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Cognitive Predictors of 5-Year-Old Students' Early Number Sense

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Abstract

Early numeracy skills can be predicted from several higher cognitive processes at early ages. Therefore, both a cognitive assessment and an early mathematics test were administered to 208 preschool participants, in order to explain the potential predictive role of higher cognitive processes in mathematics performance. Results from stepwise multiple linear regression analysis showed that the variance in the early numeracy skills scores could be partially explained by the following cognitive variables introduced to the explanatory model: emergent literacy, intelligence, working memory, verbal short-term memory, and one of the two inhibitory capacity measurements used in the study.

Keywords: Mathematical cognition, early mathematics, preschool education.

Resumen

Las habilidades numéricas pueden predecirse a través de la presencia de determinados procesos cognitivos superiores en edades tempranas. Para ello, se realizó a 208 participantes de Educación Infantil una valoración cognitiva paralela a la evaluación matemática, con el fin de constatar el posible papel predictor de los procesos cognitivos en el desempeño matemático. Los resultados del análisis de regresión lineal múltiple mostraron que las habilidades numéricas pudieron ser explicadas parcialmente por las siguientes variables cognitivas introducidas en el modelo: la medida de la alfabetización emergente, inteligencia, memoria de trabajo y a corto plazo verbal, y una de las dos medidas de inhibición empleadas.

Palabras clave: Cognición matemática, matemática temprana, educación infantil.

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Introduction

Nowadays, efforts are directed towards determining the cognitive components that can play a relevant role in the acquisition and development of mathematical skills (Miñano & Castejón, 2011; Navarro, Aguilar, Marchena, Ruiz, & Ramiro, 2011). This research topic is relevant because it can provide a basis for recognizing students that are at risk of presenting learning difficulties (Duncan et al., 2007; González-Castro, Rodríguez, Cueli, Cabeza, & Álvarez, 2014). This research also facilitates the application of intervention programs designed to rehabilitate and strengthen mathematical abilities.

We can mention two categories of predictors, which are both differentiated and related: domain-general abilities and domain-specific abilities (Passolunghi & Lanfranchi, 2012). The concept of domain-general predictor is concerning to general cognitive abilities that can predict performance on different school subjects and not just on one specific subject. Among these, we can mention the predictive role of working memory, short-term memory, intelligence and processing speed (Bull, Espy, & Wiebe, 2008; Navarro et al., 2011). On the other hand, the concept of domain-specific predictor is used to refer abilities that are capable of predicting later performance on a particular area, which is mathematics in this case. Examples of these types of predictors are skills related to the acquisition of number sense (De Smedt et al., 2009).

In recent years, researchers have studied the relevance of working memory in the development of basic school competencies (Alloway & Passolunghi, 2011; Engel de Abreu, & Gathercole, 2012). Specifically, research confirms the role that different components of working memory have as predictors of early school mathematical learning (Passolunghi & Lanfranchi, 2012). Among the multiple components of the working memory model redesigned by Baddeley (2000), the Central Executive stands out. This component is responsible for attentional resources that are the basis for the processing of complex tasks (Alloway, Gathercole, & Pickering, 2006). Research provides strong evidence involving the Central Executive in the solving of arithmetic problems (Passolunghi & Pazzaglia, 2004, 2005). Likewise, it also confirms the relationship between numeracy skills and executive functions in preschool students (Kolkman, Hoijtink, Kroesbergen, & Leseman, 2013) and primary school students (Andersson & Lyxell, 2007). In relation to the link between mathematical competencies and nonverbal intelligence, recent research confirm the existence of such relationship, in the sense that students with higher intelligence also had a better performance on symbolic and nonsymbolic number comparison tasks (Gullick, Sprute, & Temple, 2011;

Östergren & Träff, 2013). Finally, there is also research suggesting a link between emergent literacy and early number skills in preschool students (LeFèvre et al., 2010, 2013; Purpura, Hume, Sims, & Lonigan, 2011).

These recent studies on the topic lead to reflect upon the appropriateness of establishing a predicting cognitive profile in mathematical performance at an early age. This way, the level of a student in general predictor abilities can be of relevance when detecting and providing support for students showing a low-level of mathematical competencies. Therefore, in this present work we conducted an assessment of different factors that can influence early mathematical performance like: working memory, executive functions, short-term memory, intelligence and emergent literacy. In summary, the present work is focused on exploring a cognitive profile for students based on their early numeracy skills.

