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Working memory capacity and processing efficiency predict fluid but not crystallized and spatial intelligence: Evidence supporting the neural noise hypothesis

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ABSTRACT

Working memory and processing speed are related to intelligence. This study measures concurrently working memory, processing speed and processing efficiency along with fluid, crystallized and spatial intelligence. Two hundred sixty five participants took part in the study. The findings show that working memory and processing efficiency predict fluid, but not crystallized and spatial intelligence. These results are consistent with the neural noise hypothesis based on the empirical observation of synchronous activity of neurons in the brain. Higher scores on fluid intelligence are thought to be related to smaller levels of neural noise-oscillations, as well as to greater levels of processing efficiency and working memory.

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1. Introduction

Intelligence has been subjected to analytical studies through tasks tapping cognitive functions such as mental speed, attention, short-term memory, updating, or working memory (Ackerman, Beier, & Boyle, 2002, 2005; Babcock, 1994; Buehner, Krumm, & Pick, 2005; Colom, Rebollo, Palacios, Juan-Espinosa, & Kyllonen, 2004; Colom & Shih, 2004; Colom, Abad, Rebollo, & Shih, 2005a; Colom, Flores-Mendoza, Quiroga, & Privado, 2005b; Colom, Rebollo, Abad, & Shih, 2006; Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008; Engle & Kane, 2004; Friedman et al., 2006; Kail & Salthouse, 1994; Kane, Hambrick, & Conway, 2005; Kyllonen & Christal, 1990; Oberauer, Schulze, Wilhelm, & Süb, 2005; Oberauer, Süb, Schulze, Wilhelm, & Wittmann, 2000; Salthouse, 1996; Schweizer, Moosbrugger, & Goldhammer, 2005; Unsworth & Engle, 2007). These tasks demand cognitive processes thought to underlie intelligence differences, such as apprehension, discrimination or choice among stimuli, visual search, scanning of short-term memory, or retrieval of information from long-term memory. Speed of information processing and the capacity of working memory for short-term storage have been proposed as key cognitive functions for intelligence (Burgaleta & Colom, 2008; Colom et al., 2008; Oberauer et al., 2000). Here we relate concurrently these functions to measures of fluid, crystallized and spatial intelligence.

Kyllonen and Christal (1990) proposed that working memory is central for information processing. The maximum amount of information that can be retained during short periods of time contributes to determine reasoning and problem solving (Colom et al., 2005a; Colom et al., 2005b; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, 2004; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001). However, individual differences in mental speed could limit working memory, because processing information takes time. Speedier processing increases the amount of information that can be processed per unit time.

A central focus of the present study is the distinction between *speed* and *efficiency* of information processing (Jensen, 1998, 2006). The latter reflects the *consistency of information processing*. Speed is usually measured by reaction time (RT), whereas efficiency is measured by the standard deviation of RT over *n* trials (RTSD).

Processing efficiency has been thought to reflect neural noise. This view is based on the fact that the excitatory potential of neurons shows a periodicity. Speed of communication among groups of neurons depends on (a) conduction speed and (b) the probability of impulses delay as a consequence of the oscillation of the neurons excitatory potentials. The probability of stimulus propagation

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varies depending on whether the potentials are above or below the excitability threshold. This is the rule: the faster the oscillation, the shorter is the average difference in time between the quickest and slowest reactions (Jensen, 1998, 2006).

This neural oscillation model has been supported by the observation of reliable individual differences in RTSD (Fairbank, Tirre, & Anderson, 1991; Jensen, 1992), latency of evoked potential (Callaway, 1979), and neural conduction velocity (Barrett, Daum, & Eysenck, 1990). Neural oscillation is also termed "neural noise" reflecting bad (noisy) transmission among groups of neurons, reducing their efficiency of communication (RTSD), and increasing transmission time (RT).

1.1. Intelligence factors

Fluid intelligence (Gf) has been defined as "the expression of the level of complexity of relationships which an individual can perceive and act upon when he does not have recourse to answers to such complex issues already stored in memory" (Cattell, 1971, p. 99). Gf is measured by tests that have little cultural content (abstract tests such as the Progressive Matrices Test or verbal tests that depend on figuring out the relationships between certain words when the meanings of all the words themselves are highly familiar).

Crystallized intelligence (Gc) is defined by problems making use of scholastic types of knowledge and skills, such as reading or arithmetic. Therefore, Gc is measured by tests having a significant cultural content.

Finally, spatial intelligence (Gv) is defined as "the ability to generate, retain, and manipulate abstract visual images (...) spatial thinking requires the ability to encode, remember, transform, and match spatial stimuli" (Lohman, 1979, p. 126).

