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Fluid intelligence, working memory and executive functioning

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The causes underlying the correlation between working memory and fluid intelligence remain unknown. There are some researchers who argue that the answer can be found on the presumed executive component of working memory. However, the available empirical evidence is far from conclusive. The present study tested a sample of 229 participants. Intelligence, working memory, and executive functioning were measured by one analytic reasoning test (TRASI), a dual task combining a primary task of deductive reasoning with a secondary task of counting, and the Tower of Hanoi task, respectively. All the 3 measures were computer administered. The results indicate that the shared variance between executive functioning and working memory do not account for the relationship between intelligence and working memory. Some theoretical implications are discussed.

Inteligencia fluida, memoria de trabajo y funcionamiento ejecutivo. Actualmente siguen siendo desconocidas las causas que subyacen a la correlación de la memoria de trabajo con la inteligencia fluida. Algunos investigadores proponen que una respuesta posible radica en el supuesto componente ejecutivo de la memoria de trabajo. Sin embargo, la evidencia empírica disponible no es concluyente. El presente estudio considera una muestra de 229 participantes. La inteligencia, la memoria de trabajo y el funcionamiento ejecutivo se midieron con un test de razonamiento analítico (TRASI), una tarea dual que combinaba una tarea primaria de razonamiento deductivo con una tarea secundaria de recuento, y la Torre de Hanoi, respectivamente. Las tres medidas se diseñaron para su aplicación informática. Los resultados indican que la varianza común al funcionamiento ejecutivo y la memoria de trabajo no explica la relación entre inteligencia y memoria de trabajo. Se discuten algunas implicaciones teóricas.

Intelligence (defined by several diverse measures and constructs, like reasoning ability, fluid intelligence, or the general factor of intelligence, *g*) and working memory (defined by Miyake and Shah (1999) as «those mechanisms or processes that are involved in the control, regulation, and active maintenance of task-relevant information in the service of complex cognition», p. 450) are closely related. Indeed, there are several published research reports showing that they are (almost) isomorphic. Kyllonen and Christal (1990) found structural coefficients of .80 through .88 between working memory and reasoning ability. Colom, Flores-Mendoza and Rebollo (2003) found a correlation of .70 between working memory and fluid intelligence. Ackerman, Beier and Boyle (2002) found a structural coefficient of .70 between working memory and general intelligence (*g*). Colom, Rebollo, Palacios, Juan-Espinosa and Kyllonen (2004) found a mean structural coefficient of .96 between *g* and working memory across three separate large scale studies. Colom and Shih (2004) reported a structural coefficient of .86 between *g* and working memory. Finally, Colom, Abad, Rebollo and Shih (2005a) found a structural coefficient of .89 between working memory and *g*.

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However, most of these studies have employed a latent-variable approach. When the raw correlations between intelligence measures and working memory tasks are considered, the results are sharply different. Thus, for instance, there is a correlation of .24 between the Progressive Matrices Test and the working memory computation span task on the Ackerman et al.'s (2002) study, and a correlation of .32 between the Progressive Matrices Test and the working memory mental counters task on the Colom et al.'s (2004) study. Ackerman, Beier and Boyle (2005) conducted an extensive meta-analysis examining the relationship between working memory and intelligence. This study was based on a literature search ranging between 1872 and 2002. The meta-analytically derived correlation between intelligence and working memory was .36.

Nevertheless, although researchers are prone to the statement that working memory and intelligence share germane variance (Engle, 2002; Jensen, 2004) the causes underlying their relationship remain mysterious. There are some studies appealing to the fact that working memory measures simply tap the ability to temporarily store any given information in the service of complex cognition (Colom, Rebollo, Abad & Shih, 2006; Colom, Flores-Mendoza, Quiroga & Privado, 2005b; Cowan, 2004), whereas other studies claim that working memory measures should be distinguished from so-called short-term memory tasks because the former, but not the latter, comprise the executive ability to control attention. This attention ability is strongly required to successfully cope with the dual nature of working memory tasks (Coway, Cowan, Bunting, Therriault & Minkoff, 2002; Engle, Tuholski, Laughlin & Conway, 1999a).

The theoretical model proposed by Engle, Kane and Tuholski (1999b) endorses the view that the central executive (or controlled attention) component of the working memory system explains 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). The study reported by Engle et al. (1999a) considered working memory and short-term memory tasks to test their theory, finding that a latent factor derived from working memory tasks (with its storage component partialed out) predicted individual differences in intelligence, whereas a latent factor derived from short-term memory tasks did not.

