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Working memory, number sense, and arithmetical performance

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Abstract: The literature discusses the relationships between working memory (WM) and mathematical performance, but the results regarding which components of WM are most influential to numerical competence are still controversial. The correlations between number sense (NS) and WM are recent. The present study aimed at correlating (Spearman) the WM capacity (central executive component – numerical and non-numerical information; and phonological – memory for digits, sentences, short stories), the arithmetical performance (TDE arithmetic subtest) and the NS (Number Knowledge Test). The research involved 79 students, from the 4th to the 7th year of elementary school, with average and below average performance in arithmetic. A better performance in the central executive component correlated to a better performance in NS and arithmetic. We did not observe the same relation for the phonological component. Educational implications result from expanding knowledge in this area. We emphasize the importance of a more significant uniformity in the instruments that assess these domains.

Keywords: working memory; executive component; phonological component; number sense; arithmetical performance.

MEMÓRIA DE TRABALHO, SENSO NUMÉRICO E DESEMPENHO EM ARITMÉTICA

Resumo: As relações entre a memória de trabalho (MT) e o desempenho em matemática são discutidas na literatura, contudo são controversos os resultados sobre quais componentes da MT exercem maior influência à competência numérica. As relações entre o senso numérico (SN) e a MT são mais recentes. O presente estudo objetivou correlacionar (Spearman) a MT (componente executivo central – informação numérica e não numérica; e componente fonológico – repetição de dígitos, frases, relatos), o desempenho aritmético (subteste aritmético TDE) e o desempenho em SN (Teste de Conhecimento Numérico). Participaram 79 alunos, do 4º ao 7º ano do Ensino Fundamental, com desempenho aritmético baixo e mediano. Melhor desempenho no executivo central correlacionou-se a uma melhor performance no SN e na aritmética, e o mesmo não foi evidenciado para o componente fonológico. Implicações educacionais derivam da ampliação de conhecimentos nessa área. É ressaltada a importância de maior uniformidade nos instrumentos que avaliam esses domínios.

Palavras-chave: memória de trabalho; componente executivo central; componente fonológico; senso numérico; desempenho aritmético.

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MEMORIA DE TRABAJO, SENTIDO DE NÚMERO Y RENDIMIENTO ARITMÉTICO

Resumen: Relaciones entre la memoria de trabajo (MT) y el desempeño matemático son discutidas en la literatura, todavía son controvertidos los resultados sobre cuales componentes de la MT desempeñan papel destacado en competencia numérica. Relaciones entre sentido numérico (SN) y MT son más recientes. Este estudio objetivó correlacionar la MT (ejecutivo central – información numérica y no numérica; y fonológico – repetición de dígitos, frases, relatos) con el desempeño aritmético (prueba aritmética TDE) y el desempeño en SN (Prueba de Conocimiento Numérico). Participaron 79 alumnos, del 4º al 7º año de la enseñanza fundamental, con desempeño bajo y mediano en aritmética. Un mejor desempeño en el ejecutivo central se correlacionó con mejor desempeño en SN y en aritmética. El mismo no fue evidenciado para el componente fonológico. Implicaciones educativas derivan de la ampliación de conocimientos en esta área. Se resalta la importancia de uniformidad de los instrumentos que evalúan estos ámbitos.

Palabras clave: memoria de trabajo; componente ejecutivo central; componente fonológico; sentido de numérico; desempeño aritmético.

Introduction

Both the number sense and working memory are vital skills for mathematical competence (Jordan, Glutting, & Ramineni, 2010; Passalunghi & Lanfranchi, 2012; Passolunghi, Mammarella, & Altoè, 2008). The relationships between working memory and performance in mathematics have been widely discussed in the literature (Andersson, 2008; Andersson & Lyxell, 2007; McLean & Hitch, 1999; Passolunghi & Lanfranchi, 2012). Studies on the association between working memory and number sense are recent though (Friso-van den Bos, Van Der Ven, Kroesbergen, & Van Luit, 2013; Lee et al., 2012).

