. There were 4 levels of difficulty (from two to six equation-dot pairs) and three trials for each level (12 trials total). The score is obtained from the number of hits in the verification and recall tasks.

Quantitative mental speed: Several single digits are sequentially displayed for 650 ms. each. Those digits define a given memory set that can comprise two, three, or four single digits. After the last digit is displayed, a fixation point appears for 500 ms. Finally, the probe digit appears in order to decide, as quickly and accurately as possible, if it can be divided by one of the digits presented within the memory set. Half of the trials requested a positive answer. The trials ranged from two to four digits (3 levels \times 10 trials each= 30 trials total). The score was the mean RT for the correct answers only.

Spatial mental speed: Several arrows are sequentially displayed for 800 ms. each. Those arrows define a given memory set that can comprise two, three, or four arrows. The arrows can be displayed in one of seven orientations (multiples of 45°). After the last arrow is displayed, a fixation point appears for 500 ms. Finally, the probe arrow appears in order to decide, as quickly and accurately as possible, if it has the same orientation as one of the arrows presented within the memory set. The arrows had distinguishable shapes in order to guarantee that their orientation is both memorized and evaluated. Half of the trials requested a positive answer. The trials ranged from two to four arrows (3 levels \times 10 trials each= 30 trials total). The score was the mean RT for the correct answers only.

Controlled attention was measured by means of a quantitative version of the flanker task (Eriksen & Eriksen, 1974) and a spatial version of the Simon task (Simon, 1969). The quantitative task requires deciding, as fast as possible, if the digit presented in the center of a set of three digits is odd or even. The target digit (e.g. odd) can be surrounded by compatible (e.g. odd) or incompatible (e.g. even) digits. The spatial task requires deciding if an arrow (horizontally depicted) points to the left or to the right of a fixation point. The target arrow pointing to a given direction (e.g. to the left) can be presented at the left (e.g. compatible) or at the right (e.g. incompatible) of the fixation point. In both tasks, there were a total of 32 practice trials and 80 experimental trials. Half of the trials were compatible and they were randomly presented across the entire session. The mean reaction time for the incompatible trials was the dependent measure.

PMA-R. This test comprises 30 letters' series items. The rule (or rules) underlying a given sequence of letters [*a-c-a-c-a-c-a-c*] must be extracted in order to select a given letter from a set of six possible alternatives [*a-b-c-d-e-f*]. Only one alternative is correct. The score is the total number of correct responses.

DAT-AR is a series test based on abstract figures. 40 items are comprised in this test. Each item includes four figures following a given rule, and the participant must choose one of five possible alternatives. The score is the total number of correct responses.