Method

Instruments

An assessment of early mathematical abilities and cognitive parameters was conducted.

Early Numeracy Test (ENT-R). A computer version of *ENT-R* (Van Luit & Van de Rijt, 2009) was used to measure early mathematical knowledge as well as to detect students with learning difficulties in Mathematics (MLD). This test is composed of three parallel versions of 45 items each; each version of the test has a maximum score of 45 points (1 point for each correct item). *ENT-R* average test application time is about 30 minutes and it must be individually administered. This test assesses 9 components of Early Mathematical Competencies: comparison concepts, classification, one-to-one correspondence, seriation, verbal counting, structured counting and resultative counting (counting without the need to point or touch), general number knowledge and estimation. The Cronbach's alpha was .90.

Get Ready to Read! Screening Tool (GRTR). Whitehurst and Lonigan (2003) created this test to assess emergent literacy. On the one hand, this test assesses phonological awareness by means of items related to the knowledge of sounds associated to letters, rhymes and word segmentation. On the other hand, the test assesses the knowledge of written text by means of activities based on the comprehension and discrimination of letters and written words. This test is composed of 20 items and the test-taker must choose the option that he or she believes to be correct among the given options. For this present research work, the computer version of this test was used. During the computer test version, the child receives instructions from the proctor and signals one of the four possible answers available on the computer screen. The Cronbach's alpha was .78.

Raven's Colored Progressive Matrices Test (Raven). The color version of this classic test (Raven, 1996) was used. It was used to obtain a measure of the *g* factor of intelligence, regardless of cultural influence. The Raven test involves establishing logical relationships between a figure that is missing an element and the possible elements that may complete the pattern of the figure. Therefore, it places emphasis on the ability of making sense of disorganized or confusing material by managing non-verbal constructs, which allow the comprehension of a complex structure. The Cronbach's alpha was .82.

Digit span. WISC IV digit span subtest (Wechsler, 2005) is composed of two sections: the digit forward section and the digit backward section. During the digit forward section, the psychologist mentions a series of numbers that the participant must repeat in the same order that was verbalized. This is an adequate measurement of phonological short-time memory, because the sequence is stored without any manipulations and the subject is requested to repeat it exactly as said by the administrator. This section is different from the backward section, which assesses verbal working memory by means of requiring the subject to use stored information. Each section of this subtest is composed of 8 elements, and two attempts are allowed for each element. The Cronbach's alpha coefficient was .78 for digit forward tasks and .76 for digit backward tasks.

Animal Stroop (Van der Ven, Kroesbergen, Boom, & Leseman, 2012). It is based on the Stroop effect of interference and it assesses the inhibitory control capacity for processing information. During this task, animal drawings are presented to test-takers; these drawings are composed of the body of one animal and the head of a different animal. The student must name the animal corresponding to the body (not to the face), inhibiting the automatic response of naming the animal corresponding to the head (independently of the body the animal has). It is composed of 48 control items and 48 stroop items. The Cronbach's alpha was .96.

Simon task. The objective of the Simon task (Van der Ven et al., 2012) is to assess the inhibitory capacity of the natural tendency to push a button placed where the stimulus is presented. We used an adaptation of this test, in which the test-taker had to press a button located on the far left of an RB-730 keyboard at the sight of a mouse and, when seeing a dragon, a button located on the far right of the keyboard. During the control condition, the characters appeared in the center of the screen, and during the inhibition condition, the characters appeared on the sides of the screen. The test was composed of 40 items on each of the stages (control and inhibition). The Cronbach's alpha was .94.

Animal Shifting. We used an adaptation to Spanish of the test Animal Shifting (Van der Ven et al., 2012). This test is based on the task Symbol Shifting, which was created by Van der Slüis, De Jong and Van der Leij (2007) to assess attentional flexibility. During this task, two images are presented (an animal and a piece of fruit) at the same time in a computer screen. During the shifting task, the participant has to name only one of the images, according to background color. During the control section, only one image is shown and the participant must name the image. The test is composed of 40 control items and 40 shifting items. The Cronbach's alpha was .93.

Participants

Students belonged to four schools: two private and two public schools, with a middle-class socioeconomic status. Participant selection was done intentionally at schools that collaborate with educational research tasks. The total number of participants was of 208 students belonging to the last course of preschool education. Their ages ranged from 4.92 to 6 years, with a median of 5.45 years of age and a standard deviation of .29. From the total of the sample, 100 participants were girls and their ages ranged from 4.92 to 5.92 years of age (M = 5.44; SD = .29). The total number of male participants was of 108 and their ages ranged from 4.92 to 6 years of age (M = 5.46; SD = .30).