The learning of mathematics requires both numeracy skills (specific domain skills) and basic competences (general domain skills). In this article, we will highlight the number sense (as numeracy) and working memory (as basic competence), the competences that have increasingly been highlighted in the literature (Andersson & Lyxell, 2007; Jordan et al., 2010; Passolunghi & Lanfranchi, 2012). Initially, we show the advances in research on the number sense and working memory, indicating agreements and controversies surrounding the discussions of these issues. Then, we emphasize some studies that relate working memory and performance in mathematics, as well as in number sense. Finally, we present our research.

Number sense

A growing body of research suggests that an underdeveloped number sense is one of the traits that accompany students who are struggling in mathematics and that problems with the number sense can be identified early in childhood education (Jordan et al., 2010; Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Passolunghi & Lanfranchi, 2012).

There is no consensus on the concept of number sense. Its definition and characteristics have been the subject of debate since the late 1980s and early 1990s. The contributions

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of scholars such as Sowder and Shapelle (1989) and Greeno (1991) influence current research on the subject. The authors point to the number sense as a complex and multifaceted construct that does not refer to a body of knowledge or a single curricular unit, but rather to a way of thinking that entails the ability to use mathematical skills in order to meet daily needs. Spinillo (2014) reflects this view when she stresses that "this form of thinking" needs to permeate the teaching situations in all fields of mathematics and in all segments of education.

When defining number sense, some authors highlight the conceptual, abstract part of numerical processing. Dehaene (2001), for example, points out that the number sense refers to the ability to represent and mentally manipulate numbers and quantities. Other researchers (Jordan et al., 2010) use definitions emphasizing performance, which is facilitated by the conceptual understanding of number, such as counting ability, number identification and estimation, among others. We believe that both ways of defining number sense are complementary as, in order to be successful in the understanding and execution of tasks involving numbers, numerical relations and quantities, an abstract understanding of numerical processing is necessary. Therefore, the understanding of number sense that characterizes this article is that this is a general construct, which encompasses a very broad set of concepts, which the student develops gradually, from his interactions with the social environment (Corso & Dorneles, 2010).

Of course, the lack of consensus on the definition of this concept makes the discussion about how best to assess and intervene in this area controversial. Studies involving these themes have aroused the interest of researchers and offered promising results. Research shows that the number sense is a good initial detector of difficulties in arithmetic (Jordan et al., 2010; Passolunghi & Lanfranchi, 2012). Studies on the predictive power of numerical sense end up influencing research on intervention in this area (Jordan et al., 2010; Kuhn & Holling, 2014). More recently, researchers are interested in the association between the number sense and the different components of the working memory system (Friso-van den Bos et al., 2013; Kroesbergen et al., 2009; Lee et al., 2012). But the literature relating such competences remains scarce and many questions regarding this association need to be better understood, such as: what is the extent of involvement of the different components of working memory in number sense tasks? Is there a component that plays a more important role? The present study sought to contribute to this discussion by investigating the associations between two components of working memory (central executive and phonological) and the number sense performance.

Working Memory

Working memory (hereafter referred to as WM) is a memory system of limited capacity, responsible for temporarily storing the information and, at the same time, processing it during cognitive activity. The WM model of Baddeley and Hitch (1974) has been the most used in the literature to analyze the role of working memory in mathematics tasks. This model was reviewed by Baddeley (2000) and currently comprises four components: the central executive, an attention controller responsible for the manipulation of information; the phonological component, for storing verbal information; and the visuospatial component, responsible for the retention of visuospatial information. The episodic buffer is responsible for the integration of the information coming from the phonological and visuospatial components of WM with the long-term memory.

Relationship between working memory and performance in mathematics

Despite evidence that WM is critically involved in mathematical performance (Andersson & Lyxell, 2007; McLean & Hitch, 1999; Passolunghi & Lanfranchi, 2012; Passolunghi et al., 2008), the literature shows inconclusive results as to which components of WM are most strongly associated with competence in this area. For example, McLean and Hitch (1999) observed that students with math difficulties perform poorly on tasks that evaluate visuospatial sketching. Andersson and Lyxell (2007), on the other hand, found no relation between this component and the difficulties in mathematics. Research associating the phonological component of WM and mathematical performance, in turn, present both positive (Andersson & Lyxell, 2007; Passolunghi et al., 2008) and negative relations (Passolunghi & Lanfranchi, 2012). As for the central executive component of WM, the scenario is not different, as some studies show that students with difficulties in mathematics show lags in the tasks that evaluate the central executive (Andersson & Lyxell, 2007; Passolunghi & Lanfranchi, 2012), while others do not demonstrate this association (Andersson, 2008).

