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Updating executive function and performance in reading comprehension and problem solving

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Título: La función ejecutiva de actualización y el rendimiento en comprensión lectora y resolución de problemas.
Resumen: Esta investigación analizó, en niños de 5º curso de Educación Primaria, la capacidad predictora de la función ejecutiva de actualización de la Memoria Operativa (MO) en las diferencias individuales en comprensión lectora y resolución de problemas aritméticos. Además, se estudió si esta relación es directa o está mediada por variables de dominio general o específico. Con este fin se administró un conjunto de pruebas que evalúan la inteligencia fluida, la actualización de la información en la MO, la competencia aritmética, la resolución de problemas aritméticos, el procesamiento léxico y la comprensión lectora a 49 alumnos con edades comprendidas entre los 10 y 11 años. Los resultados apoyan la idea que la actualización de la MO es un importante predictor de la comprensión lectora, más allá de la influencia de las habilidades de dominio específico y de la inteligencia fluida. En el caso de la resolución de problemas, nuestros hallazgos confirman que la actualización juega un papel importante aunque, en este momento evolutivo, quizá por el propio contenido de la tarea, la relación parece mediada por la inteligencia fluida.
Palabras clave: Comprensión lectora; resolución de problemas; funcionamiento ejecutivo; actualización; habilidades de dominio específico; inteligencia fluida.

Abstract: In this investigation, the capacity of the working memory (WM) updating executive function to predict individual differences in reading comprehension and problem solving was analyzed in 5th-graders of Primary Education. In addition, we examined whether this relation is direct or mediated by domain-general or domain-specific variables. For this purpose, a series of tasks was administered to assess fluid intelligence, WM information updating, arithmetic abilities, arithmetic problem solving, lexical processing, and reading comprehension in 49 students aged between 10 and 11 years. The results support the idea that updating is an important predictor of reading comprehension, beyond the influence of domain-specific skills and fluid intelligence. In the case of problem solving, our findings confirm that updating plays an important role although, perhaps due to task content, the relation seems to be mediated by fluid intelligence at this developmental stage..
Key words: Reading comprehension; problem solving; executive functioning; updating; domain-specific skills; fluid intelligence.

Introduction

When focusing on the analysis of academic achievement in the areas of reading and mathematics, various problems have emerged, for instance, the complexity of the areas. For example, the mathematics curriculum includes such diverse aspects as arithmetic, algebra, trigonometry, or geometry. For each one of these large areas, students must master different abilities, and instruction must include all of them, which denotes the breadth and complexity of the problem. However, it is currently unclear which factors make learning difficulties more or less severe, which cognitive processes mediate the different aspects of academic achievement in reading and mathematics, and how they are related to each other. All these factors, in addition to the heterogeneity of the tests used to measure the cognitive processes involved and the lack of a globally accepted theoretical approach, frequently hinder the utilization and generalization of the results obtained.

One of aspects of the debate refers to the cognitive processes underlying academic achievement. The literature indicates that curricular achievement in mathematics and reading is related to what Tymms (1999) calls "*general developed abilities*." These imply the mastery of domain-specific skills such as phoneme-grapheme conversion, letter recognition, or knowledge of vocabulary for reading (Bull, Andrews-Spy, & Wiebe, 2008; Fletcher et al., 1998) or counting, number comprehension, and knowledge of the decimal number system in the area of mathematics (Dehaene, 1997; Landerl, Bevan, & Butterworth, 2004). However, Gathercole, Lamont, and Alloway (2006) point out that the development of these domain-specific skills requires their interaction with other basic cognitive abilities that do not depend so much on environmental aspects and that provide students with the necessary opportunities to acquire skills and knowledge during their development (Bull et al., 2008; Geary, 2007). Among these skills, the different components of the working memory (WM) system identified by Baddeley and Hitch (1974; Baddeley, 2000) have been mentioned repeatedly, particularly, the executive function, which is considered to be responsible for the individual differences that emerge when dealing with complex cognitive tasks of novel content that cannot be processed in a completely automatic way (Baddeley, 2006).

Within this context, the primary purpose of this study is to verify the capacity of the WM, analyzed through the updating executive function, to predict the performance of reading comprehension and arithmetic problem solving in children aged 10-11 years. A second goal is to analyze whether the relation between the updating executive function and performance in reading and mathematics is direct or mediated by other domain-specific variables frequently associated with reading comprehension and problem solving—such as lexical processing or basic arithmetic skills, respectively—or general-domain variables—such as fluid intel-

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ligence. Three aspects of this investigation are novel. The first aspect is the choice of the 5th educational level age range, because a large part of the studies reviewed (e.g., Blair & Razza, 2007; Bull & Scerif, 2001; DeSmedt et al., 2009; Palladino, Cornoldi, De Beni, & Pazzaglia, 2001; McVay & Kane, 2011; Seigneuric & Ehrilch, 2005) have used samples with different ages from those of this study. The second aspect is the conjoint study of the relation between the executive function and academic performance in two specific areas: reading comprehension and problem solving. Separately, these two study areas have been the object of intense research, as presented in the theoretical part of this article (Cristopher et al., 2012; Hannon & Daneman, 2001; Imbo, Vandierendonck, & Vergauwe, 2008; McVay & Kane, 2011; Swanson, Jerman, & Zheng, 2008). However, we could not find any study in which both knowledge areas were studied conjointly. The third aspect is the methodological approach, which concurrently includes executive functioning, fluid intelligence, and domain-specific skills as predictors.