Procedure

The authors conducted two assessment sessions. During the first one, emergent literacy and early mathematical skills were assessed. During the second one, the rest of the cognitive tests were administered under appropriated assessing conditions. The test was administered individually and each individual session took around 30 to 35 minutes; test administration order was random, both for intersessions and intrasessions. Informed consent was obtained both from the student's parents and teachers.

Results

Since our goal was to find the predictive value of cognitive variables in respect to early numeracy abilities, fulfillment of normality requirements (Kolmogorov-Smirnov test = .71; $p > .01$) and homoscedasticity (Levene's test = 3.32; $p > .01$) were calculated. Asymmetry and kurtosis of the dependent variable were also calculated ($g^1 = .28$; $g^2 = –35$) and they ratified the normality of the distribution. Result analysis was performed in two levels. On the one hand, by calculating the predictive value of cognitive variables regarding early numeracy abilities. On the other hand, a cognitive profile was established based on the level obtained on the ENT-R test.

Table 1

Stepwise Multiple Linear Regression Model

Model	*R*	R^2	Corrected R^2	Change statistics				Durbin Watson
				Estimation error	Change in R^2	Change in *F*	Significant. Change in *F*	
1	.539a	.291	.288	5.55	.291	84.53	.000	
2	.601b	.361	.355	5.28	.070	22.60	.000	
3	.631c	.398	.389	5.13	.037	12.53	.000	
4	.651d	.423	.412	5.04	.025	8.82	.003	
5	.659e	.435	.421	5.00	.011	4.09	.044	1.943

Note. (a) Predictor variables: (Constant), GRTR; (b) Predictor variables: (Constant), GRTR, Raven; (c) Predictor variables: (Constant), GRTR, Raven, Digit backward; (d) Predictor variables: (Constant), GRTR, Raven, Digit backward, Digit forward; (e) Predictor variables: (Constant), GRTR, Raven, Digit backward , Digit forward, Simon Task index; (f) Dependent variable: ENT-R.

Stepwise multiple linear regression was selected for multivariate analysis, in order to establish how specific variables considered in the literature as predictors or explanatory variables are related to the criterion variable.

According to the results shown in Table 1, five models emerged from the linear regression analysis; each one with its own explanatory capacity. Model 5 was the one that had the higher explanatory capacity. Therefore, 43.5% of vari-

Table 2

Multiple Linear Regression Model Coefficients

Model		Non-standardized coefficients		Typified coefficient	*t*	*Sig*	Collinearity statistics	
		B	Type error	*Beta*			Tolerance	VIF
5	(Constant)	–9.381	2.772		–3.384	.001		
	GRTR	.906	.160	.343	5.672	.000	.764	1.309
	Raven	.362	.097	.216	3.722	.000	.829	1.206
	Digit backward	.668	.237	.169	2.821	.005	.776	1.289
	Digit forward	.801	.264	.166	3.034	.003	.937	1.067
	Simon Index	.089	.044	.113	2.024	.044	.903	1.108

Note. GRTR = Get Ready to Read; VIF = Variance inflation factor.

ance in early mathematical abilities measurement can be explained in terms of the cognitive variables introduced to the model: emergent literacy, intelligence, working memory, short-time verbal memory and the effectiveness index on the Simon inhibition task. However, if we consider the number of subjects and the variables involved, 42.1% of the variance in early numeracy abilities could also be explained by the set of variables referred earlier.

Table 2 shows that *t* value probability of error was lower than .05 in the 5 variables included in the model. Likewise, standardized coefficients were obtained; the variables that showed more explanatory weight were: emergent literacy, intelligence, verbal working memory, short-term verbal memory and the effectiveness index on the Simon inhibition task. These coefficients ranked emergent literacy as the strongest predictor of early numeracy abilities along with intelligence level. The model also explained lower variance on the following variables: verbal working memory, verbal short-term memory and the measurement of the inhibition of the Central Executive assessed by the Simon task.

On the other hand, we can observe *t* test results and *t* test critical values, which were compared against the null hypothesis, which had a value equal to zero for the regression coefficient. According to the obtained results, it was assumed that the 5 analyzed variables supported the variance explanation of the dependent variable. The two remaining variables (Stroop Animal and Animal Shifting test efficiency index) were excluded.