There is ample evidence showing that Gf is biologically rooted, whereas Gc and Gv result from the cultural investment of the former. These are two instances: (a) Bigler, Johnson, Jackson, and Blatter (1995) have shown that changes in total brain volume along the life span parallel those observed for Gf, but not for Gc; (b) Gong et al. (2005) observed positive correlations between gray matter concentrations in the medial region of the prefrontal cortex and Gf, but measures of Gc did not show significant correlations with regional brain volumes.

1.2. The present study

Because (a) fluid, crystallized and spatial intelligence are highly related, and (b) fluid intelligence is frequently equal to the general factor of intelligence (g) (Carroll, 2003; Gustafsson, 1988) we employed here the operational approach reported by Colom et al. (in press) based on computing independent scores for Gf, Gc and Gv. Note that this approach must produce correlations between Gf and all the intelligence measures (this would happen if Gf = g), while Gc and Gv must be mainly related to their respective measures (Gc-residual and Gv-residual).

Once orthogonal scores for these three intelligence factors are obtained, the first hypothesis of the present study can be tested: if processing efficiency, as measured by RTSD, is an appropriate proxy behavioural estimate of neural noise (Jensen, 2006), then individual differences in RTSD would predict fluid (Gf), but not crystallized (Gc-r) and spatial (Gv-r) intelligence.

The second hypothesis states that if working memory capacity (WMC) and the general factor of intelligence (g = Gf) are highly correlated constructs (Colom & Shih, 2004; Colom et al., 2004; Colom et al., 2005a), then WMC would predict fluid intelligence, but not crystallized and spatial intelligence (with their g/Gf component removed).

2. Method

2.1. Participants

Two hundred and sixty-five university undergraduates took part in the study. 82% were females. Their mean age was 20.1 (SD = 3.5). They participated to fulfil a course requirement.

2.2. Measures

2.2.1. Intelligence Tests

Gf was measured by the advanced progressive matrices test (APM, even numbered items), the inductive reasoning subtest (*R*) from the Primary Mental Abilities (PMA) Battery, and the abstract reasoning (AR) subtest from the differential aptitude test (DAT-5) Battery (even numbered items).

The APM comprises a matrix figure with three rows and three columns with the lower right hand entry missing. Participants must choose, among eight alternatives, the one completing the 3×3 matrix figure. The score is the total number of correct responses.

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

PMA-R comprises 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.

Gc was measured by the verbal reasoning (VR) and the numerical reasoning (NR) subtests from the DAT-5 (even numbered items), as well as by the vocabulary (V) subtest from the PMA.

DAT-VR is a verbal reasoning test. A given sentence stated like an analogy must be completed. The first and last words from the sentence are missing, so a pair of words must be selected to complete the sentence from five possible alternative pairs of words. For instance: *... is to water like eating is to .... (A) Travelling-Driving, (B) Foot-Enemy, (C) Drinking-Bread, (D) Girl-Industry, (E) Drinking-Enemy*. Only one alternative is correct. The score is the total number of correct responses.

DAT-NR consists of quantitative reasoning problems. For instance:
Which number must be substituted by the letter P if the sum is correct?

5P + 2 = 58

$$5P + 2 = 58$$

(A) 3, (B) 4, (C) 7, (D) 9, (E) None of them

The score is the total number of correct responses.

PMA-V is a synonym test. The meaning of four alternative words must be evaluated against a given word that serves as model. For instance, *STOUT: Sick-Fat-Short-Rude*. Only one alternative is correct. The score is the total number of correct responses.

Gv was measured by the rotation of solid figures test, the mental rotation (S) subtest from the PMA, and the spatial relations (SR) subtest from the DAT-5 (even numbered items).

In the rotation of solid figures test each item includes a model figure and five alternatives must be evaluated against it. The participant must evaluate which alternative can be rotated within a 3D space to fit the model figure. Only one alternative is correct. The score is the total number of correct responses.

On the PMA-S each item includes a model figure and six alternatives must be evaluated against it. Some alternatives are simply rotated versions of the model figure, whereas the remaining figures are mirror imaged. Only the rotated figures must be selected. Several alternatives could be correct for each item. The score is the total number of correct responses (appropriately selected figures – simply rotated) minus the total number of incorrect responses (inappropriately selected figures – mirror imaged).

DAT-SR is a mental folding test. Each item is composed by an unfolded figure and four folded alternatives. The unfolded figure is shown at the left, whereas figures at the right depict folded versions. Participants are asked to choose one folded figure matching the unfolded figure at the left. The score is the total number of correct responses (well chosen folded figures).