A model of executive functioning

One of the most widely accepted models of executive functioning is the multicomponent model of Baddeley and Hitch (1974; see also Baddeley 1986, 1992, 2000). According to this model, the WM is made up of a central executive, with limited capacity, which is in charge of processing and storing information, and which interacts in coordination with two supporting subsystems—the phonological loop and the visuospatial sketchpad—specialized, respectively, in linguistic (Baddeley, 1992) and visuospatial (Logie, 1986; Quinn & McConnell, 1996) information processing. Subsequently, a new element was added—the "episodic buffer"—which, among other functions, is in charge of integrating information from the WM and the long-term memory (LTM). From this viewpoint, according to the System of Attentional Supervision (SAS) model of Norman and Shallice (1986), the central executive has repeatedly been considered as a system of attentional control (Baddeley & Logie, 1999; Engle, Kane, & Tuholski, 1999; Miyake & Shah, 1999) with functions of an executive nature that have been linked to individual differences in complex cognitive tasks that require planning and control, such as language comprehension or reasoning (Baddeley, 1992).

One of the current issues under debate refers to the unitary (Heaton, Chelune, Talley, Kay, & Curtis, 1993, Kyllonen & Christal, 1990) or non-unitary (Collette et al., 2005; Diamond, 2002; Friedman et al., 2006) nature of executive functioning. From the unitary perspective, both the central executive and the SAS are considered to be active aspects of the LTM, without including any subcomponent or differential function (see Cowan, 1988; Engle et al., 1999). Along these same lines, some researchers have considered the central executive as a unitary system underlying the general intelligence factor (Duncan, Williams, Nimmo-Smith, & Brown, 1991; Kyllonen & Chrystal, 1990).

From a non-unitary perspective, Baddeley (1996) establishes a series of functions that are necessary for any system of executive control: coordination of concurrent tasks, control of strategies to encode and retrieve temporarily stored information, selective attention and inhibitory processes, and retrieval and manipulation of information from the LTM. It is noteworthy that this hypothesis has been corroborated in developmental studies with children and adolescents (Lehto, Juujarvi, Kooistra, & Pulkkinen, 2003; StClair-Thompson & Gathercole, 2006), healthy adults (Friedman & Miyake, 2004; Hedden & Yoon, 2006), brain damaged adults (Burgess, Alderman, Evans, Emslie, & Wilson, 1998; Duncan, Johnson, Swales, & Freer, 1997) and people with dementia (Collette, Van der Linden, & Salmon, 1999).

Years later, Miyake et al. (2000) published an influential work in which they differentiated three executive functions: response inhibition (the capacity to inhibit dominant, automatic, or prepotent information); updating of WM representations (the capacity to monitor and encode and maintain input according to task relevance, updating and replacing outdated, irrelevant information); shifting or alternating (the capacity to shift strategies when attending to multiple tasks or mental processes). Miyake et al. (2000) draw on an integrative model in which they choose an intermediate position, considering executive functioning simultaneously as unitary and non-unitary (see Friedman et al., 2008; Garon, Bryson, & Smith 2008). As mentioned, these authors distinguish three functions associated with executive functioning but, at the same time, they deem it necessary to have a measure of executive functioning as a unit, using for this purpose WM span tasks, such as the Reading Span test of Daneman and Carpenter (1980).

In studies following that of Miyake et al. (2000), other executive functions have been examined, such as the capacity to coordinate dual tasks (Logie, Cocchini, Della Sala, & Baddeley, 2004; Salthouse, Atkinson, & Berish, 2003), resistance to proactive interference (Friedman & Miyake, 2004), more global constructs such as planning (Das, Naglieri & Kirby, 1994; Fournier-Vicente, Larigauderie, & Gaonac'h, 2008) and specific subfunctions such as flexibility, self-regulation, or verbal fluidity (Andersson, 2002; Collette & Van der Linden, 2002). However, the three executive functions pointed out by Miyake et al. have united and dominated research in the field and have been empirically corroborated in studies with participants of diverse ages: preschool and primary education children (e.g., Garon, Bryson, & Smith, 2008; Lehto et al., 2003), youth (e.g., Huizinga, Dolan, & van der Molen, 2006), and adults (e.g., Fisk & Sharp, 2004).