In order to confirm the validity of the model, residual independence was analyzed. A value of $D = 1.943$ was obtained from the *D* Durbin-Watson statistic, confirming the absence of positive (values close to 0) and negative (values close to 4) autocorrelation. The absence of collinearity and, therefore, the stability of estimations, when obtaining high values of tolerance and low VIFs (Table 2), was also assumed.

On the other hand, in Table 3 we can appreciate how students that had better results in ENT-R also had a better performance in the rest of the analyzed variables. Likewise, with the exception of the shifting ability measurement, the students with lowest scores in ENT-R also obtained the worst results on the other tested variables.

In *post-hoc* comparisons (Table 4), all groups differed significantly in the measurements of emergent literacy, intelligence, verbal working memory and Stroop inhibition task ($p < .05$). However, in the measurements of short-term memory and the Simon inhibition task, no significant differences in mathematics performance were found between the medium and low-level groups. Finally, on the shifting task the differences were significant ($p < .05$) just between the medium-level and

Table 3

Administered Tests Means and Standard Deviations according to Early Numeracy Skills Level

		GRTR	Raven	Digit backward	Digit forward	Simon task	Animal Stroop	Animal Shifting
Low	*M*	15.10	13.90	2.64	5.38	27.58	14.74	6.19
n = 58	*(SD)*	(2.77)	(3.69)	(1.85)	(1.21)	(11.02)	(6.86)	(5.36)
Medium	*M*	16.56	15.66	3.99	5.45	30.54	17.35	5.33
n = 97	*(SD)*	(2.24)	(3.37)	(1.37)	(1.28)	(6.26)	(5.43)	(5.53)
High	*M*	18.25	18.23	4.58	6.32	33.61	20.91	7.90
n = 53	*(SD)*	(1.32)	(3.92)	(1.27)	(1.45)	(7.11)	(4.36)	(6.41)
Total	*M*	16.58	15.82	3.76	5.65	30.50	17.53	6.22
N = 208	*(SD)*	(2.49)	(3.93)	(1.66)	(1.36)	(8.32)	(6.04)	(5.79)

Note. GRTR = Get Ready to Read.

Table 4

Post-hoc Comparisons Between the Three Groups according to their Performance on ENT-R

(I)	(J)		GRTR	Raven	Digit backward	Digit forward	Simon task	Animal Stroop	Animal Shifting
Low	Medium	I-J	–1.45*	–1.76*	–1.35*	–.074	–2.95	–2.60*	.85
		d	–.58	–.50	–.83	–.06	–.33	–.40	.15
		r	–.28	–.24	–.38	–.03	–.17	–.20	.07
	High	I-J	–3.14*	–4.33*	–1.94*	–.94*	–6.03*	–6.16*	–1.71
		d	–1.45	–1.14	–1.22	–.70	–.65	–1.07	–.29
		r	–.59	–.49	–.52	–.32	–.31	–.47	–.14
Medium	Low	I-J	1.45*	1.76*	1.35*	.074	2.95	2.60*	–.85
		d	.58	.50	.83	.06	.33	.40	–.15
		r	.28	.24	.38	.03	.17	.20	–.07
	High	I-J	–1.68*	–2.56*	–.59*	–.86*	–3.07*	–3.56*	–2.57*
		d	–.91	–.70	–.45	–.64	–.46	–.72	–.43
		r	–.42	–.33	–.22	–.30	–.22	–.34	–.21
High	Low	I-J	3.14*	4.33*	1.94*	.94*	6.03*	6.16*	1.71
		d	1.45	1.14	1.22	.70	.65	1.07	.29
		r	.59	.49	.52	.32	.31	.47	.14
	Medium	I-J	1.68*	2.56*	.59*	.86*	3.07*	3.56*	2.57*
		d	.91	.70	.45	.64	.46	.72	.43
		r	.42	.33	.22	.30	.22	.34	.21

$^*p < .05$. GRTR = Get Ready to Read.

high-level performance groups, favoring the high performance group.