Engle et al. (1999a) considered a key measure of executive functioning, namely, the random number generation task, finding correlations ranging between .14 and .18 with their working memory measures (operation span, computation span, and reading span). Furthermore, those researchers measured fluid intelligence through the standard progressive matrices and the culture fair intelligence tests. The correlation between the random number generation task and those intelligence tests were .05 and .06, respectively. Finally, the correlation between the intelligence measures and their working memory tasks ranged from .24 to .34.

Miyake, Friedman, Emerson, Witzki and Howerter (2000) studied 3 key executive functions: *shifting* between tasks or mental sets, *inhibition* of dominant or prepotent responses, and *updating* and monitoring of working memory representations. Each function was measured by several tasks. The corresponding latent factors were correlated with several contrast measures: the Wisconsin Card Sorting Test, Tower of Hanoi, random number generation, operation span, and dual tasking. To give an example of their findings, the correlation between the operation span task and the Tower of Hanoi and random number generation tasks were .04 and .17, respectively. Therefore, the Miyake et al.'s (2000) study shows that one key measure of working memory capacity employed by Engle et al. (1999a) –the operation span task– is not informatively related to executive functioning.

Miyake, Friedman, Rettinger, Shah and Hegarty (2001) considered two key measures of executive functioning, namely the Tower of Hanoi and the random number generation tasks. Those researchers measured working memory through the letter rotation and dot matrix tasks. Further, they assessed spatial intelligence through the paper folding and space relations tests. The correlation between their executive measures and the working memory tasks ranged from .17 to .26, the correlation between the executive measures and the intelligence measures ranged from .21 to .44, and the correlation between the intelligence measures and the working memory tasks ranged from .31 to .49.

Oberauer, Lange and Engle (2004) correlated dual task costs –as estimates of executive functioning– with a complex measure of working memory, finding a mean correlation of .15 (range from .01 to .33). Their results strongly rejected theories identifying working memory with the ability to control attention for coordinating two concurrent tasks. Further, their findings suggest that the difference between complex (working memory) and simple (short-term memory) span tasks cannot be interpreted as measuring the added contribution of a general executive device. The unique predictive power of complex span tasks cannot be attributed to general executive attention: «several promising current ideas about the nature of so-called complex span tasks might have to be rethought (…) our data should at least motivate proponents of the interference account of working memory (including ourselves) and proponents of the central executive account to specify more precisely under which conditions the amount of dual task interference should reflect working memory (or the capacity of the central executive)» (Oberauer et al., 2004, p. 93).

In summary, the evidence supporting the view that executive functioning underlies the relationship between working memory and intelligence is far from conclusive. In order to find new empirical evidence, the present study considers 3 key measures of the constructs of interest, namely, intelligence, working memory, and executive functioning, to test a large sample of participants. The main purpose is to check the view according to which the relationship between working memory and intelligence must be accounted for the presumed executive component of the former construct.

Method

Participants

The participants were 229 applicants for admissions to an Air Traffic Control Training Course which qualifies to a highly demanded and complex job. All the participants were university graduates from several diverse educational branches (humanities, social sciences, engineering and so forth). There were 72 females and 157 males, whose mean age was 28.2 (SD= 3.9).

Measures and procedures

Intelligence was measured by one analytic reasoning test called TRASI (Rubio and Santacreu, 2003). TRASI is a computerized test comprising 27 items designed to measure analytic or fluid intelligence. Every item is composed by several abstract figures related by some rules. The participant is requested to extract those rules in order to select the correct answer from a set of four alternatives (Figure 1). The specific instructions the participants face comprise four screens. The first one presents the task: «In what follows, you will be asked to complete a sequence of images such as the one shown next [one item is presented]. In doing so, you will have to select one out of the four options by clicking on it [a set of options is shown]. *For each series, there is just one and only one correct answer.* There is a time limit for each item. Clicking on the NEXT button an example will be shown». Afterwards two different examples are shown (screens two and three). Participants cannot continue if they do not deliver a response to each example. If the choice is not correct, the system gives an error message and shows the correct response. Otherwise a correct message is delivered and the following screen is shown. The fourth screen lets the participant to star with the test: «When you are ready just click the START button».

Three scores were obtained: the total of correct responses, the correct responses for the most difficult items (difficulty index ≤ .40), and the correct responses for the less difficult items (difficulty index ≥ .70). Easy and difficult items were considered in order to get information about the potential role of reasoning complexity on both executive functioning and working memory (Unsworth & Engle, 2005).