The WM updating executive function

The updating function was defined by Morris and Jones (1990) as "*the act of modifying the current status of representation of schema in memory to accommodate new input*" (p.112), a definition that implies not only the replacement of current memory content with new content, but also the *modification* of outdated information as a function of new input.

According to this definition, the Reading Span test of Daneman and Carpenter (1980) that we used in our work requires the updating of information because, as noted by Miyake et al., (2000), Morris and Jones (1990), and Yntema and Meuser, (1962), WM contents change constantly during complex span tasks. These changes emerge from two sources while performing this task. Firstly, the input must be stored and combined with prior information (already stored). Secondly, changes can occur in the WM when it is necessary to store the product of the manipulations performed on the stored information. According to this, updating is necessary in most of the usual measures of WM capacity (see Conway, 2005 for a review).

Furthermore, numerous empirical studies have related complex WM span tests, such as the one we used, to the updating function. For example, in a seminal work in the field, Miyake et al. (2000) found that the operation span test (with the same structure as the reading span test, but using arithmetic operations instead of phrases) correlated highly with other updating tests (Keep track task, Tone monitoring task, and Letter memory task) but not with measures of shifting and inhibition. Accordingly, these authors concluded that there was a common WM factor underlying both updating and operation span. Similarly, St Clair-Thompson and Gathercole (2006) found very high correlations between complex verbal and visuo-spatial measures of span and update measures, concluding therefore that performance of complex span tasks is conditioned by the capacity to control the input and to update WM contents (see Conway & Engle, 1996; Engle, Tuholski, Laughlin, & Conway, 1999; Lehto, 1996; Miyake et al., 2000; Towse, Hitch, & Hutton, 1998).

In 2009, Schmiedek, Hildebrandt, Wilhelm, Lövdén, and Lindenberger carried out a study to compare a series of complex span tests—Reading span, Counting span, and Rotation span—with different tests that have been used specifically to measure updating: N-back, Memory updating, and Alpha span; all of them—span and updating tests—from different domains: verbal, numerical, and visuo-spatial. The results found showed that all three updating tasks made up a latent factor that was statistically identical to the latent factor of the complex span tasks (both factors had a virtually perfect correlation of .96, not statistically different from the unit), and also the correlations of the two factors with the Raven test were of the same magnitude. Therefore, individual differences in WM capacity may be explained by either one of the families of tasks. Hence, these authors suggested that WM updating tasks and WM span tasks could be used indistinctively and interchangeably (see also Ecker, Lewandowky, Oberauer, & Chee, 2010). Therefore, in numerous studies, both WM updating and span tasks are used (e.g., Bull & Scerif, 2001; Conway & Engle, 1996; Espy, 1997; Gathercole, Brown, & Pickering, 2003; Gathercole & Pickering, 2000; Hitch, Towse, & Hutton, 2001; Huizinga et al., 2006; Jarvis & Gathercole, 2003; St Clair-Thompson & Gathercole, 2006; Rosen & Engle, 1998; Towse, Hitch, Hamilton, Peacock, & Hutton, 2005; Andersson, 2008, among others).

In addition, the relation between the concepts of updating and WM span have not only been confirmed in behavioral studies, as seen above, but also in neurological studies observing that the left frontopolar cortex and the left medial frontal cortex are activated concurrently when WM span tasks and updating tasks are performed (Collette & Van der Linder, 2002).

From a developmental viewpoint, although there has been scarce research at first, it has been noted that complex executive skills such as updating information develop as of the second year of life (Alloway, Gathercole, Willis, & Adams, 2004) and that by the age of 6 years, this executive component is sufficiently developed to resolve complex tasks requiring the intervention of the central executive (Gathercole, Pickering, Ambridge, & Wearing, 2004). Thus, during childhood and adolescence, the evolution of simple and complex skills seems to follow a similar pattern (Gathercole et al., 2004), although a differential development associated with task complexity takes place during the entire stage of adolescence (Conklin, Luciana, Hooper, & Yarger, 2007; Luciana, Conklin, Hooper, & Yarger, 2005).

However, beginning with the seminal work of Yntema and Mueser (1962), the updating function has also been related to fluid intelligence. In this sense, different studies have pointed to WM updating as a predictor of fluid intelligence (Bellaci, Carretti, & Cornoldi, 2010; Friedman et al., 2008; Klauer, Wilmes, & Phye, 2002), although some authors question this relation (Ackerman, Beier, & Boyle, 2005)—or at least, they relativize the role of the WM with regard to the short-term memory—because in some investigations, individual differences in fluid intelligence are associated both with short-term memory and with WM (Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008; Swanson, 2008). More specifically, it has been reported that WM updating is the executive function that best predicts fluid intelligence (Friedman et al., 2008), and moreover, it has been confirmed that this relation is independent of the nature (verbal, numerical, or spatial) of the task employed (Kane et al., 2004).