Also concerning the central executive, despite the controversial results, it is important to highlight that several studies point to this component as the most impaired in students who face problems in mathematics (Andersson & Lyxell, 2007; Friso-van den Bos et al., 2013; Kroesbergen et al., 2009; McLean & Hitch, 1999). It should be reminded, as described in Andersson e Lyxell (2007), that the central executive deals with tasks of greater cognitive demand, and therefore presents three specific functions: a) Updating – perform active processing and updating of information in WM; b) Shifting – option for a task, strategy or operation; c) Inhibition – to prevent irrelevant information from entering or remaining in the WM.

Studies show compromises of the different functions of the central executive in students with problems in mathematics. For example, difficulties with inhibitory control are pointed out in McLean and Hitch (1999) and problems with the update function are evidenced in Friso-van den Bos et al. (2013). Another focus of this study was to investigate the association between working memory, in its phonological and central executive components, and performance in arithmetic. The research involved only the updating function of the central executive.

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Relationship between working memory and number sense

More recently, research has investigated the associations between the different components of WM and the performance in number sense. Among the components of WM, the central executive, with its distinct functions, has been the most studied. There is no consensus about the role each central executive plays in the number sense. Some studies suggest that inhibition plays an important role in predicting number-sense performance (Kroesbergen et al., 2009), but this result was not found in the study by Lee et al. (2012). The updating function is most commonly pointed out as a predictor of number sense (Kroesbergen et al., 2009; Lee et al., 2012).

Friso-van den Bos et al. (2013) conducted a meta-analysis involving 15 studies with children aged 4 to 12 years. These comprised at least one number sense measure and one or more of the functions of the central executive component of WM under evaluation (updating, inhibition, shifting). The author found an association between number sense and the update and inhibition functions, among which updating showed the strongest correlation with the number sense.

Based on the above, the aim in this study is to: a) verify if there is a correlation between the capacity of the WM (through the central executive component – update function) and the performance in arithmetic and number sense; b) verify if the WM capacity (through the phonological component) is correlated with the performance in arithmetic and number sense. The study seeks to contribute to the literature as, although research in this field has stood out for some time (particularly the associations between WM and arithmetic performance, while less attention has been paid to the associations between WM and number sense), its results remain controversial and hardly conclusive. Therefore, further knowledge in this area is highly necessary. The hypothesis we raise is that the WM capacity, through the central executive and phonological components, is correlated with the arithmetic performance as well as the number sense performance of the students who participated in this research.

Method

Participants

In total, 79 students between 10 and 14 years old (36 girls and 43 boys) participated in the research, taking the 4th to 7th grade at five public schools in the city of Porto Alegre, Rio Grande do Sul. The mean age was 11.9 years (Table 1). The schools are located in surrounding neighborhoods and show similarity in the teaching method and socioeconomic characteristics. Three criteria were used for the sample composition. The first was the teacher's indication of students performing at or below average in math. The second was the students' performance in the math subtests of the TDE – Stein's School Achievement Test (1994). We selected the students who presented average and below-average scores in arithmetic in relation to the expected scores for the respective grades. The third criterion was performance on the Wechsler intelligence scale for children WISC-IV (Wechsler, 2013) in the Blocks and Vocabulary subtests (Wechsler, 2013). As a criterion for exclusion, besides not completing the three aspects mentioned above, the presence of sensory impairment and the diagnosis of neurodevelopmental disorder were considered. Of the 120 students who were referred by the teachers, 79 met the inclusion / exclusion criteria. The parents of all participating students gave their authorization through the signing of the Free and Informed Consent Form and the Dissent Form. Approval for this study was obtained from the Research Ethics Committee of Universidade Federal do Rio Grande do Sul. Table 2 shows the sample description data.