The test manual reports a reliability index of .84 (Rubio & Santacreu, 2003). The reliability estimated for the current sample is .72 (Cronbach's Alpha). Further, the correlation between the TRASI and the Advanced Progressive Matrices Test is .75, whereas the correlation between the TRASI and the Culture Fair Intelligence Test is .74 (Rubio & Santacreu, 2003). Therefore, this reasoning test can be considered a nice proxy estimate of fluid intelligence.

Working memory was measured by a computerized dual task. Here we follow the straight definition of a good working memory measure, namely, the involvement of «not only a storage requirement but also an explicit concurrent processing requirement» (Miyake et al., 2001, p. 622). Conway, Kane, Bunting, Hambrick, Wilhelm, and Engle (in press) emphasize the next features for a good working memory measure: «while the active maintenance of information can be useful in many situations, it is more necessary under conditions of interference. This is because in the absence of interference, task-relevant information or goals may be easily retrieved from long-term memory as needed. Under interference rich conditions, however, incorrect information and response tendencies, are likely to be retrieved, and so such contexts set the occasion for the reliance on active maintenance of information» (p. 7). These features are *domain-general*, which implies that one single measure could request them all, at least to some theoretically relevant degree. The working memory measure considered in the present study closely resembles the requirements of a classical working memory measure, so we do think that it can be considered an appropriate measurement device.

The *primary task* was defined by three-term series problems or linear syllogisms (Colom, Contreras, Arend, Botella & Santacreu, 2002). Linear syllogisms comprise two premises and each premise describes the relationship between two of 3 terms (A-B-C). One of those terms (B) overlaps between the premises in order to find the relation between the pairs of terms not presented in a single premise. The participants must combine the information from the two premises in order to make an inference about the relationship between A and C. This basic formal structure allows the construction of 32 syllogisms combining the relation between the terms on the two premises and the localization of the response (Arend, Colom, Botella, Contreras, Rubio & Santacreu, 2003). Sixteen syllogisms are characterized by positive comparative forms (better than), whereas the remaining are characterized by negative equatives (not better than). Only the latter type of syllogism was considered in the present study. Each syllogism was presented in a sequence: first premise (John is not better than Mary), second premise (Mary is not better than Paul), question (Who is worst?), and response (Mary-Paul-John). The participant presses the mouse within a square in which the to-be processed information is presented. She is required to code the premises and respond to the question accurately, but as soon as possible.

The *secondary task* was the requirement of counting the number of uppercase and lowercase letters randomly presented together with the first premise, the second premise, and the question that defined the primary task. Thus, for instance, the first screen could depict the first premise and immediately below the letters *L A e F z*. The second screen could depict the second premise and the letters *O u w M r q*. The third screen could depict the question and the letters *t S e Y*. Finally, the answer screen appears, including the 3 names considered at the linear syllogism, as well as 3 buttons in order to decide if the total number of uppercase letters was larger than the number of lowercase letters, if the total number of lowercase letters was larger than the number of uppercase letters, or if there was the same total number of lowercase and uppercase letters (Figure 2). The participant's score was obtained after the number of hits in the primary and secondary tasks. The reliability estimate (Cronbach's Alpha) was .77.