WM updating and reading

Efficient reading requires the concurrence of different perceptive and cognitive processes. Some researchers have focused on the study of the influence on reading comprehension of domain-specific skills, such as lexical and phonological processing (Adams, 1990; Hulme & Snowling, 2009; Torgensen, 2000). The results of these studies indicate that difficulties to decode and process words influence reading comprehension negatively (Shankweiler, 1999; Sesma, Mahone, Levine, Eason, & Cutting, 2009).

From a developmental viewpoint, reading comprehension and lexical processing are closely related to early educational experiences (Byrne et al., 2007) but later on, as word reading improves and becomes automatic, comprehension is more closely related to general language comprehension skills (Keenan, Betjemann, & Olson, 2008; Vellutino, Tunmer, Jaccard, & Chen, 2007). Hence, deficits associated with reading comprehension go beyond these more domain-specific lexical processing difficulties and are more directly related to different domain-general functions, such as difficulties to retain relevant information in the WM, to inhibit information that is not needed to perform the ongoing task, and to access the LTM (Swanson, 2006).

According to the main theoretical models of reading comprehension, understanding a text requires maintaining active a large quantity of information, constantly updating the information during the reading process, and also inhibiting the information that is considered irrelevant. All these processes are related to the attentional control of information attributed to the central executive of the WM (Carriedo, Elosúa, & García-Madruga, 2011; Palladino et al., 2001; Radvansky & Copeland, 2001) and, specifically, to the updating and inhibition executive functions (Carreti, Cornoldi, De Beni, & Romanó, 2005; Carreti, Borella, Cornolodi, & de Beni, 2009). Singularly, as noted by Palladino et al. (2001), the updating executive process fulfills the first two functions with regard to the reading comprehension: activation of the relevant information to interpret the text or part of the text at a given moment and updating the information in the WM while keeping the relevant information available for reading comprehension.

In this sense, since the initial works of Daneman and Carpenter (1980), the executive component of the WM has traditionally been measured with complex span measures and classical updating tasks like that of Morris and Jones (1990). However, there have recently been many studies postulating that WM span and updating are the same construct. The relation between WM or updating and reading comprehension (e.g., Carriedo et al., 2011; Carriedo & Rucián, 2009; Daneman & Carpenter, 1980; Daneman & Merikle, 1996; Just & Carpenter, 1992; McVay & Kane, 2011; Sesma et al., 2009) and word reading (e.g., Cristopher et al., 2012; Swanson & Berninger, 1995) is well established in the literature, especially when the processing task in the span tests is of a verbal nature, like the above-mentioned reading span test of Daneman and Carpenter (1980) (e.g., Berninger, Abott, Vermeulen, & Fulton, 2006; De Beni, Borella, & Carretti, 2007; Swanson & Jerman, 2007). However, in some current studies (Cristopher et al., 2012; Hanon & Daneman, 2001, McVay & Kane, 2011), this relation is shown to be independent of the type of processing task included in these tests (verbal, numerical, or spatial).

WM updating and problem solving

As in the case of reading comprehension, the relation between the executive aspects of the WM and performance in mathematics is well established in the literature. They have been related to the coordination of different activities involved in counting (McLean & Hitch, 1999), global performance in mathematics (Bull et al., 2008; Toll, Van der Ven, Kroesbergen, & Van Luit, 2011) and, specifically, in arithmetic problem solving (Imbo et al., 2008; Swanson & Beebe-Frankenberger, 2004; Swanson et al., 2008).

Specifically, solving an arithmetic problem requires the competent use of different cognitive skills. Children must first understand what they are reading (Lee, Ng, & Ng, 2009). In addition, they must understand the underlying arithmetic operations (Rasmussen & Bisanz, 2005) and be capable of manipulating and understanding number relations (Fuchs et al., 2006). Lastly, they must distinguish the arithmetic problems based on the arithmetic operations involved (Rittle-Johnson, Siegler, & Alibali, 2001), construct a mental representation of the problem (Mayer & Hegarty, 1996), and effectively use the strategies they have learned (Geary, Hoard, Byrd-Craven, & Desoto, 2004). Research is still scarce but all these processes appear to require the intervention of the executive component of the WM (Passolungui & Mammarella, 2010; Rassmussen & Bisanz, 2005; Swanson et al., 2008) and, specifically, the executive processes of inhibition (Passolungui & Siegel, 2001) and updating of information, the latter assessed through specific updating tasks (Lee et al., 2009; Passolungui & Pazzaglia, 2004, 2005), or with complex WM span tasks (Swanson, 2006; Swanson et al., 2008).

With regard to the updating executive function, various authors (e.g., Blessing & Ross, 1996, Passolungui & Pazzaglia, 2004; Kotsopoulosa & Leeb, 2012) have pointed to updating as a key mechanism for solving arithmetic problems. The practical implementation of a problem would require the construction of a mental model of each step and its progressive modification when going on to the next step (Passolungui & Pazzaglia, 2005). In addition, as noted by Kotsopoulosa and Leeb (2012), both the linguistic and the mathematical complexity of the problem have been related to the results achieved in problem-solving. For instance, updating should not be considered a mere process of exclusion and inclusion of information but a complex process that attributes different levels of activation and that updates items continuously, retaining various simultaneously activated items (Passolungui & Pazzaglia, 2005).