Table 1. Pearson's correlation coefficient (r) and the level of significance (p) between the numerical-sense measures (TCN) and performance in arithmetic (SA-TDE) with the different components of working memory (central and phonological executive component)

	WM1		WM2		DM		MS		MSS	
	r	p	r	p	r	p	r	p	r	p
NKT	0,44	0,000*	0,316	0,005*	0,153	0,177	0,169	0,137	0,226	0,45*
SA-TDE	0,303	0,007*	0,344	0,002*	0,189	0,096	0,12	0,915	0,069	0,547

NKT = Numerical-sense measures; AS = TDE arithmetic subtest; WM1 = Working memory 1 (non-numeric task); MT2 = Working memory 2 (numeric task); MD = Digit memory; MS = Memory of sentences; MSS = Memory of short stories.

* level of significance, p-value < 0,05.

Source: The author.

Table 2. Description of total sample

	Mean	Median	Standard deviation	Minimum	Maximum
Age	12,19	12,30	1,51	10,0	17,7
IQ	105,81	107,00	11,74	89,0	129,0
NKT	38,46	39,00	5,64	22,0	50,0
AS-TDE	20,15	20,00	4,46	12,0	34,0
WM1	24,82	25,00	3,57	15,0	32,0
WM2	8,14	8,00	2,34	3,0	16,0
DM	9,53	10,00	1,70	6,0	12,0
MS	9,19	9,20	0,59	6,0	10,0
MSS	21,81	23,00	4,69	4,0	28,0

NKT = Number Knowledge Test; AS = TDE arithmetic subtest; WM1 = Working memory 1 (non-numerical task); WM2 = Working memory 2 (numerical task); DM = Digit memory; MS = Memory for Sentences; MSS = Memory for Short Stories.

Source: The author.

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Instruments used

Arithmetic – Arithmetic subtest of TDE (AS-TDE) – Stein's School Achievement Test (1994), standardized instrument for the South of Brazil, composed of 38 questions involving arithmetic calculations with increasing degree of difficulty.

Number Sense – Number Knowledge Test (NKT) (Okamoto & Case, 1996) composed of a series of questions structured in four levels of complexity, from the simplest to the most complex. The instrument makes it possible to evaluate the knowledge of concepts and basic arithmetic operations of the child, as well as to evaluate his/her understanding of those concepts and operations.

Working Memory – The study evaluated the central executive component and the phonological component of working memory. The central executive component (update function) was measured using two distinct tasks: task with non-numerical information (adapted from Hecht et al., 2001) and task with numerical information (task adapted from Yuill et al., 1989). In the first, students answer "yes" or "no" to sets of two to four questions and then repeat the last word of each question. For example, in the set of two questions "Do the tables walk?" and "Do the lamps run?", the correct answers would be "no" to each question, followed by "walk" and "run". In the second task, students read aloud increasing series of three-digit groups and, at the end of each series, they need to remember, in order, the final digit of each group. For example, for the groups (2 5 7) and (1 6 8), the digits "7" and "8" need to be recalled. The phonological component was evaluated through the phonological memory for digits, sentences and short stories (adapted from Golbert, 1988).

Procedures

The researcher applied the tasks individually in a room provided by the schools. A psychologist applied the WISC block and vocabulary tests. The order of the tasks was the same for all participants. It took three periods of 50 minutes per student to perform the tasks.

Data analysis

Initially, we analyzed the distribution of the research variables using the Kolmogorov-Smirnov and Shapiro-Wilk normality tests. The results indicated that the variables did not follow a normal distribution and, therefore, non-parametric statistics were used for data analysis. The Spearman correlation test was then performed with a 5% significance level to show the correlations between the variables discussed in this study: working memory (phonological and central executive component), arithmetic performance and number sense performance.