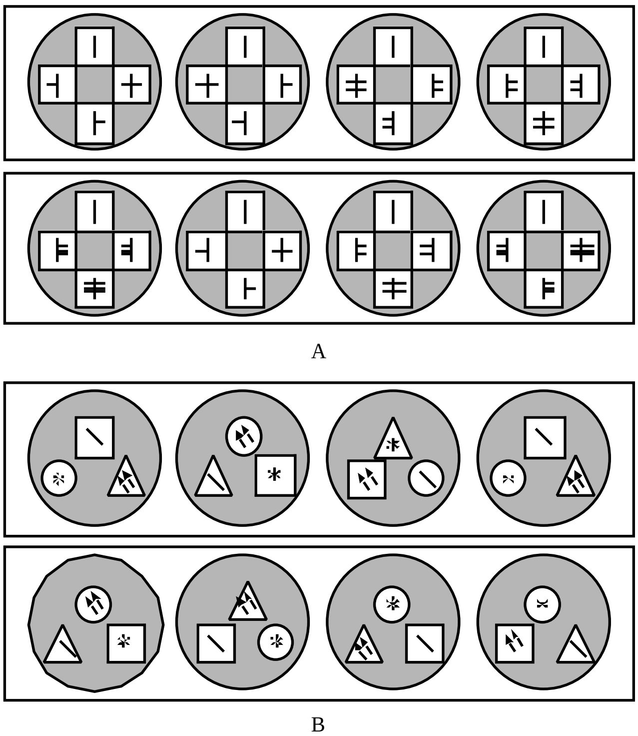

Figure 1. *Examples from the TRASI (difficult –A– and easy –B– items)*

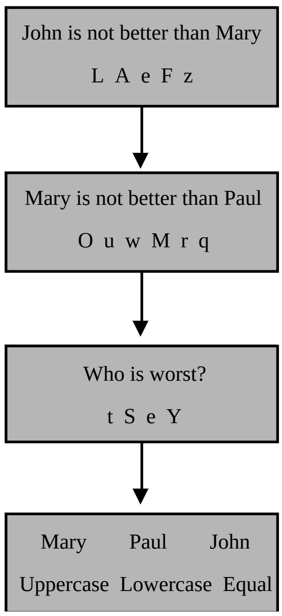

Figure 2. *Example from the working memory task*

Finally, the measure of executive functioning was a computerized version of the well-known Tower of Hanoi task. However, its administration without any restrictions could preclude the implication of executive functioning by the use of simple perceptual strategies. For that main reason, we requested participants to use the goal recursion strategy considered by Carpenter, Just, and Shell (1990) and Miyake et al. (2001). The requirement is to set up a hierarchy of goals monitoring their place in the hierarchy to keep the correct goals active and shift between goals within the hierarchy when appropriate. Therefore, this task requires the activation and tracking of goals and sub-goals. There are conflict moves deriving from the goal representations suggesting one move and the perceptual representation of a given disk configuration suggesting a different move. Failing to keep the goal representations, results in errors drive by the salient perceptual display. There were four trials ranging from four to seven disks and the score was obtained after the average proportion of errors across trials. The reliability estimate (Cronbach's Alpha) was .88.

One may wonder if the Tower of Hanoi task appropriately taps the construct of interest. Specifically, is the Tower of Hanoi task a nice proxy measure of the controlled attention component comprised in the Engle et al.'s (1999b) theoretical model? Admittedly, we can only use indirect evidence on this particular issue. First, Miyake et al. (2001) employed the Tower of Hanoi and the random number generation tasks to define one executive latent factor. Engle et al. (1999a) used the later task to measure executive attention. From that point of view, it is reasonable to assume that both the random number generation and the Tower of Hanoi tasks measure executive attention. Second, from the three executive functions analyzed by Friedman, Miyake, Corley, Young, DeFries and Hewitt (in press), namely, inhibition, shifting, and updating, the later was the only showing significant correlations with intelligence. Third, Miyake et al. (2000) found significant correlations between the Tower of Hanoi task and key measures of updating. Finally, Salthouse, Atkinson and Berish (2003) found that (a) there is no evidence about the existence of distinct constructs (i.e., inhibition, updating, or time sharing) corresponding to executive functioning, and (b) «instead of investigating aspects specific to executive functioning or executive control, the reliable variance in the target variables [inhibition, updating, or time sharing] may represent combinations of other cognitive constructs, such as fluid intelligence, episodic memory, perceptual speed, or vocabulary» (Salthouse et al., 2003, p. 588). Therefore, we think that the Tower of Hanoi task is a good bet for the measurement of executive functioning.

The participants were assessed in a facility comprising 60 testing stations, but each station was isolated to prevent the participant being disturbed.

Results

Table 1 shows the descriptive statistics for the dependent measures of interest.

Firstly, the correlation between intelligence (TRASI), working memory (WM), and executive functioning (Tower of Hanoi, TH) was computed. As previously noted, there were 3 scores derived from TRASI: the total of correct responses, the correct responses for the most difficult items (*high*), and the correct responses for the less difficult items (*low*). The results are shown in Table 2.

All the correlations are statistically significant at $p<.01$. The correlation between working memory and intelligence was .20 (.27 corrected for attenuation), the correlation between working memory and executive functioning was -.20 (-.24 corrected for attenuation), and the correlation between intelligence and executive functioning was -.33 (-.42 corrected for attenuation). Note that these raw correlations are in the same range as those observed in key previous studies such as those reported by Engle et al. (1999a), Miyake et al. (2000), Miyake et al. (2001), or Oberauer et al. (2004).