Specifically, Passolunghi et al. (2004, 2005) found in their studies that updating could be related to performance in problem solving, inasmuch as children with lower updating functioning would obtain worse results when solving arithmetic problems. In particular, the authors note the individual differences that become evident when the problem requires the processing, suppression, and retaining of information. Comparable results in recent studies using similar tests have been reported (e.g., Palladino et al., 2001; Kotsopoulosa & Leeb, 2012). In view of the above, the results are still inconclusive (see Fuchs et al., 2006, Hecht, Close, & Santisi, 2003) because a large part of the studies have analyzed the link between executive functions and mathematics from a global viewpoint (Bull et al., 2008; Iglesias-Sarmiento & Deaño, 2011; Mazzocco & Kover, 2007; Toll et al., 2011), without analyzing the specific relation with numerical representation, simple arithmetic, algorithmic calculation, or problem solving. Likewise, the use in most of the studies of measures such as the backward digit span, about which there is some controversy concerning its executive nature (Colom, Abad, Rebollo, & Shih, 2005; Rabhubar, Barnes, & Hecht, 2010), hinders the generalization of results.

The present study

The main purpose of this investigation is to study the relation between executive functioning, concretely the function of WM information updating, and performance in two specific areas of reading and mathematics: reading comprehension and arithmetic problem solving. A second goal is to analyze whether the relation between the updating executive function and performance in reading and mathematics is direct or mediated by other domain-specific variables frequently associated with performance in reading comprehension and problem solving—such as lexical processing or basic arithmetic skills, respectively—or domain-general variables—such as fluid intelligence.

Following the proposals of Swanson et al. (2008), we used two hierarchical regression analyses to determine whether fluid intelligence or domain-specific skills mediate the relation between the WM updating executive function and reading comprehension and problem solving. It is assumed that, if the relation between updating and the criterion variables —reading comprehension and problem solving—is mediated by fluid intelligence or by domain-specific variables, the relation with WM would be nonsignificant when introducing these variables in the analysis. In contrast, if updating is the predictor variable of performance in reading comprehension or problem solving, then updating will continue to be significant when the variables of fluid intelligence or domain-specific variables are introduced in the analysis.

Method

Participants

The sample was made up of all the 5th-graders of Primary Education attending the groups-classrooms in a subsidized urban school in Ourense (Spain), declared plurilinguistic, although the children's maternal languages are Spanish and Galician. Specifically, a total of 49 students (16 boys and 33 girls) aged between 10 and 11 years (M =10.4, SD = .32) participated. None of the children presented developmental disorders or sensory or cognitive deficits or special education needs due to socio-cultural aspects. Although the variable gender was not considered in this study, no significant interactions were found between gender and the dependent variables of interest (p > .05).

It was decided to select children of this age range because it is one of the age ranges in which executive functioning has been the object of the most research—along with 6-8 years, 14-16 years,—in which a greater increase of brain development is observed and which also coincide with large changes observed at the cognitive level (Epstein, 1986).

Measures

Fluid intelligence. We used the Standard Progressive Matrixes (SPM, General) of Raven, Court and Raven (1996). The general scale has 60 items organized in five sets (A to E) with 12 items in each set. In each item, the children must complete a series of complex spatial figures by means of analogical reasoning. The final score is the sum of the number of correctly solved problems.

WM information updating. To measure the executive capacity to update information in the WM, we used the Reading Span Test for Children (PAL-N; Carriedo & Rucián, 2009) adapted by Daneman and Carpenter (1980). Like the original version, the test presents a series of semantically nonrelated phrases. The child should read each one of the 60 phrases aloud and remember the last word of each phrase in the same order in which the phrases were presented. The phrases were presented in sets of 2, 3, 4, 5, and 6 phrases. Therefore, the number of phrases in each set and the number of words to be remembered increase progressively. At the end of each set, the children were asked a comprehension question to control that they not only read aloud but also understood what they were reading. The test was scored according to the integrated criterion developed by Elosúa, Gutiérrez, García-Madruga, Luque, and Gárate (1996), which weights the children's performance at each of the established levels.

Basic arithmetic abilities. Basic arithmetic abilities were assessed through performance in the calculation and counting tasks of the subtests of "Aprendizajes Matemáticos" (Learning Mathematics) from the Psychopedagogical Battery "Evalúa" (Assess; García & González, 1996), version 4. These tasks, organized in six subtests, assess various automatisms related to number and quantity comprehension: the decimal number system, seriation and retrieval of facts, implementation of the algorithms of addition, subtraction, multiplication, and division. The final score of the test ranges between 0 and 35.