2.2.2. Working memory tasks

The reading span task was modelled after Kane et al. (2004). Participants verified which discrete sentences, presented in a sequence, did or did not make sense. Sentences were adapted from the Spanish standardization of the Daneman and Carpenter's (1980) reading span test (Elosúa, Gutiérrez, García-Madruga, Luque, & Gárate, 1996). Each display included a sentence and a to-be remembered unrelated capital letter. Sentences were 10–15 words long. As soon as the sentence-letter pair appeared, participants verified whether it did or did not make sense (it did half the time) reading the capital letter for latter recall. Once the sentence was verified by pressing the answer buttons (yes/1-no/2) the next sentence-letter pair was presented. At the end of a given set, participants recalled, in their correct serial order, each letter from the set. Set sizes of the experimental trials ranged from 3 to 6 sentence/letter pairs per trial, for a total of 12 trials (4 levels × 3 trial = 12 trials total). The score was the number of correct answers in the verification and recalling tasks.

The computation span task included a verification task and a recall task. Six seconds were allowed to see a math equation (but no time limit was set to verify its accuracy) like (10/2) + 4 = 8, and the displayed solution, irrespective of its accuracy, must be remembered (Ackerman et al., 2002). After the final equation of the trial was displayed, the solutions from the equations must be reproduced in their correct serial order. Each math equation included two operations using digits from 1 to 10. The solutions were single-digit numbers. The experimental trials ranged from three to seven equation/solutions (5 levels × 3 trials each = 15 trials total). The score was the number of correct answers in the verification and recalling tasks.

The dot matrix task was modelled after Miyake et al. (2001). A matrix equation must be verified and then a dot location displayed in a 5 × 5 grid must be retained. The matrix equation required adding or subtracting simple line drawings and it was presented for a maximum of 4.5 s. Once the response was delivered, the computer displayed the grid for 1.5 s. After a given sequence of equation-grid pairs, the grid spaces that contained dots must be recalled clicking with the mouse on an empty grid. The experimental trials increased in size from two to five equations and dots (4 levels × 3 trials = 12 trials total). The score was the number of correct answers in the verification and recalling tasks.

2.2.3. Speed tasks

On the speed task items (letters, numbers or arrows) were sequentially displayed for 650 ms. each. Those items defined a memory set comprised by one or two uppercase and lowercase letters (verbal), numbers, or arrows (displayed in one of seven orientations, multiples of 45°). After the last displayed item, a fixation point appeared for 500 ms. Finally, the probe item appeared in order to decide, as quickly and accurately as possible, if it had the same meaning as one of the letters presented within the memory set (verbal; note that their physical appearance – uppercase or lowercase – must be ignored), can be divided by one of the digits presented within the memory set (numerical), or had the same orientation as one of the arrows presented within the memory set (spatial; note that the arrows have distinguishable shapes in order to guarantee that their orientation is both memorized and evaluated). Half of the trials requested a positive answer. The experimental trials ranged from one to two items (2 levels × 30 trials each = 60 trials total). For these speed tasks, the obtained scores were: mean accuracy, mean RT, and mean RTSD for the correct answers only.

In the working memory and speed tasks, participants completed a set of three practice trials as many times as desired to ensure they understood the instructions.

2.3. Procedure

Testing took place in three sessions. The first and second sessions were dedicated to intelligence testing, whereas the third session was dedicated to the computerized working memory and speed tasks. The tests and tasks were administered in groups of no more than 20 participants. Each session lasted for approximately 45 min.

3. Results

Table 1 shows the descriptive statistics along with the zero-order correlations.

Firstly, the intelligence tests were submitted to a confirmatory factor analysis (CFA) to test the measurement model: three primary factors for Gf, Gc and Gv were defined by their respective tests. Further, a higher order factor representing general intelligence (*g*) was defined. The fit for this model was appropriate: $\chi^2_{(24)} = 55.7$, $\chi^2/df = 2.3$, CFI = .95, RMSEA = .071. Fig. 1 depicts the results. Note that Gf was the first-order factor best predicted by the higher order factor (*g*).

Secondly, standardized scores (*z*) for the intelligence tests were used to compute averages for Gf, Gc and Gv. A regression analysis was then computed using Gf as predictor, whereas Gc and Gv were the dependent scores. Gc and Gv variance unpredicted by Gf defined crystallized and spatial residual scores. This procedure resulted in three orthogonal scores for Gf, crystallized (Gc-r), and spatial intelligence (Gv-r). As Table 2 shows, Gf was related to all the measures, while Gc-r and Gv-r were mainly related to their respective measures.