Discussion

This work attempted to find out the predictive value of a series of cognitive variables in early numeric abilities. This was done to establish a profile of 5-year-old students, according to ENT-R scores. Different researches have taken a deeper look at the aspects that suggest a link between linguistic competencies and early mathematics (Krajewski & Schneider, 2009; LeFèvre et al., 2010, 2013; Purpura et al., 2011). In this specific research, the possible existence of a synchronic relationship between linguistic competencies and early mathematics at the beginning of the last year of preschool education was analyzed and a strong relationship between these two variables was found. Along the same research line, Krajewski et al. (2009) found that 34% of the differences in mathematics at the age of 5 were explained by means of early linguistic abilities. Likewise, a favorable predictive relationship between emergent literacy and early numeracy skills was found; these findings are also supported by previous studies (Simmons, Singleton, & Horne, 2008). It is worth mentioning that in the work of Krajewski et al. (2009), the predictive role diminishes with the development and acquisition of more complex arithmetic competencies. It seems that early linguistic abilities contribute positively to the development of early mathematical competencies, but become less relevant throughout the schooling process. This aspect can help us understand the existence of contradictory results in the study of the predictive role of emergent literacy on arithmetic performance. Other works did not confirm this predictive relationship (Fuchs et al., 2006).

On the other hand, specialized literature determines, in line with the results of this work, an existing relationship between non-verbal intelligence and numeracy abilities (Östergren et al., 2013). Some researches underlined the predictive role of intelligence in mathematics performance (Lu, Weber, Spinath, & Shi, 2011). Other considered it a causal factor in academic performance and regard it as the factor responsible for individual differences among students (Kvist & Gustafsson, 2008). A close relationship between intelligence and working memory was also observed. Therefore, a combination of both these variables can help us make a more complete prediction of mathematics success (Gullick et al., 2011).

Working memory is also linked to short-term memory. But, separately from working memory, verbal short-time memory contributes to the acquisition of academic abilities, like mathematics and reading (Gathercole, Alloway, Willis, & Adams, 2006; Swanson & Jerman, 2007). Some studies have highlighted its relevance in maintaining temporary results, which would explain the differences found in mathematics problem solving attributed to phonological system difficulties (Gathercole et al., 2004). For example, Bull et al. (2008) found that children with better verbal short-time memory also showed better performance in mathematics.

Also, several research provided evidence of relationship at the beginning of schooling between working memory and different academic abilities, like mathematics (Alloway & Alloway, 2010). Or, vice-versa, children that show difficulties in mathematics learning showed low performance on working memory (Passolunghi & Siegel, 2004).

Abilities related to language, like phonological awareness, vocabulary and verbal working memory are able to predict mathematical results (LeFèvre et al., 2010, 2013; Östergren et al., 2013). In our case, verbal working memory showed some impact on numeracy abilities in 5-year-olds. But, unlike other studies, in which verbal working memory is regarded as the main predictor for early mathematics performance (Rasmussen & Bisanz, 2005), the relationship was not as strong in this research. This can be due to the type of instrument used to measure working memory. According to Pickering (2011), one could expect a higher impact of visuo-spatial working memory over verbal working memory at the age of 5, due to model of mathematical representation and of information coding at preschool ages.

Likewise, many studies report a direct association between the executive function and mathematics both at early years (when school abilities are at an emergent state) as well as later (Gathercole et al., 2004). Results show that at preschool level inhibition abilities are predictive of mathematics performance (Espy et al., 2004). And that later, at the age of 7, shifting capacity plays a predictor role in mathematics along with inhibition ability (Bull & Scerif, 2001). However, as age progresses (10-11 years), this relationship becomes less clear (Navarro et al., 2011; St. Clair-Thompson & Gathercole, 2006). There is evidence that the first component to develop is inhibition (Senn, Espy, & Kaufmann, 2004), which plays a relevant role in the first years. It seems that performing shifting tasks correctly demands earlier capacity of inhibition, which constitutes a step further in the development of executive dimensions (Best, Miller, & Jones, 2009).

The results presented are along the same lines. Regression analysis excluded the measurement of the shifting capacity at 5 years of age. However, one of the two measurements used for the assessment of inhibitory processes was added to the explanatory model of the variance of mathematics performance. Like this present study, other studies did not find a relationship between shifting and different mathematics aspects (Bull et al., 2008; St. Clair-Thompson et al., 2006). However, there are works that confirm this relationship (Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Yeniad, Malda, Mesman, van Ijzendoorn, & Pieper, 2012).

In conclusion, according to this study, the cognitive profile of skillful students in early mathematics would be one that includes a good level of emergent literacy, working memory and general intelligence, as well as an adequate inhibition control capacity of irrelevant information. This type of cognitive profile could help in the development of early mathematics teaching methods. Future research should examine if the different cognitive variables that outline the mental capacities associated with mathematical competencies are maintained in time and are also efficient in the performance of other type of mathematical activities, like problem resolution and complex arithmetic calculation.

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