Arithmetic problem solving. We used the arithmetic problem-solving test from the subtests of Learning Mathematics of the Psychopedagogical Battery Assess (García & González, 1996), version 4, which assesses the basic acquisitions of the mathematical curriculum of the second cycle of Primary Education. Each task presents 15 written arithmetic problems that imply knowledge of numbers lower than one million, the decimal number system, number sequences, the differences in value between numbers, and the acquisition of the operations of addition, subtraction, multiplication, and division. The problems are formulated to pose two main requirements: comprehension of the problem and selection of the adequate procedure to solve it. The total score ranges between 0 and 15 points.

Reading comprehension. Reading comprehension was assessed from the results in the text comprehension task of the PROLEC-SE test (Ramos & Cuetos, 1999). Each individually administered task includes two expositive texts that pose several questions of a literal and inferential nature. The final score of the test ranges between 0 and 20 points.

Lexical processes. Lexical processes were assessed by means of the PROLEC-SE test (Ramos & Cuetos, 1999): pseudoword reading and isolated word reading (i.e., without any specific context).

The Pseudoword reading test requires reading aloud 40 pseudowords of diverse grapheme complexity and length. Of the 40 pseudowords, 20 are made up of simple syllables with a CV (consonant vowel) structure and 20 are made up of syllables with a complex structure (CCV, CCVC, and CVVC). Half of the pseudowords are long (4-5 syllabic structures) and the other half are short (2 syllabic structures). The final score of the test is the number of correctly read words.

In the Word reading test, children must read a list of 40 words made up of 20 frequently used words and 20 infrequent words. In each case, half of the words are short (2 syllables) and half are long (4 and 5 syllables). The score obtained is the sum of the correctly read words.

Procedure

The participants were assessed at their school, after receiving the corresponding permission from the families and the educational authorities. Each child was assessed in three sessions. The tests that can be applied in groups (Raven test and mathematics tasks) were administered collectively. The remaining tasks were administered individually in different sessions. Session duration ranged between 45 minutes and one hour. The administration order of the tests was counterbalanced in the two groups-classrooms.

Results

Table 1 presents the means and standard deviations of each dependent variable. Presentation of results is organized in two sections. In the first section, the relations between all the variables of interest are analyzed. In the second section, using hierarchical regression analysis, we assess the capacity of the selected variables to predict reading comprehension and arithmetic problem solving.

Pearson's correlation was calculated to analyze the relations between the different variables. As seen in Table 2, the measure of fluid intelligence correlated significantly with text comprehension (r = .43, p < .01), problem solving (r = .58, p < .0005), and arithmetic abilities (r = .42, p < .01). Likewise, it was significantly related to the measure of WM updating provided by the PAL-N (r = .49, p < .0005). No significant relationships were obtained with the other two variables that measure surface reading processes, such as word and pseudoword reading.

Table 1. Means and Standard Deviations of the Variables of Interest.

Variable	*M*	*SD*
1. Fluid intelligence	40.37	7.79
2. WM Updating	2.96	.49
3. Text comprehension	6.22	4.53
4. Problem solving	10.12	3.64
5. Arithmetic abilities	31.18	3.90
6. Pseudoword reading	36.55	4.78
7. Word reading	38.86	1.28

Correlational analyses

Regarding the measure of WM updating, a similar pattern of correlations was obtained: robust relations with text comprehension (r = .61, p < .0005) and arithmetic problem solving (r = .48, p < .01). The relation with the measure of arithmetic abilities was also significant (r =. 34, p < .05). The relations of updating executive function with lexical processing tasks did not reach statistical significance (p > .05).

Table 2. Correlations between the different Variables.

Variable	1	2	3	4	5	6	7
1. Fluid intelligence	-						
2. WM Updating	.49***	-					
3. Text comprehension	.43**	.61***	-				
4. Problem solving	.58***	.48**	.49***	-			
5. Arithmetic abilities	.42**	.34*	.34*	.60***	-		
6. Pseudoword reading	-.07	-06	-.19	.13	.13	-	
7. Word reading	.24	.08	.19	.35*	.35*	.33*	-

Note: *p < .05; **p < .01; ***p < .0005

Lastly, a robust relation between both measures of mathematics was observed (r = .60, p < .0005). Moreover, the variables that measure word and pseudoword reading were significantly related to each other (r = .33, p < .05) but not to the measure of text comprehension (p > .05).

Regression Analysis

In order to determine the contribution of the selected variables to academic performance, we carried out hierarchical regression analysis for each criterion variable: reading comprehension and problem solving. For this purpose, the variable related to updating information in WM was entered in Step 1. Subsequently, the variables related to lexical processing (pseudoword and word reading) and arithmetic abilities were included. Lastly, in both cases, the measure of fluid intelligence (Raven test) was entered in order to verify the predictor capacity of the measure of executive function in the presence of other variables to which it has been linked in the literature and which measure fluid intelligence and domain-specific abilities.