Thirdly, standardized scores (*z*) for working memory, processing speed and processing efficiency measures were used to compute averages for WMC, speed and efficiency. These scores were used to predict Gf, as well as crystallized and spatial intelligence both without and with Gf statistically removed (Gc, Gc-r, Gv, and Gv-r). Beta (β) values are shown in Table 3.

The results indicate that WMC predicts Gf, as well as Gc and Gv when their Gf component is not removed. However, WMC no longer predicts these latter scores when Gf is removed (Gc-r and Gv-r).

Further, processing efficiency predicts Gf only, whereas processing speed (a) predicts Gc and Gv irrespective of the removal of Gf, and (b) does not predict Gf.

4. Discussion

4.1. Summary of findings

This study postulated two straightforward hypotheses and both proved to be highly consistent with the findings. First, the

Table 1
Descriptive statistics and correlation matrix*.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. Raven																		
2. PMA-R	.281																	
3. DAT-AR	.507	.468																
4. PMA-V	.218	.316	.341															
5. DAT-VR	.331	.243	.423	.330														
6. DAT-NR	.310	.347	.382	.349	.341													
7. Solid Fig.	.367	.296	.49	.302	.371	.297												
8. PMA-S	.266	.282	.461	.333	.333	.204	.578											
9. DAT-SR	.439	.411	.537	.171	.362	.348	.571	.429										
10. Verbal-RT	−.115	−.240	−.181	−.191	−.127	−.134	−.237	−.262	−.208									
11. Verbal-RTSD	−.144	−.203	−.153	−.093	−.190	−.029	−.211	−.200	−.134	.715								
12. Num-RT	−.214	−.187	−.276	−.313	−.148	−.478	−.243	−.213	−.302	.516	.194							
13. Num-RTSD	−.269	−.119	−.279	−.284	−.206	−.428	−.244	−.149	−.288	.342	.138	.851						
14. Spatial-RT	−.170	−.202	−.224	−.290	−.065	−.180	−.260	−.269	−.195	.665	.306	.646	.440					
15. Spatial-RTSD	−.184	−.207	−.211	−.186	−.039	−.110	−.210	−.180	−.221	.403	.211	.396	.335	.657				
16. Reading span	.204	.171	.277	.111	.320	.123	.219	.176	.129	.035	−.035	.055	.007	.053	.046			
17. Computation span	.311	.255	.373	.169	.229	.420	.248	.240	.214	−.084	−.050	−.241	−.280	−.122	−.114	.355		
18. Dot matrix	.340	.309	.455	.192	.244	.248	.316	.307	.384	−.220	−.163	−.254	−.201	−.236	−.260	.276	.394	
MEAN	10.9	18.5	12.7	30.6	12.7	10.5	7.5	24.9	14.5	650.7	260.3	985.1	473.1	666.6	214.4	97.4	18.4	54.3
SD	2.5	4.7	3.8	6.6	3.1	3.5	3.8	10.4	4.8	171.7	248.8	308.5	265.1	158.0	122.1	7.3	5.3	5.4

* r below .122 are not significant; r between .122 and .153 are significant at $p < .05$; r above .153 are significant at $p < .01$.

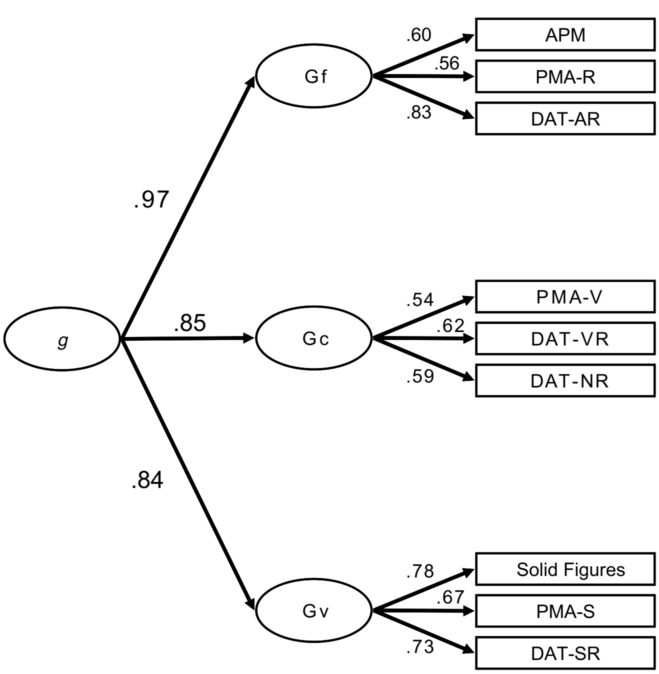

Fig. 1. CFA model for the intelligence measures.