Table 2 also indicates that TRASI difficult items ($TRASI_{high}$) correlate higher with executive functioning than those less difficult TRASI items ($TRASI_{low}$). However, the correlation between working memory and TRASI remains the same irrespective of the distinction between difficult and easy TRASI items.

Secondly, the variance shared between working memory and executive functioning was partialed out. This analysis was intended to obtain a working memory score unrelated to the executive control measured by the Tower of Hanoi task. This was done after a regression analysis in which working memory was predicted by the Tower of Hanoi task and the variance unpredicted by the latter measure defined a working memory residual score (Beta= .20, t= 3.1, p<.01). This residual score was thought to tap those components of working memory beyond executive functioning. If the theoretical model endorsed by Engle et al. (1999b) is likely, namely, if executive functioning drives primarily the correlation between working memory and intelligence, then the correlation between the obtained working memory residual score and intelligence must be non-significant.

Table 1
Descriptive statistics for the measures considered in the study (N= 229)

Measures	**Mean**	**SD**	**Skew**	**Kurt**
TRASI	15.9	3.5	.11	-.43
$TRASI_{high}$	1.6	1.31	.89	.60
$TRASI_{low}$	5.0	1.38	-.14	-.99
WM	25.3	3.2	-.77	.31
TH	.087	.06	.59	-.50

TRASI= analytic reasoning test, $TRASI_{high}$= difficult items (n= 6) from the analytic reasoning test, $TRASI_{low}$= easy items (n= 7) from the analytic reasoning test, WM= working memory task, TH= Tower of Hanoi, SD= standard deviation, Skew= skewness, Kurt= kurtosis

Table 2
Descriptive statistics for the measures considered in the study (N= 229)

	$TRASI_{high}$	**$TRASI_{low}$**	**WM**	**TH**
TRASI	–	–	.20	-.33
$TRASI_{high}$		.37	.18	-.32
$TRASI_{low}$			.17	-.21
WM				-.20
TH				

TRASI= analytic reasoning test, $TRASI_{high}$= difficult items from the analytic reasoning test, $TRASI_{low}$= easy items from the analytic reasoning test, WM= working memory task, TH= Tower of Hanoi, SD= standard deviation, Skew= skewness, Kurt= kurtosis

However, the result revealed that the correlation between the working memory residual score (with executive control partialed out) and intelligence, was still statistically significant (*r*= .14, *p*<.05).

Finally, the working memory residual score was correlated with the participants' performance on both the more difficult and less difficult TRASI items. The resulting correlations were .12 (*p*= .07) and .13 (*p*<.05), respectively. Therefore, the correlations diminish, but in no way disappear.

Discussion

The findings derived from the present study have several points of interest. First, the relatively low raw correlations observed in previous key studies between intelligence, working memory, and executive functioning measures is largely replicated. Those correlations ranged between .20 and .33 in the present study (between .24 and .42 corrected for attenuation), whereas they ranged between .01 and .49 on the referenced previous key studies (Engle et al., 1999a; Miyake et al., 2000; Miyake et al., 2001; Oberauer et al., 2004).

Second, the correlation between executive functioning and intelligence is higher than the correlation between intelligence and working memory. This finding is quite consistent with the results reported by Miyake et al. (2001), but not with the results observed by Engle et al. (1999a).

Third, the complexity level of the intelligence measure makes a difference for executive functioning, but not for working memory. Thus, harder TRASI items correlate higher with executive functioning than easy TRASI items. However, the correlation of hard and easy TRASI items with working memory remains at the same value. The implication is that harder intelligence problems require more executive involvement, but not more working memory capacity.

Finally, the results are not consistent with the theoretical model proposed by Engle et al. (1999b). Their model states that the executive component of working memory accounts for the relationship between working memory and intelligence. However, we found that the correlation between working memory (with its executive component partialed out) and intelligence is still significant. Further, this is true even when the intelligence problems are separated by their complexity level.

The straight theoretical implication is that executive functioning does not account for the relationship between intelligence and working memory. Given that working memory tasks require the temporary storage of the information of interest in the service of complex cognition, it seems parsimonious to state that the overall capacity devoted to reliably store that information underlies the relationship between working memory and intelligence (Colom & Shih, 2004; Colom et al., 2005a, b; Colom et al., 2006). The results observed in the present study, as well as those reported by Oberauer et al. (2004) did not support theoretical models appealing to one presumed controlled attention ability or executive device.

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