Table 3 presents the results of the analyses with regard to reading comprehension. In Model 1, we introduced the updating executive function as predictor variable, which explains 37.1% of the variance of reading comprehension, [β = .61, $t(47) = 5.26$, $p < .0005$]. The introduction of the variables of lexical processing in Model 2 increased the percentage of explained variance to 43.7%, and the introduction of fluid intelligence in Model 3 produced a further increase in the percentage of explained variance, reaching 44.6%. However, these increases in explained variance were nonsignificant, so that all the models point to WM updating as the single predictor of reading comprehension ($p < .0005$).

Table 3. Hierarchical Regression Analysis: Predictors of Reading Comprehension Performance.

Variable	R^2	Δ R^2	β	t	p
Model 1	.371	-			
WM Updating			.61	5.26	.000
Model 2	.437	.066			
WM Updating			.58	5.12	.000
Word reading			.22	1.87	.069
Pseudoword reading			-.22	-1.90	.064
Model 3	.446	.009			
WM Updating			.52	4.07	.000
Word reading			.19	1.58	.121
Pseudoword reading			-.21	-1.76	.084
Fluid intelligence			.07	.82	.412

The results of the analyses conducted with regard to arithmetic problem solving (see Table 4) are somewhat different. In Model 1, we only entered the updating executive function as predictor variable, explaining 22.7% of the variance of problem solving, [β = .48, $t(47) = 3.71$, $p = .001$].

Table 4. Hierarchical Regression Analysis: Predictors of Problem Solving Performance.

Variable	R^2	Δ R^2	β	t	p
Model 1	.227	-			
WM Updating			.48	3.71	.001
Model 2	.449	.222			
WM Updating			.31	2.65	.011
Arithmetic abilities			.50	4.30	.000
Model 3	.520	.071			
WM Updating			.18	1.49	.142
Arithmetic abilities			.41	3.52	.001
Fluid intelligence			.32	2.58	.013

In Model 2, the introduction of arithmetic abilities, also as a predictor variable, increased the explained variance to 44.9%, underlining the influence of the executive variable, [β = .31, $t(46) = 2.65$, $p < .05$], together with arithmetic abilities as predictors of problem solving, [β = .50, $t(46) = 4.30$, $p < .0005$]. Lastly, the introduction of fluid intelligence in Model 3 increased the explained variance of problem solving to 52%, but, in this case, the influence of updating ceased to be significant, whereas arithmetic abilities, [β = .41, $t(45) = 3.52$, $p = .001$], and fluid intelligence became significant, [β = .32, $t(45) = 2.58$, $p < .05$].

Discussion

The initial purpose of this study was to analyze the relation between the WM updating executive function and academic performance in reading comprehension and problem solving in the 5th grade of Primary Education. For this purpose, we analyzed the nature and direction of the relation and whether it was mediated by domain-specific skills inherent to each area or by domain-general abilities, such as fluid intelligence. We shall first discuss the results concerning reading comprehension and then, those regarding mathematical performance.

With regard to the relation between the executive function of WM information updating and reading comprehension, the results obtained support the capacity of complex span tests—understood as the measure of the WM updating executive function—to predict individual differences in reading comprehension, an aspect underlined in diverse investigations performed with people of different ages (e.g., Berninger et al., 2009, Daneman & Carpenter, 1980; De Beni et al., 2007; Swanson & Jerman, 2007). The results also corroborate the predictor value of the updating executive function in reading comprehension in children between 10-11 years of age (Carriedo & Rucián, 2009; Christopher et al., 2012; Sesma et al., 2009). Furthermore, the results of this study replicate those obtained in the adaptation of the Reading Span Test of Daneman and Carpenter (1980) for children carried out by Carriedo and Rucián (2009), despite the fact that, in our study, we added a comprehension control question to each series of phrases.

But our results go beyond this, revealing that the updating executive function is the only predictor of reading comprehension, even when controlling for domain-specific skills—lexical processes—and domain-general skills—fluid intelligence. These results are in line with the study of Seigneuric and Ehrlich (2005) with 3rd-graders of Primary Education, in which no predictor relations were found between WM and word reading, although there were relations between WM and reading comprehension. These results also provide important support to the results of Cristopher et al. (2012) regarding the role of WM in reading comprehension, although—in clear contrast to our results—these authors did find significant relationships between WM and word reading. A possible explanation of these contradictory results is that at, these educational levels, reading comprehension requires cognitive resources that go beyond phonological decoding and the identification of letters (Sesma et al., 2009). In a similar vein, the lower demand for attentional resources in lexical processing could be due to the fact that these processes are already automated at this age.

However, with regard to the relation between WM information updating and mathematical performance, it can be stated that, in general, our results support the hypothesis that WM updating is related to individual differences in problem solving. These results are consistent with the conclusions of different works focusing both on children of lower educational levels (e.g., Passolungui & Pazzaglia, 2004; Swanson et al., 2008) and of similar levels to that of this study (Lee et al., 2009).