Table 2
Correlations among constructs and measures.

	Gf	Gc-residual	Gv-residual
APM	.760**	−045	−.040
PMA-R	.746**	−.009	−.071
DAT-AR	.841**	.054	.111
PMA-V	.373**	.651**	.125**
DAT-VR	.424**	.604**	.216**
DAT-NR	.443**	.616**	.091
Solid Figures	.492**	.192**	.718**
PMA-S	.430**	.178**	.691**
DAT-SR	.591**	.079	.559**

** $p < .01$.

Table 3
Standardized beta (β) values.

Intelligence	Standardized β values		
	WMC	Speed (mean RT)	Efficiency (mean SDRT)
Gf	.45**	−.03	−.26**
Gc	.36**	−.27**	−.10
Gc-r	.12	−.20**	.00
Gv	.35**	−.28**	−.14
Gv-r	.08	−.20**	−.02

** $p < .01$.

regression analyses showed that processing efficiency predicts fluid intelligence only. This is the expected result if processing efficiency indexes the brain property usually termed "neural noise". Fluid, but not crystallized and spatial intelligence is biologically rooted, as noted by Vernon, Wickett, Bazana, and Stelmack (2000): "*brain volume correlates most highly with g, fluid abilities, and memory but less (and not significantly) with crystallized ability (...) the more g-loaded, fluid ability-loaded, or memory loaded a test, the higher its correlation with brain volume, but the more spatially loaded a test, the lower its correlations with brain volume*" (p. 249).

Second, WMC was the best predictor of fluid, crystallized, and spatial intelligence. Importantly, this was only true when the *g/Gf* component of Gc and Gv was not removed. However, when Gc-r and Gv-r were entered into the regression analyses, they were no longer predicted by WMC.

Third, processing speed was a significant predictor of crystallized and spatial intelligence, regardless of the removal of their *g*-component. This finding suggests, but do not prove, that processing speed per se is not a core component underlying individual differences in general intelligence (*g* = Gf).

Therefore, the observed empirical evidence is consistent with the statement that both working memory and processing efficiency predict fluid intelligence, whereas they do not predict crystallized and spatial intelligence with their *g*/Gf component removed. Moreover, the speed component of reaction time tasks does not predict fluid intelligence, whereas it predicts crystallized and spatial intelligence.

4.2. Neural noise and working memory capacity

What is neural noise? Neurons can be described as oscillators in which the voltage across the cell membrane changes according to two processes: (1) the fast action potential (or spike), and (2) the slower-varying post-synaptic potential (FitzHugh, 1961).

Ward (2003) has suggested that neural oscillations are closely related to basic cognitive processes. These processes arise from the synchronous activity of neurons in the brain. Moreover, certain cognitive processes correspond to specific oscillations: (1) theta and gamma rhythms are related to encoding and retrieval, (2) alpha and gamma rhythms are related to attentional suppression and focusing, and (3) global synchronization at the gamma frequency is related to consciousness and awareness.

Lisman and Idiart (1995) have related neural oscillations to memory processes (Almeida & Idiart, 2002; Clayton & Frey, 1997). Their model postulates a connection between theta and gamma oscillations produced from the neural basis of memory span tasks (e.g. short-term and working memory tasks). Memory items are stored in groups of pyramidal neurons firing in synchrony. This firing dissipates with time, thus requiring refreshing processes. The individual items are refreshed at the gamma frequency, whereas the overall refresh cycle is repeated at the theta frequency.

If items are refreshed at the gamma rate once per theta cycle, then the number of items that can be held in short-term memory corresponds to the gamma frequency divided by the theta frequency (40/6 = 7) without experiencing a significant loss (Ward, 2003). This model may account for variations in working memory capacity: theta ranges from 3.5 to 7 Hz, whereas gamma ranges from 30 to 70 Hz. These values translate to capacities ranging from 4 to 20 items.

These suggestions can be associated with the neural noise hypothesis regarding the biological base of cognitive functions such as working memory (Colom, Jung, & Haier, 2007). Individual differences in theta and gamma may underlie processing efficiency as indexed by RTSD. The findings reported in this article have shown that the biologically rooted intelligence factor (Gf) is the only one predicted by RTSD. Therefore, participants with higher levels of fluid intelligence show cognitive patterns reflecting less neural noise-oscillations and more processing efficiency and working memory capacity.

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