Results

The study showed a significant correlation between the instruments that evaluated arithmetic performance and the number sense ($r = 0.562$, $p = 0.001$), suggesting the internal consistency of the instruments used in the research to measure the numeracy (AS-TDE and NKT). A significant correlation was found between the two tasks that evaluated the central executive component of WM and the number sense performance (WM1 r = 0.408, p = 0.001; WM2 r = 0.340, p = 0.002). Likewise, a significant correlation was evidenced between these tasks and the arithmetic performance (WM1 r = 0.268, p = 0.017, WM2 r = 0.335, p = 0.003). On the other hand, the phonological component of the WM did not reveal a significant correlation in any of the three tasks used to assess this variable and the number sense, nor did it reveal a significant correlation with the arithmetic performance. The correlations among the measures are displayed in Table 3.

Table 3. Spearman correlation coefficient (r) and significance level (p-value) between the number sense (NKT) and arithmetic performance measures and the different components of working memory (central executive and phonological components)

	WM1		WM2		DM		MS		MSS	
	r	p-value	r	p-value	r	p-value	r	p-value	r	p-value
NKT	0,408	0,001*	0,340	0,002*	0,166	0,144	0,119	0,298	0,158	0,163
AS-TDE	0,268	0,017*	0,335	0,003*	0,152	0,181	0,003	0,980	-0,023	0,841

NKT = Number Knowledge Test; AS= TDE arithmetic subtest; WM1 = Working memory 1 (non-numerical task); WM2 = Working memory 2 (numerical task); DM = Digit memory; MS = Memory for Sentences; MSS = Memory for Short Stories.

* p-value < 0.05.

Source: The author.

Discussion

The aim of this study was to investigate the associations between WM (central executive and phonological component) and numerical competence assessed through two tasks: one number sense (NKT) and the other arithmetic performance (AS-TDE).

As expected, there was a significant correlation between the number sense and arithmetic performance tasks, evidencing an internal consistency of the instruments used to measure numerical competence. This result corroborates the research that points out the critical role of number sense for arithmetic competence (Jordan et al., 2010; Lee et al., 2012; Passolunghi & Lanfranchi, 2012).

A significant correlation was evidenced between the two tasks that evaluated the central executive component of WM and the number sense, reinforcing the fact that dealing with proposals that include counting, operations, estimates and mental calculation (tasks that composed the NKT) requires the involvement of WM, in this case, especially through the central executive system, as no positive relation was found

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between the phonological component of WM and the number sense measure. This result converges with other studies that demonstrate the strong association between the central executive (updating function) and the number sense (Lee et al., 2012). In the same sense, Friso-van den Bos et al. (2013) evidenced that, among the functions of the central executive, updating has the strongest correlation with the number sense.

As for the associations between WM and arithmetic performance, our results corroborate those that emphasize the positive association between these variables (Passolunghi & Lanfranchi, 2012; Passolunghi et al., 2008), reinforcing that WM is critically involved in a range of numerical and arithmetic skills. In this study, this positive association refers to the central executive component of WM (in the two tasks involved), but not to the phonological component.

Therefore, in the sample surveyed, it was observed that a better performance in the central executive component of WM is associated with a better performance in numeracy (number sense and arithmetic). This result suggests that these skills involve the storage and simultaneous processing of information in WM, that is, they require integrating the information that is being encoded with the knowledge already stored in the long-term memory. During counting, for example, in performing a simple arithmetic calculation, maintaining and processing intermediate results in WM is necessary until the final calculation result can be reached. The central executive component of WM seems to be quite demanded while students have not yet acquired an automatism concerning many of the skills needed to succeed in mathematics (e.g., automatic retrieval of basic arithmetic facts), which is expected to happen as the student progresses in school. The transition from more conscious student monitoring (using earlier counting strategies, for example) to an automatism in the calculation, however, goes through a process that, until being more mature, will require a greater demand for WM. It is possible that the students in our sample, composed of low and median performance in arithmetic, still are not very automatic and, accordingly, rest more intensely on WM, in this case, through the central executive component. It should be reminded, however, that the study did not evaluate the types of counting strategies and procedures students used, which would allow us to confirm this interpretation.