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References

- Ackerman, P.L., Beier, M.E., & Boyle, M.O. (2002). Individual differences in working memory within a nomological network of cognitive and perceptual speed abilities. *Journal of Experimental Psychology-General*, *131*, 567-589.
- Ackerman, P.L., Beier, M.E., & Boyle, M.O. (2005). Working memory and intelligence: The same or different constructs? *Psychological Bulletin*, *131*, 30-60.
- Babcock, R.L. (1994). Analysis of adult age differences on the Raven's Advanced Progressive Matrices test. *Psychology and Aging*, *9*, 303-314.
- Bayliss, D.M., Jarrold, C., Gunn, D., & Baddeley, A. (2003). The complexities of complex span: Explaining individual differences in working memory in children and adults. *Journal of Experimental Psychology: General*, *132*, 71-92.
- Bennett, G.K., Seashore, H.G., & Wesman, A.G. (1990). *Differential Aptitude Test (5th edition)*. Madrid, TEA.
- Colom, R., Abad, F., Rebollo, I., & Shih, P.C. (2005 a). Memory span and general intelligence: A latent-variable approach. *Intelligence*, *33*, 623-642.
- Colom, R., Abad, F.J., Shih, P.C., Quiroga, M.A., & Flores-Mendoza, C. (in press). Working memory and intelligence are highly related constructs, but why? *Intelligence*.
- Colom, R., Escorial, S., Shih, P.C., & Privado, J. (2007). Fluid intelligence, memory span and temperament difficulties predict academic performance of young adolescents. *Personality & Individual Differences*, *42*, 1503-1514.
- Colom, R., Flores-Mendoza, C., Quiroga, M.Á., & Privado, J. (2005 b). Working memory and general intelligence: The role of short-term storage. *Personality & Individual Differences*, *39*, 1005-1014.
- Colom, R., Rebollo, I., Abad, F., & Shih, P.C. (2006 b). Simple span tasks, complex span tasks and cognitive abilities: A re-analysis of key studies. *Memory & Cognition*, *34*, 158-171.
- Colom, R., Rebollo, I., Palacios, A., Juan-Espinoso, M., & Kyllonen, P.C. (2004). Working memory is (almost) perfectly predicted by *g*. *Intelligence*, *32*, 277-296.
- Colom, R., Rubio, V., Shih, P.C., & Santacreu, J. (2006 a). Fluid intelligence, working memory and executive functioning. *Psicothema*, *18*, 816-821.
- Colom, R., & Shih, P.C. (2004). Is working memory fractionated onto different components of intelligence? *Intelligence*, *32*, 431-444.
- Conway, A., Cowan, N., Bunting, M., Theriault, D., & Minkoff, S. (2002). A latent variable analysis of working memory capacity, short-term memory capacity, processing speed and general fluid intelligence. *Intelligence*, *30*, 163-183.
- Engle, R.W., & Kane, M.J. (2004). Executive attention, working memory capacity and a two-factor theory of cognitive control. *Psychology of Learning and Motivation: Advances in Research and Theory*, vol. *44*, 145-199.
- 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*. Cambridge, Cambridge University Press, 102-134.
- 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.
- Eriksen, B.A., & Eriksen, C.W. (1974). Effects of noise letters upon the identification of target letter in a non-search task. *Perception and Psychophysics*, *16*, 143-149.
- Fry, A.F., & Hale, S. (1996). Processing speed, working memory and fluid intelligence: Evidence for a developmental cascade. *Psychological Science*, *7*, 237-241.
- Heitz, R.P., & Engle, R.W. (2007). Focusing the spotlight: Individual differences in visual attention control. *Journal of Experimental Psychology: General*, *136*, 217-240.
- Jensen, A.R. (1998). *The g factor. The science of mental ability*. Westport, Connecticut, Praeger.
- Kail, R., & Salthouse, T.A. (1994). Processing speed as a mental capacity. *Acta Psychologica*, *86*, 199-225.
- 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.
- Kyllonen, P.C., & Christal, R.E. (1990). Reasoning ability is (Little more than) working-memory capacity. *Intelligence*, *14*, 389-433.
- Miyake, A., Friedman, N.P., Rettinger, D.A., Shah, P., & Hegarty, M. (2001). How are visuospatial working memory, executive functioning and spatial abilities related? A latent-variable analysis. *Journal of Experimental Psychology: General*, *130*, 621-640.
- Oberauer, K., Süß, H., Schulze, R., Wilhelm, O., & Wittmann, W. (2000). Working memory capacity. Facets of a cognitive ability construct. *Personality and Individual Differences*, *29*, 1017-1045.
- Simon, J.R. (1969). Reactions toward the source of stimulation. *Journal of Experimental Psychology*, *81*, 174-176.
- Süß, H., Oberauer, K., Wittman, W., Wilhelm, O., & Schulze, R. (2002). Working memory capacity explains reasoning ability-and a little bit more. *Intelligence*, *30*, 261-288.
- Thurstone, L. (1938). Primary mental abilities. *Psychometric Monographs*, *1*.
- Unsworth, N., & Engle, R.W. (2007). On the division of short-term memory and working memory: An examination of simple and complex span and their relation to higher order abilities. *Psychological Bulletin*, *133*, 1037-1066.