In addition, as in the case of reading comprehension, the updating executive function contributes to explaining a considerable percentage of the variance of problem solving, beyond the contribution of domain-specific skills. The hierarchical regression analysis indicates that, when introducing the variable related to the executive functioning of the WM, the model explains about 22.7% of the variance of problem solving. The inclusion of the domain-specific measure, which involves numerical competence, knowledge of arithmetic algorithms, and retrieval of arithmetic facts from the LTM, does not eliminate the influence of WM updating in arithmetic problem solving, and it produces a significant increase in the proportion of explained variance, which reaches 44.9%, as expected in accordance with the literature (Rassmusen & Bisanz, 2005; Geary et al., 2004). This finding replicates and extends the results obtained by Swanson et al. (2008) in their study with 1st and 2nd graders from Primary Education, indicating that, in contrast to the results for reading comprehension, the mastery of the basic arithmetic competences is not completely automated at this age. It also indicates that, together with updating, these competences still contribute significantly to the explanation of individual differences in problem solving, compensating for the influence of individual differences in WM, as mentioned by Swanson et al.

However, our results contrast with those of other works that did not obtain predictor relations between WM and problem solving (e.g., Fuchs et al., 2006; Hecht, Close, & Santisi, 2003). A possible explanation of these differences may lie in the different tests used to study WM and problem solving. A large part of the studies carried out in this area (see Rabghubar et al., 2010, for a review) have used domain-specific WM tasks—forward and backward digit span, counting span—to assess the executive functioning of the WM, tests that some authors (Colom et al., 2005) have regarded as passive storage. Concerning the tests used to measure mathematical performance, different standardized tests or ad hoc tests and oral (Bull et al., 1999; Fuchs et al., 2006) or written formats (Passolungui & Pazzaglia, 2005; Swanson et al., 2008) have been used habitually, making comparison and generalization of the results obtained difficult.

Lastly, another interesting aspect of our work refers to the differential role of fluid intelligence in problem solving and reading comprehension. The introduction of fluid intelligence in the hierarchical regression analysis did not change the predictor relations between WM updating and reading comprehension, and its weight in the regression was nonsignificant However, in the case of problem solving, as a result of the incorporation of fluid intelligence in the hierarchical regression analysis (see Model 3 in Table 4), updating ceased to predict problem solving. This seems to suggest overlapping between the variance explained by updating and fluid intelligence, two variables that the literature has repeatedly related to each other (e.g., Bellaci et al., Friedman et al., 2008) but has not totally identified (Conway, Kane, & Engle, 2003).

A possible explanation of these results could be related to the verbal nature of the processing task included in the WM span test in this study (which consisted of reading phrases aloud), whereas the processing tasks included in other span tests that were employed in most of the reviewed studies in the area of mathematics involve number processing—backward digit tasks or counting span. These data question the domain independence of WM span tests, as found by Carriedo and Rucián (2009), in contrast to statements by authors like Cristopher et al. (2012), Hanon and Daneman (2001), or McVay and Kane (2011).

Another possible interpretation of the differential relations could be the demands of the criterion task used. Solving problems like those presented in this study seems to require, in addition to constructing a mental representation of the problem and its solution (Mayer & Hegarty, 1996), the mastery of basic mathematics abilities, as shown in the results. Different authors (e.g., Battista, 1994; Hermelin & O'Connor, 1986) have stated that mathematical logical reasoning is facilitated by the individual's capacity to interrelate spatial images and verbal propositions. The relations between spatial capacity and individual differences may be reconsidered from the PASS model of Das et al. (1994), which redefines intelligence as a function of four basic psychological processes: Planning, Attention, and Simultaneous and Successive Processing. From the viewpoint of this theory, spatial capacity can be considered as a simultaneous and quasi-spatial format and, therefore, linked to simultaneous processing (Das & Varnhargen, 1986). Thus, tasks associated with spatial capacity such as mathematics (Diezmann & Watters, 2000) seem to be easier for students who process information simultaneously than for students who process it sequentially (Das & Verhargen, 1986; Watters & English, 1995). Progressive matrix tasks—such as the Raven test we used in this study—have been considered a measure of simultaneous processing in a large number of publications (e.g., Das, Kirby, & Jarman, 1979; Das et al., 1994); hence, the robust relation between fluid intelligence, as analyzed with this kind of task, and a mathematical reasoning test, such as problem solving, seems obvious. Therefore, our results indicate that neither the WM span test nor the Raven text are as domain independent as formerly assumed, which could open a new line of research for future works.

Summing up, this study extends the results of previous research with regard to the role of executive functioning and, specifically, of WM span, in high-level cognitive activities such as reading comprehension and problem solving. The results point to WM updating as a significant predictor of reading performance and arithmetic problem solving. In the area of reading comprehension, it is the only predictor at this educational stage, whereas in the case of problem solving, perhaps due to the task content, its influence appears to be mediated by fluid intelligence.

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