On the other hand, contrary to what we hypothesized, in the study, no association was found between the phonological component of WM (responsible for retaining numbers during the arithmetic process) and numerical competence (number sense and arithmetic). Although some studies point to the correlation of all components of WM with mathematical performance (Friso-van den Bos et al., 2013) – although highlighting a greater association with the central executive component – other studies did not find a correlation between the phonological component and numerical competence (Passolunghi & Lanfranchi, 2012).

Meyer, Salimpoor, Wu, Geary and Menon (2010) point out that the variation in the strength of the association between the different components of WM and numerical competence can be explained by methodological aspects such as: variation in the subjects' ages, distinct tasks used to measure mathematical performance and the different

WM measures found in the literature. In this study, we used informal research tasks to measure the phonological component of WM. Perhaps these tasks were not sensitive enough to evaluate this component. Meyer et al. (2010) emphasize the importance of research using standardized instruments to evaluate the various components of WM.

Also considering the methodological aspects of research on WM, Friso-van den Bos et al. (2013) observe that the correlations between the different components of WM and numerical competence are more influenced by the characteristics of the studies' mathematical measures (larger or more specific tests involving only a certain mathematical skill) and the type of sample (students with or without difficulties in mathematics, for example) than by the measure of WM or the subjects' age. Regarding the characteristics of the tests used, our study involved broader instruments that tend to produce stronger correlations than the more specific tests (Friso-van den Bos et al., 2013), because the more extensive assessments of mathematics require that the student have to alternate the various operations and mental models to account for the challenges the task imposed, recruiting more intensively the different components of working memory. For example, the AS-TDE involved calculations containing different operations and the NKT comprised different aspects of this domain. As for the type of sample, greater statistical associations are found in groups of students facing difficulties in mathematics (Andersson & Lyxell, 2007; McLean & Hitch, 1999; Passolunghi et al., 2008). It is possible that if our sample included only students with poor performance in this area, we would find a significant correlation between the phonological components of WM and the measures of number sense and arithmetic performance used.

The investigation of associations between WM, number sense and arithmetic performance entails important educational implications. Greater knowledge about the cognitive skills underlying mathematics learning can help teachers to develop curricula in which the demands of WM are appropriate to the possibilities of the students, considering the age group and the requirement level of the task.

It should be noted that the way the teaching process is conducted will directly influence the effect the cognitive deficit has on learning. For example, students who are too slow to calculate end up overloading the WM and thus increase the chance of error in the calculation. These students need interventions designed to teach effective strategies, such as decomposition and immediate retrieval of basic facts for support while solving the more complex calculations. In this case, the teaching of strategies is used to compensate for the students' WM difficulty.

Research suggests that the WM capacity can be amplified through specific intervention strategies by means of computer games (Kuhn & Holling, 2014). The results of these papers are still controversial though (Melby-Lervag & Hulme, 2013). In the intervention study by Kuhn and Holling (2014), the mathematical skills of students with no difficulties in mathematics who received intervention in WM or number sense were compared between the pre-test and the post-test. Both interventions resulted in improvements in students' math skills compared to the control group. The combination

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of WM interventions with the specific sub-areas of mathematics in which the student demonstrates delays has been highlighted (Melby-Lervag & Hulme, 2013). Interventions of this kind can offer promising results.

A limitation in our study is the non-inclusion of the visuospatial component of WM and the central executive's inhibition and shifting functions, which could enrich the analyses. We also point out that the study does not present a more homogeneous number of students representing the different school years, especially in the case of the 4th and 6th year. It should be reminded, however, that the objective of the study did not involve the correlation during each school year between the variables in question, but rather the search for correlation in the context of this sample, constituted by students with different levels of education. This fact generated the need for non-parametric statistical treatment and permitted evidencing positive and significant correlations between the numerical competencies evaluated and WM in this study sample.

Finally, this research contributed to the discussion about the association between WM, number sense and arithmetic performance. As we pointed out throughout the study, there are still many contradictions in the literature correlating these three domains, which generates the need for further research. We know that the existing controversies present a great challenge for research in this area, as well as the need for methodological attention in future studies, especially with regard to the search for greater uniformity in the instruments that evaluate the numerical and basic competences, thus permitting the production of research data for comparison and validation.

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